The Impact of Spatiotemporal Calibration on Sense of Embodiment and Task Performance in Teleoperation

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Abstract

In teleoperation, the spatiotemporal calibration of the system can significantly impact both performance and user experience, which may not necessarily be causally linked. This study asks if Sense of Embodiment (SoE) varies with spatiotemporal calibration of a teleoperated system, which in turn affects task performance. Most SoE studies are passive and they do not represent a great paradigm to study the impact of calibration on SoE in active teleoperation. Therefore, we designed an active RHI in mixed reality where we manipulated both the spatial calibration (shifts) and visuo-proprioceptive synchronicity (temporal delay). We investigated if this manipulation affected performance, proprioceptive mapping, SoE and the perception of the setup as a mediator. The results suggest a potential direct influence of SoE on task performance, particularly through enhanced calibration due to synchronicity, indicating potential benefits for sustained usage. Additionally, SoE is explored comprehensively, employing multiple tests assessing implicit and explicit dimensions of calibration.

Keywords: Sense of Embodiment, Proprioception, Task Performance, Mixed Reality, Teleoperation, Calibration

Introduction

This study explores the complex relationship between teleoperation and the Sense of Embodiment (SoE) (Falcone et. al, 2023), addressing the challenge of bridging physical distances and experiencing remote events in real-time. Teleoperation, defined as the remote control of devices or machines (Hokayem & Spong, 2006), is closely tied to the concept of telepresence, which involves feeling present in a location other than one's physical body (Cowan & Ketron, 2019, Yousif, 2021, Fitter et al., 2021). Thanks to the new developments in virtual reality (VR), robotics, and multisensory systems, the implementation of telepresence can be extended beyond the mere feeling of being present at a remote location. Now, SoE can be extended over an avatar, making people cognitively and emotionally engaged with their task at hand. The SoE, encompassing a sense of ownership (feeling of self-attribution), agency (feeling of control), and self-location (the perception of being located in a volume of space) over a remote avatar, is crucial in understanding the immersive experience of teleoperation.

Building on previous research linking a high level of SoE to improved telepresence and task performance (Kilteni et al., 2012, Krom et al., 2019, Longo et al., 2008, Falcone et al., 2023, Forster et al., 2022), this study aims to identify the factors influencing the sensorimotor calibration process over an avatar and its ultimate impact on embodiment and task performance. It would seem intuitive that in a teleoperation scenario the feeling of embodiment is likely to play a major factor in good performance. This most likely hinges on how well the system is calibrated (in space and time). In designing a user study to uncover objective and subjective factors contributing to SoE, assessing its reliability and stability, we considered five main aspects: the sensory cues manipulation, the task, the impact of designing an active Rubber Hand Illusion (RHI), the artificial hand position, and the assessment measures. The classic RHI is a perceptual phenomenon where participants perceive a rubber hand as their own when it is stroked simultaneously with their hidden real hand, leading to a SoE over the rubber hand (Botvinick & Cohen, 1998). Based on previous findings, we selected the most relevant sensory cues that can evoke the SoE, such as synchronicity in multisensory information, visual perspective, and human-like visual appearance of the telepresence avatar (Toet et al., 2020; Falcone et al., 2022). Falcone and colleagues (2022) presented a ranking of the most relevant perceptual cues that affect each component of the SoE and task performance in a teleoperation scenario. In particular, they found that visuo-proprioceptive synchronicity appears to be the most influential perceptual cue. Therefore, we reduced our choice to the manipulation of visuo-proprioceptive synchronicity and, as in the classic RHI, to manipulating the virtual hand shift. The choice was determined by a distinction pointed out in the literature between ‘knowing where’ and ‘knowing how to get there’, that is between the body image for perception (i.e. judgment of one's own bodily properties) and the body schema for action (i.e. information about the body necessary to move such as posture, limb size, and strength) (Paillard, 1991). While numerous studies have demonstrated that perceptual judgments are affected by the RHI, it is less clear if this is true for motor responses. Indeed, Kammers and colleagues (2009) found a dissociation between illusion-insensitive ballistic motor responses and illusion-sensitive perceptual bodily judgments, suggesting that action resists the RHI and that RHI resists action. By manipulating both the sense of agency and ownership in a virtual RHI with both active and

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passive induction, they showed that the embodiment illusion can be achieved without a sense of agency, and that the action has less effect on the perceived hand position. However, the results presented in the paper refers to a passive embodiment experience, limiting the generality of the findings. As such, we sought to bridge this gap by testing SoE in an active teleoperation context, using a similar paradigm and measuring different dimensions of the potential SoE experience. We focused on the motor and proprioceptive judgment, and we measured it through the proprioceptive perception, task performance, and a SoE questionnaire.

In RHI questionnaires, subjective experiences relating to the sense of ownership over the artificial hand, the sense of agency over movements of the artificial hand, and the sense of self-location are typically rated on a Likert scale (Botvinick & Cohen, 1998; Peck & Gonzalez-Franco, 2021). Verbal or behavioral judgments about the own hand's location usually reveal a systematic mislocation of the unseen hand towards the artificial hand, a phenomenon commonly referred to as proprioceptive drift (Kramers et al., 2009; Romano et al., 2015). We used a combination of explicit and implicit measures. In our experiment, we adopted a combination of embodiment (Peck & Gonzalez-Franco, 2021) and mediator (that we introduced) surveys, and we assessed the proprioceptive drift and task performance. Unlike traditional Rubber Hand Illusion experiments (Botvinick & Cohen, 1998), in which there is neither agency over the surrogate nor a control setup, this study introduces the concept of a *mediator* in the teleoperation context, representing the perception of the setup, and transparency between the controller and the remote avatar. Ideally, if the mediator between the operator and the avatar is low in teleoperation, then it should afford a high level of SoE. The goal is to minimize mediator perception, achieving a one-to-one perception of the avatar as the operator's new body. This means that the body schema and image of the operator are completely updated and the avatar becomes the new body (De Vignemont, 2010).

Three research questions guided the investigation: (1) Does spatio-temporal calibration affect SoE and task performance? (2) Does enhancing SoE affect, as consequence, task performance and proprioceptive mapping? 3) Are explicit and implicit measures of SoE congruent, or do they represent different perspectives?

To answer these questions, we realized a within-design user study in Mixed Reality (MR). Participants performed a training task that manipulated two dependent variables: visuo-proprioceptive synchronicity (synchronous or asynchronous) and spatial mismatch (no shift, horizontal, or vertical shift) between movements of the real hand and the virtual avatar. Before and after training, participants were required to accomplish a reaching test and a proprioceptive judgment test (Kammer et al., 2009) in six different conditions of synchronicity and spatial mismatch, randomly presented, which served as our implicit measures of the SoE experience. In addition, following each condition, participants completed several SoE surveys to measure their explicit or subjective degree of SoE experience.

Findings reveal that spatiotemporal calibration affects both SoE and task performance. We could also observe that a high SoE corresponds to better performance, but not proprioceptive recalibration. Finally, explicit and implicit measures yielded incongruent results, emphasizing their assessment of different aspects of the SoE experience. This research provides valuable insights into the nuanced dynamics of SoE in teleoperation contexts, advocating for continued exploration of these concepts.

Experimental Design

Method

We performed a within-subjects design user study in MR, in which we manipulated visuo-proprioceptive information (by adding and removing delay) and the virtual avatar's hand location (shifted right, forward, or in the same position as the operator's real hand). We opted to apply a visuo-proprioceptive mismatch of 5cm right, as in the classic RHI, and forward, since this axis has been shown to result in stronger tactile expectations (Smit et al., 2018). To measure embodiment, we opted to use both subject self-report questionnaires (explicit measures) and proprioceptive alignment judgments (implicit measures), which are the most common methods for quantifying the strength of the embodiment illusion (Riemer et al., 2019; Falcone et al., 2023).

Participants

We recruited 30 participants (17 females and 13 males, between 18 and 28 years old) from the student participation pool in the Department of Psychology at Princeton University. The sample size was determined based on previous similar studies that we found in the literature (Marasco et al., 2018; Tsakiris et al., 2010; Slater et al., 2008; Slater et al., 2009). The study was approved by the IRB of Princeton University (reference number: 14912). Participants received course credit for their participation.

Setup and Materials

Participants viewed a virtual scene through a head-mounted display (HMD), the HTC Vive. 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 scene consisted of controlling a virtual floating right hand covered by a glove and holding a Vive controller, in a first-person player perspective. The primary display of the virtual environment consisted of a light gray table with, depending on the task, either five targets (virtual dots) of different colors or a 5x4 grid. The virtual table was calibrated to be at the same height of a real table that was placed in front of the participants in the experiment room while performing the tasks. This was done to create mixed haptic feedback between the virtual and real tables at which the participants were sitting during the experiment (see Fig. 1 for an overview of the setup and the VR environment). The project was created in Unity 2019.2.17f1 and Visual Studio 2019. The scene was visualized using SteamVR 1.15.19 and the SteamVR Unity Plugin 2.6.1., which also provided the hand model holding the Vive controller. The latter was used to control the virtual hand that was either vertically or horizontally shifted by 5cm, or the position corresponded to the self-one hand of the operator.

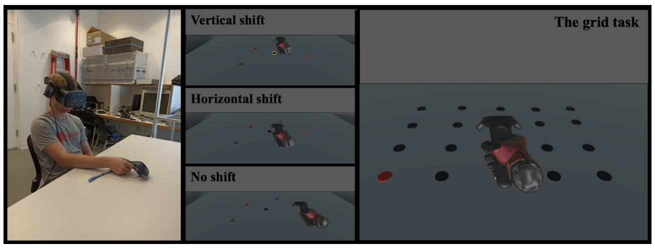

Figure 1: On the left, the operator performing User Study 3, in the middle we can observe the three manipulated hand shifts, and on the right, we can observe the extracted frame from the training task.

Procedure

Participants were asked to fill the consent form and then they were given detailed instructions about the experiment, the tests, and the task. Participants were also instructed that if they were unsure how the task worked, they could ask the experimenter for further explanations. The experiment duration was approximately 75 minutes. For each condition of the task, six in total, participants experienced three phases: pre-test, training, post-test. Our implicit measures (reaching and proprioceptive tests, see below) of SoE were matched in terms of feedback and task procedure. In between each condition, participants were required to fill out surveys, which served as our explicit measures of SoE. The conditions were presented in a random order and participants had to experience each condition; therefore, they repeated the set of tasks six times.

Implicit Measures and Training Task

Participants were instructed to perform both a *reaching test* and a *proprioceptive judgment test*. For the reaching test, virtual targets were displayed one at a time in a random order on the virtual table and participants were asked to reach to the displayed target while holding the Vive controller in their right hand. They repeated the test two times, first attempting to bring the avatar's virtual hand to the target before attempting to reach the target without seeing the avatar's hand. Then, participants grasped the controller with their left hand and were asked to align it with their right hand index finger, which was placed in five different unseen locations that were below the surface of the real table.

Next, participants performed the *training task*. Participants were asked to touch a red target every time they spotted it in a 5x4 grid of black targets. When they touched the red target, it turned black and another target would turn red at random. The task lasted 5 minutes. Following the training task, they again performed the reaching and the judgment tests without any visual feedback of the avatar (or real) hand. In this way we could measure the proprioceptive drift in the same condition and between conditions, and we could also observe the effect of the SoE manipulation on task performance.

Explicit Measures

To measure SoE, we adopted a combination of two implicit measures (described above) and also two explicit measures. Here, we administered a reduced version of the embodiment questionnaire from (Peck & Gonzalez-Franco, 2021). Participants were asked to assess items on ownership, agency, and self-location. Moreover, we introduced a questionnaire to assess the level of perception of the mediator. The items were evaluated using a Likert scale from 1 (strongly disagree) to 7 (strongly agree). The items evaluated were: 1) I was so immersed that I forgot I was experiencing the virtual avatar and environment through a setup; 2) the experiment setup allowed to perceive every single stimulus as I would perceive it with my own body; 3) I feel I went through a process of motor adaptation, and that I improved my motor skills over the virtual avatar; 4) every sensory and physical prediction on the interaction between the virtual avatar and the environment was correct.

Analyses

We conducted a 2x2 ANOVA and we compared four conditions: asynchronous-shifted (AS), asynchronous-not-shifted (ANS), synchronous-shifted (SS), and synchronous-not-shifted (SNS). In case of significant p-value, we conducted a Tukey's HSD post-hoc test to further investigate the nature of the significant differences.

For the questionnaire on the SoE, we averaged the score (expressed using a Likert scale from 1 to 7) attributed to the items addressing each embodiment component (i.e., sense of ownership, agency, self-location, mediator).

Task performance was determined by measuring efficiency metrics, such as the number of correct actions or outputs per unit of time (i.e., touching the target on the table). This approach accounts for variations in time and focuses on the effectiveness of completing the task regardless of the delay introduced in the manipulation visuo-proprioceptive variable.

For the reaching and proprioceptive tests, we compared the Euclidean distance between the locations reached by the participants while not seeing the virtual hand in the pre-test phase and the locations reached by the participants while not seeing the virtual hand in the post-test phase following the training task. We averaged the distances for the five targets, to get one unique value of the distance.

Results

We manipulated two independent variables: the synchronicity of the virtual hand response (synchronous, asynchronous), and the spatial mismatch between the real and virtual hand (right shift, forward shift, no shift). Our initial planned analyses were to conduct a 2x3 ANOVA to examine the effect of delay (synchronicity) and shift (mismatch) on six dependent variables: the SoE components (sense of ownership, agency, and self-location), the mediator perception, the task performance, and the proprioceptive information of the participants in both a reaching test and a proprioceptive judgment test. However, since we did not find any interaction effects between the variables, and there was no difference in between the shifted conditions, we decided to merge the vertical and horizontal shift conditions, to simplify the presentation of our results. Therefore, we conducted a 2x2 ANOVA and we compared four conditions: asynchronous-shifted (AS), asynchronous-not-shifted (ANS), synchronous-shifted (SS), and synchronous-not-shifted (SNS).

Training

An ANOVA was conducted to examine the effect of the synchronicity and spatial mismatch manipulations on performance in the training task, which revealed a significant main effect of synchronicity ($F(3, 29) = 17.2$, $p < .001$) (see Fig. 2). A Tukey's HSD post-hoc test was conducted to further investigate the nature of these differences. The synchronous-shifted condition displayed a greater performance compared to the asynchronous conditions-shifted ($p < .001$) and asynchronous-not-shifted conditions ($p = .004$). Likewise, the synchronous-shifted condition exhibited the greater performance compared to the asynchronous, with a significant difference of $p < .001$ for the three comparisons. Performance in the synchronous conditions were not significantly different ($p > 0.05$). To summarize, participants performed significantly better in all the synchronous conditions, while the hand shift did not appear to play a major role.

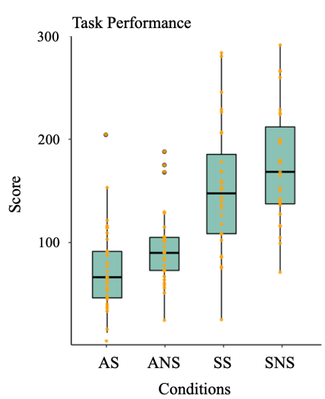

Figure 2: The plot represents the task performance among the six conditions. Legend: AS = Asynchronous, shifted; ANS = Asynchronous, not shifted; SS = Synchronous, shifted; SSO = Synchronous, shifted; SNS = Synchronous, not shifted.

Implicit Measures of SoE

In the reaching test, we compared the Euclidean distance between the locations reached by the participants while not seeing the virtual hand in the pre-test phase and the locations reached by the participants while not seeing the virtual hand in the post-test phase following the training task. We averaged the distances for the five targets, to get one unique value of the distance. We found a significant effect of the manipulated variables ($F(3, 29) = 19.04$, $p < .001$). We conducted a Tukey's HSD post-hoc test to further investigate the nature of these distance differences. We observed a significant effect only in the synchronous conditions when the hand was shifted. Particularly, we found a significant difference between the distances in the asynchronous-shifted and synchronous-not-shifted conditions ($p < .001$) (see Fig. 3).

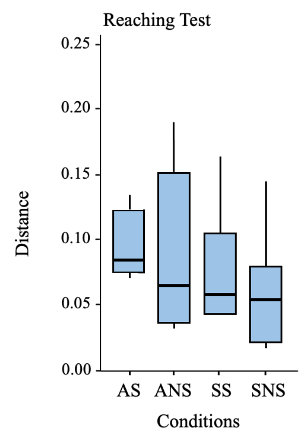

Figure 3. The plot represents the distances between the points reached by participants during the no feedback pre-test and post-test phases. We average the distances of the five targets to get one unique distance value. Each bar represents the distances between the point reached during the pre-test when the hand was not visible and the point reached when the hand was not visible in the post-test after the training task. This set of data is reported for each condition. *Legend*: AS = Asynchronous-shifted; ANS = Asynchronous- not-shifted; SS = Synchronous-shifted; SNS = Synchronous-not-shifted.

In the proprioceptive test, we compared the Euclidean distance between the locations reached by the participants in the pre-test and post-test phases. We averaged the distances for the five targets, to get one unique value of the distance. The analysis revealed a significant main effect of the variables manipulation on the dependent variable ($F(3, 29) = 4.46$, $p < .001$). A Tukey's HSD post-hoc test revealed that the distance from the pre-test was much higher in the AS condition compared to all the other conditions ($p < .001$). We did not find other significant effects among the other conditions (see Fig. 5).

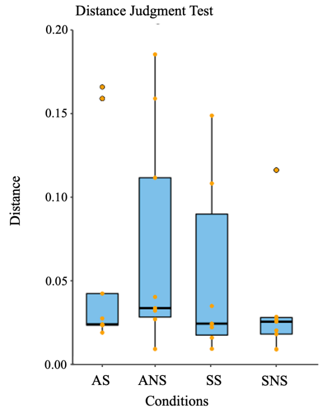

Figure 4. The plot represents the distances between the points reached by participants between the pre-test and post-test for the distance judgment test. We average the distances of the five targets to get one unique distance value. These data are reported for each condition. *Legend*: AS = Asynchrnous, shifted; ANS = Asynchrnous, no shift; SS = Synchrnous, shifted; SNS = Synchrnous, no shift.

Explicit Measures of SoE

Following each condition, participants were surveyed regarding sense of ownership, agency, self-location, and mediator perception. In terms of ownership, the ANOVA revealed a significant main effect of synchronicity on the sense of ownership ($F(3, 29) = 3.67$, $p = .003$) (see Fig. 5a). A Tukey's HSD post-hoc test was conducted to determine which conditions differed significantly from each other. Post-hoc comparisons revealed that the sense of ownership was higher in the synchronous-not-shifted condition than in the asynchronous-shifted condition ($p = .03$) – the two conditions that would presumably be the most and least supportive of SoE. No other pairwise comparison reaches statistical significance.

For the sense of agency, we found a significant main effect of synchronicity ($F(3, 29) = 2.66$, $p = .02$) (see Fig. 5b). Tukey's HSD post-hoc comparisons revealed that the sense of agency in the synchronous-not-shifted condition was evaluated significantly better than in asynchronous-shifted ($p = .02$), again, in the two conditions that are most and least supportive of SoE. No other pairwise comparisons reached statistical significance.

The sense of self-location did not show a significant main effect of the conditions manipulation (synchronicity and hand shift) ($F(3,29) = 1.20$, $p = .36$) (see Fig. 5c). Finally, for what concerns the mediator perception, the analysis shows a significant effect of conditions on the dependent variable ($F(3, 29) = 3.63$, $p = .004$) (see Fig. 5d). Tukey's HSD post-hoc comparisons revealed that the setup in the synchronous-not-shifted condition was perceived significantly less than in asynchronous-not-shifted condition ($p = .01$). The difference between the shifted and no-shifted conditions, in both cases of asynchronicity and synchronicity (AS compared to ANS, and SS compared to SNS) only approached statistical significance ($p = .07$); no other pairwise comparisons reached statistical significance. Taken together, it is clear that synchronicity is the driving force behind SoE across all potential explicit measures of SoE (ownership, agency, self-location, and mediator perception).

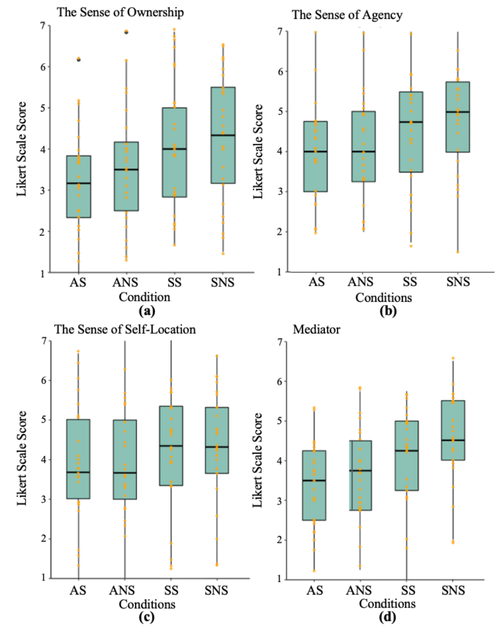

Figure 5. The plots represent the evaluation of the sense of ownership, agency, self-location and mediator among the conditions. *Legend*: AS = Asynchronous, shifted; ANS = Asynchronous, no shift; SS = Synchronous, shifted; SNS = Synchronous, no shift.

Discussion

The goal of this study was to determine the impact of spatiotemporal calibration on SoE and task performance. We hypothesized that synchronicity and spatial mismatch would be key determinants of these two factors. We manipulated synchronicity by introducing a delay between movement of the real hand and the avatar's hand and spatial mismatch by shifting the visual location of the avatar's hand relative to the real hand during a teleoperation training task. SoE was measured using implicit tests (reaching and proprioceptive tests) and explicit tests (ownership, agency, self-location, and mediator perception). Overall, we found that synchronicity was critical to explicit assessments of SoE and task performance, while having virtually no impact on implicit assessments of SoE.

Starting with the explicit measures, our analysis revealed a significant main effect of synchronicity on the sense of ownership and agency, emphasizing the significance of optimizing this factor for fostering a robust SoE. However, the sense of self-location did not exhibit a significant effect across conditions, suggesting that alterations in synchronicity and hand shift might not substantially influence the perceived spatial location of the self in the virtual environment. Differently from the implicit representation of spatial location, even if they both address the same dimension, in the explicit representation the participants are consciously asked to evaluate their proprioceptive perception. The perceived mutation and the actual mutation of the body schema can differ, such as the explicit and implicit memory system for motor learning and control (Hwang et al., 2006; Rand and Heuer, 2013; Taylor et al., 2014; Falcone et. al 2021). The analysis of mediator perception emphasizes differences in how participants perceived the setup as a mediator between the operator and the avatar among conditions. Post-hoc comparisons revealed that in the synchronous conditions, the mediator was perceived significantly less compared to the suppressive asynchronous conditions, aligning to minimize mediator perception when enhancing the SoE.

Moving to the implicit data, the task performance during the training task exhibited a significant main effect of synchronicity. Participants performed significantly better in synchronous conditions, irrespective of hand shift; emphasizing the dominance of synchronicity in influencing participants' performance and a possible adaptation effect to postural congruency manipulation.

In the proprioceptive data from the reaching test, significant effects were observed in the synchronous conditions with a hand shift (SS). The analysis revealed a significant effect on the distance between pre-test and post-test points reached with and without seeing the virtual hand. Notably, the absence of a significant effect in asynchronous conditions suggests that synchronicity and hand shift, when combined, impact participants' proprioceptive judgments.

For the distance judgment test, a significant main effect of conditions highlighted differences in participants' judgments of distances from pre-test points. Post-hoc tests revealed that the AS condition significantly differed from all other conditions, indicating that spatial mismatch in asynchronous conditions substantially influenced participants' distance judgments.

Sensorimotor Recalibration

Maintaining calibration of the body is arguably one of the most important and common forms of sensorimotor learning we do on a daily basis. While the origin of this capacity likely has its roots in learning how to control the body with precision, the demands for this capacity to extend beyond the body has only accelerated in the modern age given the need to interact with a variety of digital platforms (e.g., smartphones, computers, virtual reality, etc.) across a range of applications (e.g., teleoperation, telesurgery, etc.). Sensorimotor adaptation studies have found that spatiotemporal synchronicity is critical for this (re)calibration to take place. Spatial mismatches on the order of a few centimeters can fail to be integrated into the body schema (Wei and Kording 2010) and delays in sensory feedback as little as a few hundred milliseconds can significantly blunt recalibration processes (Kitazawa and Yin 1995; Brudner et al., 2016; Schween et al., 2017). The failure of the motor system to recalibrate for these spatiotemporal mismatches results in worse performance and, what's more, a shift in the psychological and neural processes to improve performance (Bond and Taylor 2015; Brudner et al., 2016; Butcher et al., 2017), often resulting in a higher cognitive workload (McDougle and Taylor 2019). These findings in the sensorimotor adaptation domain may explain the superiority of synchronous conditions in promoting favorable outcomes in embodiment experiences (Riemer et al., 2019; Falcone et al., 2023). The visuomotor interactions in virtual reality are not unlike those in adaptation paradigms, which have emphasized the importance of sensorimotor recalibration and cue reweighting. Identified in the context of biased and noisy 3D shape cues (from the avatar and the virtual environment), these two distinct learning processes are suited to resolve prediction errors caused by an initial lack of calibration of the operators. Moreover, this provides a foundation for understanding the complexities observed in the relationship between perception and action. These two processes are often found to be dissociated in experiments where some cues are consistent with sensory feedback while others are faulty (Cessanek et al., 2020). This further reinforces the importance of calibration in teleoperation setups, highlighting potential implications for user experiences and performance optimization in virtual environments.

Integrating these previous findings across research domains, underscores the intricate interplay between spatiotemporal calibration (synchronicity and hand shift manipulation) and their influence on the SoE components, task performance, and proprioceptive mapping. Additionally, the effects observed in different SoE components and task performance suggest that, even if these phenomena are multifaceted, they may be related. The observed dissociation between aspects of SoE, particularly in the absence of significant effects on self-location, prompts further investigation into the underlying mechanisms shaping these perceptual cues. The influence of synchronicity and hand shift on mediator perception also highlights the importance of the operator's perception of the teleoperation setup, which may have implications for user acceptance and engagement. While it remains an open question as to whether successful sensorimotor calibration is necessary to induce SoE, our results contribute valuable insights into the intricate dynamics of SoE and task performance in teleoperation setups.

Conclusions

We explored the intricate relationship between SoE manipulation, motor adaptation, and task performance in teleoperation. The results emphasize the pivotal role of temporal synchronicity in fostering a robust SoE and optimizing task performance. Further research may delve into individual differences, long-term effects, and applications across diverse teleoperation contexts, advancing our understanding of embodied experiences. Ultimately, this study serves as a stepping stone in exploring embodied experiences in teleoperation, laying the foundation for future investigations that will shape the evolution of human-machine interactions in increasingly immersive and sophisticated teleoperated systems.

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