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Individuals Prioritize the Reach Straightness and Hand Jerk of a Shared Avatar over Their Own

Straighter and less jerky motion

Shared avatar in VR

Participant 1   Participant 2

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HIGHLIGHTS

We embodied two human participants within a shared avatar in virtual reality

Movements of the shared avatar were the average of the participant's movements

Avatar's hand movements were straighter and less jerky than participant's

Humans prioritize movement of a shared body over their own
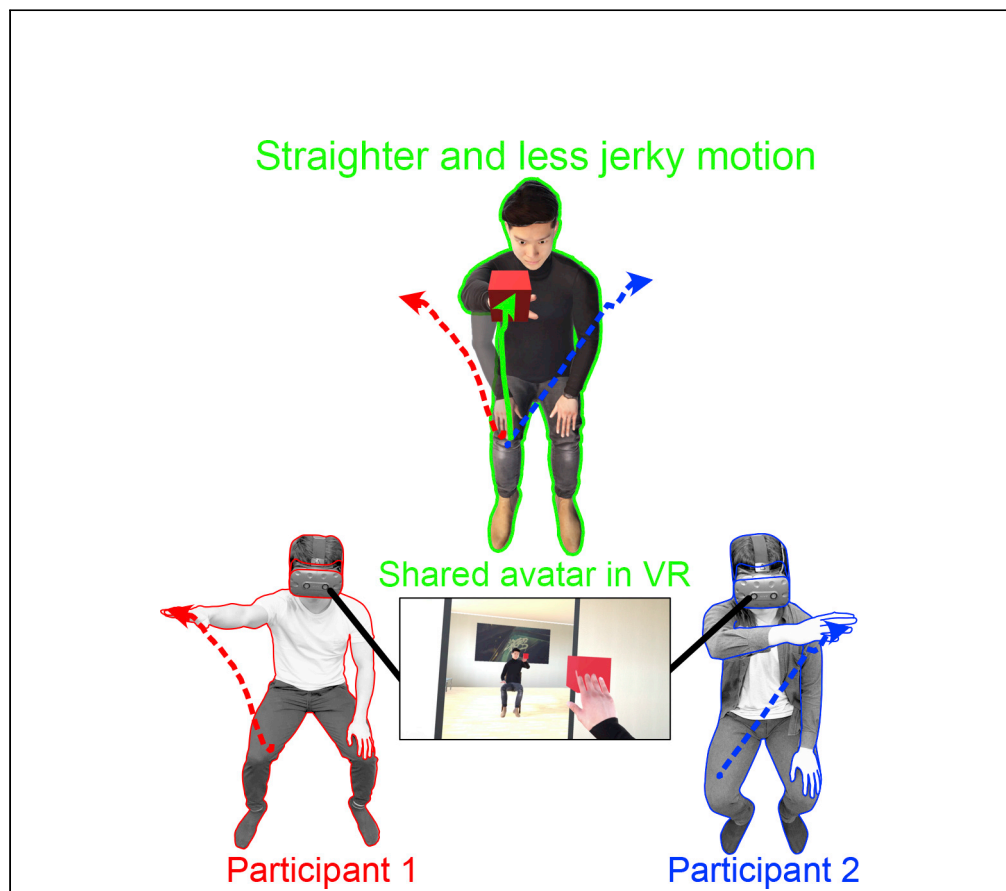
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Individuals Prioritize the Reach Straightness and Hand Jerk of a Shared Avatar over Their Own

Takayoshi Hagiwara,[1,6,*] Gowrishankar Ganesh,[2,*] Maki Sugimoto,[3] Masahiko Inami,[4] and Michiteru Kitazaki[5,*]

SUMMARY

Cyber space enables us to "share" bodies whose movements are a consequence of movements by several individuals. But whether and how our motor behavior is affected during body sharing remains unclear. Here we examined this issue in arm reaching performed by a shared avatar, whose movement was generated by averaging the movements of two participants. We observed that participants exhibited improved reaction times with a shared avatar than alone. Moreover, the reach trajectory of the shared avatar was straighter than that of either participant and correlated with their subjective embodiment of the avatar. Finally, the jerk of the avatar's hand was less than either participant's own hand, both when they reached alone and in the shared body. Movement straightness and hand jerk are well known characteristics of human reach behavior, and our results suggest that during body sharing, humans prioritize these movement characteristics of the shared body over their own.

INTRODUCTION

The use of the cyber space has seen a substantial expansion through the COVID-19 crisis. The cyber space enables us to work together at distant places and can even enable us to interact with remote environments and individuals by "embodying" virtual avatars, as well as real avatars, like robots. Such interactions using avatars is seen as a major future mode of communication between people. But for these to be possible, we need to understand the limits of avatar embodiment and how these embodiments affect the human users in terms of behaviors and emotions.

A plethora of studies have shown that, given the right sensory and/or motor stimulations, humans can elicit embodiment of virtual and physical objects other than their own body. Embodiment has been shown toward not only virtual bodies that are visually similar to one's own body (Gonzalez-Franco et al., 2010) but also toward bodies or objects that differ from one's own (Aymerich-Franch and Ganesh, 2016) in terms of size (Banakou et al., 2013; Tajadura-Jiménez et al., 2017; Falconer et al., 2014; Falconer et al., 2016), skin color (Peck et al., 2013), and arm length (Kilteni et al., 2012), as well as when the body is that of a robot (Aymerich-Franch et al., 2017; Aymerich-Franch, Petit, Ganesh and Kheddar, 2016a, 2016b; Aymerich-Franch et al., 2015; Aymerich-Franch, Petit, Ganesh and Kheddar, 2016a, 2016b). Furthermore, ownership can also be induced when different body parts are re-associated (Kondo et al., 2020) or even when the body is partially invisible (Kondo et al., 2018). Crucially, while these illusory bodies' appearances were different from the participants' own body, only few rare studies (like Burin et al., 2019; Kokkinara et al., 2016) have investigated the scenario where the movements of the illusory body did not correspond to the movement of the actual body. And even in these studies, the control of the body was still determined by a sole participant. Furthermore, in each of these studies participants perceived sole ownership of the body.

On the other hand, few studies have examined the case in which several people share a body (or avatar), or a limb, where the movement of an artificial body (or limb) is determined by more than one individual. Sharing thus enables multiple individuals to collaborate and contribute in the task performed by an avatar potentially decreasing the workload for each user and improving task performance. Sharing of body parts has been shown to lead to changes in the perceived ownership and agency (Fribourg et al., 2020; Hagiwara et al., 2019). On the other hand, it still remains unclear whether and how shared embodiment affects an individual's motor behavior. Here, we examined this issue using an arm reaching task in virtual reality,

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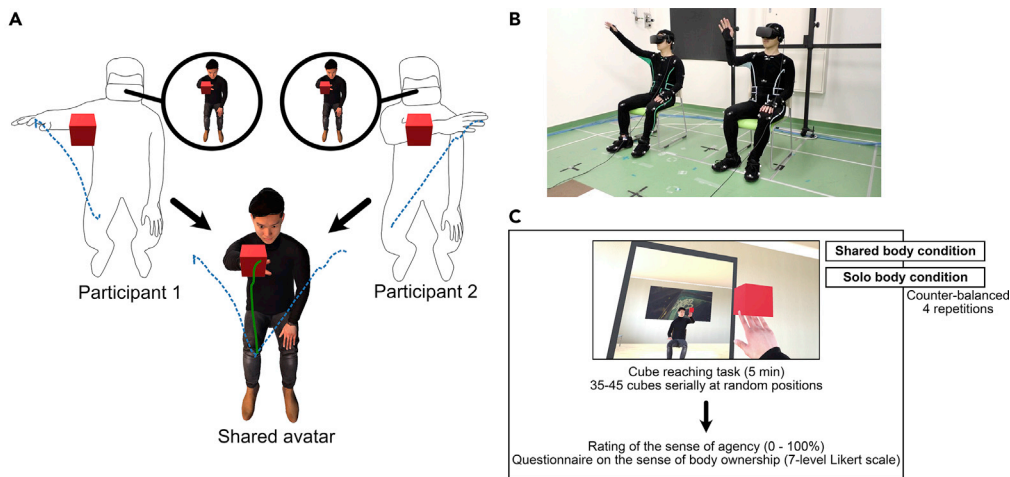https://doi.org/10.1016/j.isci.2020.101732

Figure 1. Shared Avatar Setup

(A) The avatar's arm movement was developed by averaging the arm movements performed by the two participants in the Shared-body condition. Both participants observed the same shared avatar through their HMD.

(B) The two participants wore the motion capture suites and HMD and performed the experiment.

(C) Cube reaching tasks were performed for 5 min followed by the rating of the sense of agency and body ownership. The Shared-body condition and the Solo-body condition were repeated four times in counter-balanced order in the within-participant design.

performed by a shared avatar who's arm movement was the average of arm movements by the two participants who share it.

Motor neuroscience studies have shown that individual human movement trajectories are a result of sensori-motor planning and control (Wolpert et al., 2011; Franklin and Wolpert, 2011; Ganesh and Burdet, 2013) as well as memory-related processes (Diedrichsen et al., 2010; Ganesh and Burdet, 2013; Ganesh et al., 2010). Considering these results, in this study we investigated what the individuals prioritize when they share a virtual body, specifically whether they still optimize their own movements or whether they optimize the movements of the avatar, and, consequently, how the sharing affects the avatar control. Here, we chose to investigate this issue during arm reaching, that is well-established empirical task to investigate motor behavior. Previous studies have shown that point-to-point arm reaching is roughly straight and tends to minimize the jerk measured at the hand (Flash and Hogan, 1985). Hence, here we compared the reach movement straightness and hand jerk exhibited by human individuals when they were embodied in individual avatars (Solo-body condition) with their hand movements when they were embodied in a same avatar (Shared-body condition), with the avatar movements representing their average hand movement (Figure 1, please also see Video S1). To anticipate our results, we observed that individual's movements change in the Shared-body condition (relative to the Solo-body condition) to minimize the trajectory length and jerk of the avatar hand, rather than that of their own hand.

RESULTS

Perceived Sense of Agency and Ownership to the Shared Body

Our experiment was performed in a virtual reality (VR) environment. The participants performed our experiment in dyads. They worked in two conditions. In each condition they were presented with a virtual avatar that replaced their own body in VR and were required to make reaching movements with their right hand, toward target cubes presented at various locations in front of both of them (see Transparent Methods for details). Both participants were presented with the same target at any time. In the *Solo-body* condition, the participant arm movement was replicated on the avatar, whereas in the *Shared-body* condition, the avatar's arm movement was the average of the arm movements performed by the two participants in the dyad (see Transparent Methods for details).

After each condition, the participants were asked to rate the sense of agency (0%–100%: 0 is "I did not control the avatar hand at all"; 100 is "I fully controlled the avatar hand") and the sense of body ownership
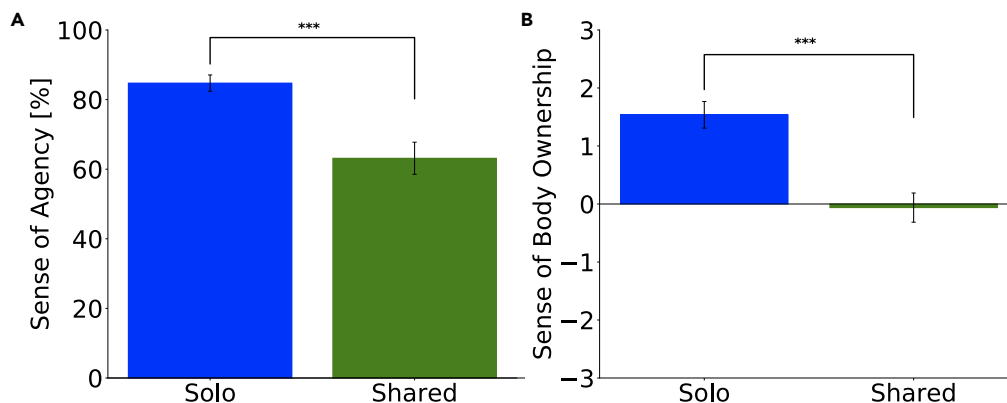
Figure 2. Sense of Agency and Body Ownership

Perceived sense of agency was more than 50%, and the Solo-body condition was better than the Shared-body condition both in the sense of agency and the sense of body ownership.

(A) Rating of the sense of agency. A Wilcoxon signed-rank test showed that the sense of agency was significantly higher in the Solo-body condition than in the Shared-body condition (***p < .001). In the Solo-body condition, the sense of agency was significantly lower than 100%, and in the Shared-body condition, the sense of agency was significantly higher than 50%. The sense of agency was higher in the Solo-body condition than in the Shared-body condition.

(B) Likert scale data of the sense of body ownership. A paired t test showed that the sense of body ownership was significantly higher in the Solo-body condition than in the Shared-body condition (***p < .001). Bar plots in the figure show means +/− SE measures.

(Questionnaire: I felt as if the avatar's body I saw was my body; −3 to +3; 7 level Likert scale. −3 is "I did not feel it at all"; +3 is "I felt it extremely strongly").

A Wilcoxon signed-rank test was conducted on the rated sense of agency to compare the Solo-body and Shared-body conditions because the data significantly deviated from normality (Shapiro-Wilk test, W = 0.828, p = .002). We found that the sense of agency was significantly higher in the Solo-body condition than in the Shared-body condition (W(19) = 190.000, p < .001, d = 1.000, Figure 2A). We conducted a Wilcoxon signed-rank test to test whether the rated sense of agency was different from the actual weights (100% in the Solo-body condition, 50% in the Shared-body condition). In the Solo-body condition, the sense of agency was significantly lower than 100% (W(19) = 0.000, p < .001, d = −1.000). Interestingly the sense of agency was significantly higher than 50% in the Shared-body condition (W(19) = 153.000, p = .021, d = 0.457), even though each participant contributed equally to the avatar movements.

A paired t test (one-sample t test) was conducted on the rated sense of body ownership in the Solo-body and Shared-body conditions because the data did not deviate from normality (Shapiro-Wilk test, W = 0.916, p = .083). As would be expected, a paired t test between the Solo-body and Shared-body conditions indicated that the sense of body ownership was significantly higher in the Solo-body condition than in the Shared-body condition (t(19) = 5.643, p < .001, d = 1.45, Figure 2B).

Avatar Hand Movements Were Straighter Than That of Participants

We evaluated the straightness of the hand reach by measuring *hand reach deviation (D)*, which was defined as the difference between the length of the hand movement trajectory and the straight line joining the start and endpoint of the hand during a reach (See Transparent Methods and Figure S1 for detail). We evaluated the hand reach deviation by the participants in the Solo-body condition (D^{solo}_{human}), the actual hand reach deviation by the same participants in the Shared-body condition (D^{shared}_{human}) and the hand reach deviation by their shared avatar in the Shared-body condition (D^{shared}_{avatar}).

A one-way repeated measures ANOVA across the three reach deviations (D^{solo}_{human}, D^{shared}_{human}, D^{shared}_{avatar}) was conducted because the data did not deviate from normality (Shapiro-Wilk test, D^{solo}_{human}: W = 0.932, p = .468, D^{shared}_{human}: W = 0.928, p = .433, D^{shared}_{avatar}: W = 0.849, p = .056) or sphericity (Mauchly's sphericity test, p = .319). We found a significant main effect (F(2, 18) = 19.278, p < .001, η^2_p = 0.682, Figure 3A). Holm's post hoc test indicated that D^{solo}_{human} was significantly larger than D^{shared}_{human} (t(9) = 4.150, adj.p = .005, d = 1.312), indicating that, in the Shared-body condition, the participants adopted a straighter path than when they
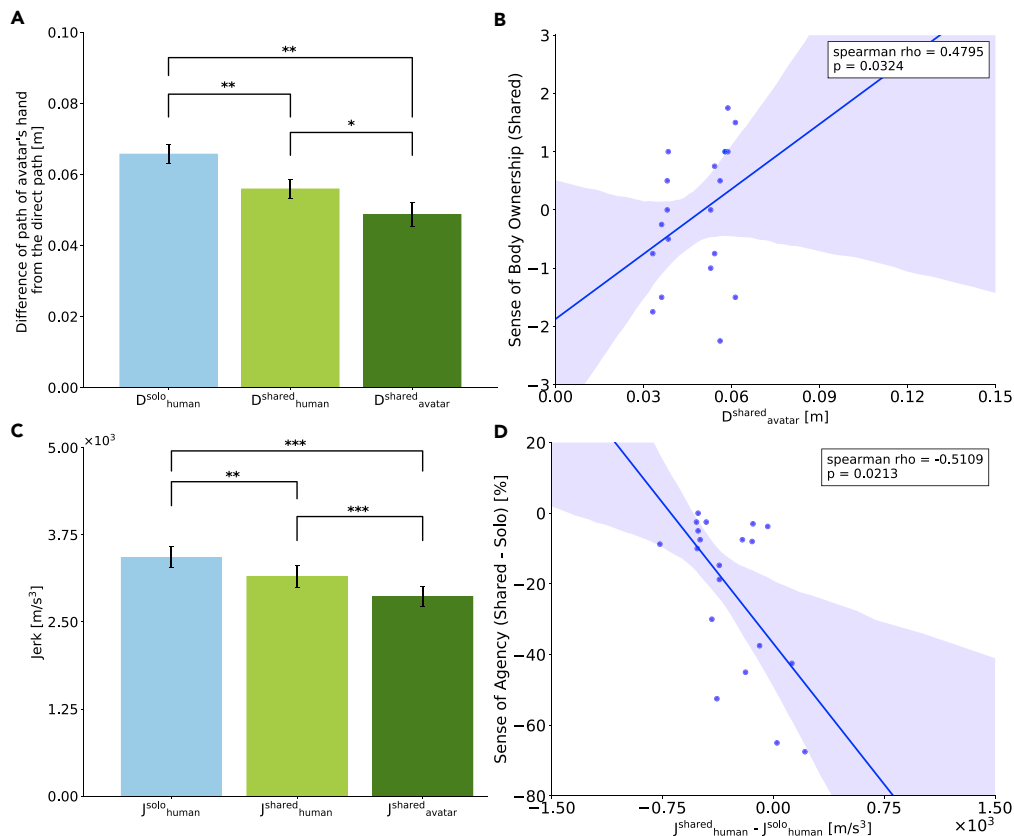
Figure 3. Avatar Hand Movements were Straighter and Exhibited Less Jerk

(A) Difference of path of participant's hand (Solo-body condition, Shared-body condition) and shared body avatar's hand from the direct path. Holm's post hoc tests after a one-way repeated measures ANOVA were conducted (*p < .05, **p < .01). D^{solo}_{human} was significantly larger than D^{shared}_{human}, indicating that in the Shared-body condition the participants adopted a straighter path than when they performed in the reach alone. D^{shared}_{avatar} was significantly smaller than both D^{solo}_{human} and D^{shared}_{human}, indicating that the avatar attained hand trajectories that were straighter than the individual participant when they reached alone, as well as when they reached in the Shared-body condition.

(B) Data are represented as each participant's D^{shared}_{avatar} (horizontal axis) and the rated sense of body ownership in the Shared-body condition (vertical axis). The sense of body ownership in the Shared-body condition positively correlated with the hand reach deviation D in the Shared-body condition (please also see the rank order plot in Figure S2).

(C) Average jerk in reaching. Tukey's post hoc tests with Kenward-Roger degrees of freedom approximation after a one-way repeated measures ANOVA with ART were conducted (**p < .01, ***p < .001). J^{shared}_{avatar} was smaller than both J^{solo}_{human} and J^{shared}_{human}. Also, J^{shared}_{human} was significantly smaller than J^{solo}_{human}. Thus, the shared avatar's movements were smoother than when they were solo.

(D) Data are represented as each participant's difference between J^{shared}_{human} and J^{solo}_{human} (horizontal axis) and difference of the rated sense of agency between the Shared-body condition and the Solo-body condition (vertical axis). The change in the sense of agency between the Shared-body and Solo-body conditions inversely correlated with the change in hand jerk between the conditions (please also see the rank order plot in Figure S3). Bar plots in (A) and (C) show means +/− SE measures.

performed in the reach alone. Interestingly, D^{shared}_{avatar} was smaller than both D^{solo}_{human} (t(9) = 5.054, adj.p = .002, d = 1.598) and D^{shared}_{human} (t(9) = 2.998, adj.p = .015, d = 0.948) indicating that the avatar attained hand trajectories that were straighter than the individual participant when they reached alone, as well as when they reached in the Shared-body condition.

Avatar Hand Jerk Was Less Than That of Individual Participants

Next, we calculated the average hand jerk in reaching in the same three cases (J^{solo}_{human}, J^{shared}_{human}, J^{shared}_{avatar}; Figure 3C). A one-way repeated measures ANOVA with ART (aligned rank transformation) procedure (Wobbrock et al., 2011) was conducted because the data significantly deviated from normality (J^{shared}_{avatar}: W = 0.823,
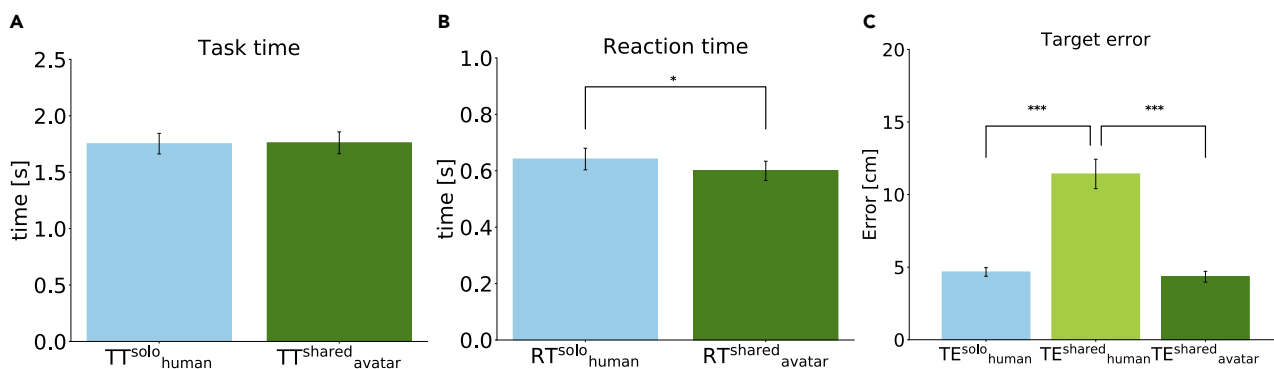
Figure 4. Performance by Avatar Changed Compared with Individual Participants

(A) Participants' task time in the Solo-body condition (TT$^{solo}_{human}$) and the shared avatars' task time in the Shared-body condition (TT$^{shared}_{avatar}$). There was no difference.

(B) A paired t test showed that the shared avatar's reaction time in the Shared-body condition (RT$^{shared}_{avatar}$) was significantly faster than the participants' reaction time in the Solo-body condition (RT$^{solo}_{human}$) (*p < .05).

(C) Tukey's post hoc tests with Kenward-Roger degrees of freedom approximation after a one-way repeated measures ANOVA with ART showed that the target errors of hand reaching TE$^{shared}_{avatar}$ and TE$^{solo}_{human}$ were significantly smaller than TE$^{shared}_{human}$ (***p < .001). TE$^{shared}_{avatar}$ was slightly smaller than TE$^{solo}_{human}$ but the difference did not reach significance. Bar plots in the figure show means +/− SE measures.

p = .028). We found a significant main effect (F(2, 18) = 37.238, p < .001, η^2_p = 0.805) across the three measures. Tukey's post hoc tests with Kenward-Roger degrees of freedom approximation (Kenward and Roger, 1997) indicated that J$^{shared}_{avatar}$ was significantly smaller than both J$^{solo}_{human}$ (t(18) = 8.629, adj.p < .001, d = −3.86) and J$^{shared}_{human}$ (t(18) = 4.438, adj.p = .001, d = −1.98). Also, J$^{shared}_{human}$ was smaller than J$^{solo}_{human}$ (t(18) = 4.191, adj.p = .002, d = −1.87). These results show that the shared avatar's movements were smoother that when they were solo. Furthermore, in the Shared-body condition, the participants might achieve smoother movements with the avatar than with their own hands.

Task Performance: Reaction of Avatar Was Better, Target Error Was Similar

We quantified the task performance in our experiment by evaluating the *task time, reaction time*, and *target error*. We compared the participants' task time in the Solo-body condition (TT$^{solo}_{human}$) and the shared avatars' task time in the Shared-body condition (TT$^{shared}_{avatar}$, Figure 4A). The task time was defined as a time between the appearance of the target and the hand's touching the target. A paired t test was conducted on the task time because the data did not deviate from normality (Shapiro-Wilk test, W = 0.950, p = .667). There was no difference (t(9) = 0.174, p = .866, d = 0.055). We similarly compared the participants' reaction time in the Solo-body condition (RT$^{solo}_{human}$) and the shared avatars' reaction time in the Shared-body condition (RT$^{shared}_{avatar}$, Figure 4B). The reaction time was defined as the time between the appearance of the target and the time at which the hand velocity goes over 10% of the maximum velocity. A paired t test was conducted on the reaction time because the data did not deviate from normality (Shapiro-Wilk test, W = 0.942, p = .574). The shared avatars' reaction time was shorter than the participants' reaction time (t(9) = 2.357, p = .043, d = 0.745).

Target error was defined as the difference between the endpoint of the participant's reach and the center of the target object and was again calculated for the three cases as before (TE$^{solo}_{human}$, TE$^{shared}_{human}$, and TE$^{shared}_{avatar}$; Figure 4C). A one-way repeated measures ANOVA with ART procedure was conducted because the data significantly deviated from normality (TE$^{shared}_{human}$: W = 0.774, p = .007). We found a significant main effect (F(2, 18) = 117.839, p < .001, η^2_p = 0.929) in the target error across the cases. Tukey's post hoc tests with Kenward-Roger degrees of freedom approximation indicated that TE$^{shared}_{avatar}$ was significantly smaller than TE$^{shared}_{human}$ (t(18) = 14.017, adj.p < .001, d = −6.27). TE$^{solo}_{human}$ was significantly smaller than TE$^{shared}_{human}$ (t(18) = 12.430, adj.p < .001, d = 5.56). TE$^{shared}_{avatar}$ was slightly smaller than TE$^{solo}_{human}$, but the difference did not reach significance (t(18) = 1.587, adj.p = .277, d = −0.71). These results show that the participant's reach performance improved when sharing the avatar body, in terms of the reaction time, while remaining same in terms of the target error. In the Shared-body condition, the avatar task performance improved, even when individual participant errors increased.

Interpersonal Distance Changes: An Argument against Averaging Effects

In our experiment we observed that the participants attained a straighter (Figure 3A) and smoother hand trajectories (Figure 3C) than they could do with their own hands under the Solo-body condition. They could also achieve similar target errors with the avatar, as the Solo-body condition (Figure 4C). It is, however, important to note that the participant movements suffer from sensory as well as motor noise (Harris and Wolpert, 1998), and the avatar movement is generated by averaging the hand movements of the participants. Therefore, there is the possibility that, in fact, the participants behave the same in the Solo-body (IP^{solo}_{human}) and Shared-body (IP^{shared}_{human}) conditions and that the improvements in straightness, jerk, and target errors we observed are just a consequence of the averaging of the individual participant movements.

To ensure that the participant behaviors did change between the Shared-body and Solo-body, we evaluated the inter-participant distance (IP) between the participants' hand trajectories during reaching in the Shared-body and Solo-body conditions (Figure 5A). A Wilcoxon signed-rank test was conducted because the data significantly deviated from normality (Shapiro-Wilk test, W = 0.826, p = .030). We found that IP^{solo}_{human} was significantly lower than IP^{shared}_{human} (W(9) = 0.000, p = .002, d = 1.000). This result indicates that, although participants took similar hand trajectories in the Solo-body condition (even though they embodied separate avatars), their hand trajectories deviated away from one another in the Shared-body condition such that the inter-participant distance was higher. We also compared the evolution of IP^{solo}_{human} and IP^{shared}_{human} over three phases of the reach (Figure 5A). These three phases were obtained by dividing the reaching between the appearance of the target and the hand's touching the target into three equal parts in time. Because the data did not deviate from normality (Shapiro-Wilk's normality test, phase 1: W = 0.990, p = .996; phase 2: W = 0.921, p = .365; phase 3: W = 0.851, p = .060), we conducted paired (one-sample) t-tests. IP^{solo}_{human} and IP^{shared}_{human} were similar during the first phase of the participant reach (t(9) = 1.064, p = .315, d = 0.336), but showed considerable difference in the second and third phase of the movement, near the targets (t(9) = 3.155, p = .012, d = 0.998; t(9) = 7.037, p < .001, d = 2.225).

We also compared the modifications in IP over trials (Figure 5B). Participants worked in Solo-body condition and Shared-body condition across eight sessions (each condition presented four times). We performed a two-way repeated measures ANOVA across these sessions with ART procedure because the data significantly deviated from normality (Shapiro-Wilk test, Session 1 of IP^{shared}_{human}: W = 0.805, p = .016, Session 2 of IP^{shared}_{human}: W = 0.833, p = .037). A significant main effect (F(1, 9) = 55.216, p < .001, η^2_p = 0.772) between the IPs in the Solo-body condition and the Shared-body condition was found. There was no main effect of sessions (hence trials) (F(3, 27) = 2.088, p = .111, η^2_p = 0.179) and no interaction (F(3, 27) = 0.578, p = .632, η^2_p = 0.095).

These results clearly show that the participant behaviors changed significantly between the Solo-body and Shared-body conditions.

Overall, the results in Figures 3 and 4 suggest that the increase in straightness (Figure 3A), decrease in jerk (Figure 3C), and similar target error (Figure 4C) by the avatar compared with the individuals in the Solo-body condition cannot be explained by the averaging of trajectories alone. On the other hand, these results suggest that the participants changed their behavior in the Shared-body condition to optimize these movement variables of the avatar, while ignoring the same on their own hands.

DISCUSSION

To evaluate how the control of a shared avatar affects the motor behavior of the controlling participants, we developed an avatar reaching task in virtual reality. We compared the participant hand trajectories in the Solo-body condition, in which the avatar was controlled alone by individuals, with the Shared-body condition in which the avatar movement was the average of the movements made by two participants. Movement straightness and jerk are known to be optimized by individuals for their hand movements (Flash and Hogan, 1985). However, interestingly, here we observed that the shared avatar hand trajectories were straighter (Figure 3A) and displayed less jerk (Figure 3C) than the hand movements by the participants, both alone and when they were controlling the avatar. The shared avatar also displayed faster reaction times than participants alone (Figure 4B). These results indicate that participants prioritize the optimization of the hand trajectories by the shared avatar over their own individual arm trajectories.
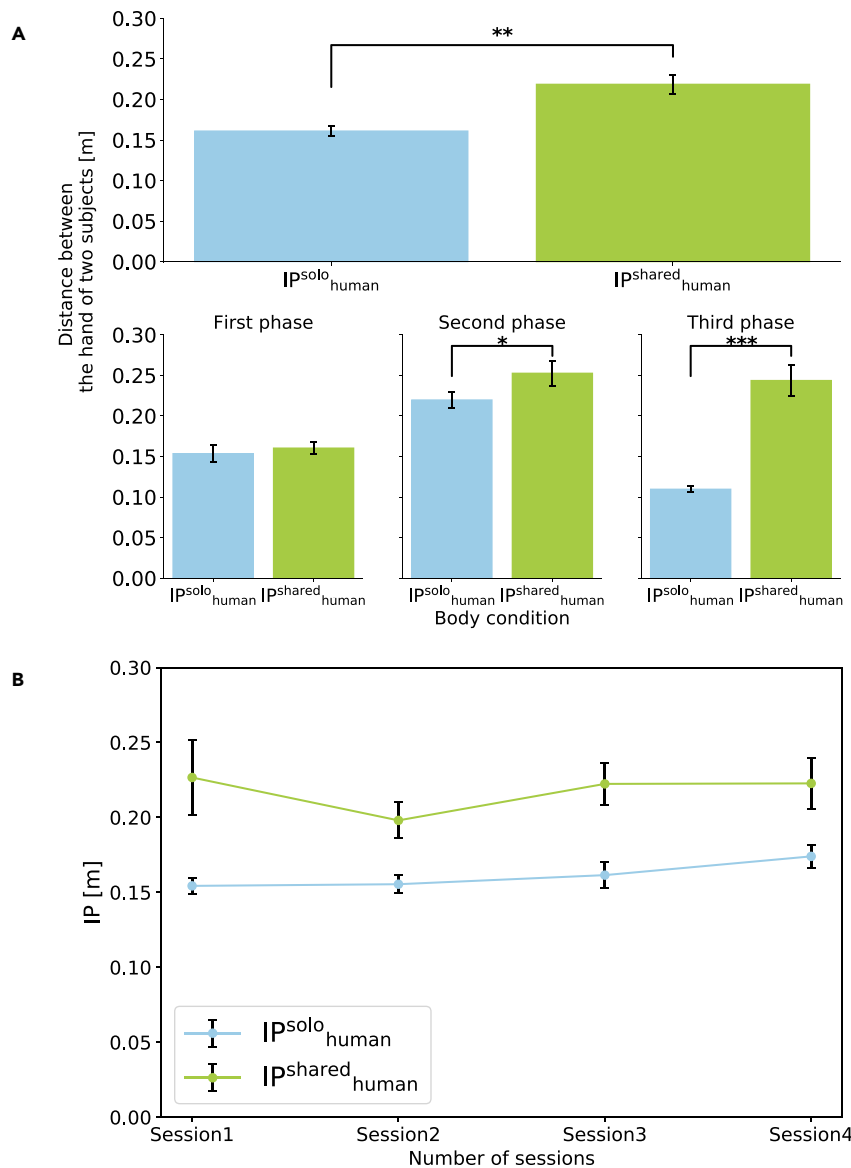
Figure 5. Interpersonal Distance was Larger in the Shared-Body Condition Than in the Solo-Body Condition

(A) Distance between the hand of two participants (top row: Full phase, bottom row: First phase, Second phase, Third phase). IP^{solo}_{human} was significantly lower than IP^{shared}_{human}, indicating that, although participants took similar hand trajectories in the Solo-body condition, their hand trajectories deviated away from one another in the Shared-body condition such that the inter-participant distance was higher. (Full phase) A Wilcoxon signed-rank test showed that IP^{shared}_{human} was significantly larger than IP^{solo}_{human} (**$p < .01$). (First phase) A paired t test did not show significant difference. (Second phase, Third phase) Paired t-tests showed that IP^{shared}_{human} was significantly larger than IP^{solo}_{human} (*$p < .05$, ***$p < .001$).

(B) There was a significant main effect between the IPs in the Solo-body condition and the Shared-body condition but not main effect of sessions (hence trials) or an interaction (a two-way repeated measures ANOVA with ART procedure). Bar plots in the figure show means $+/-$ SE measures.

A previous study that examined reaching with a dynamic tool showed that humans optimize the movement of the endpoint of the tool rather than their hand (Dingwell et al., 2002). Although our results here look seemingly similar, there are two fundamental differences. Primarily, the previous task involved a single person controlling and working with the tool. In contrast, the current task examined shared control, where two individuals cooperated to achieve a common task by the avatar they controlled. Second, we observed that

the reach task performance was significantly improved while using the shared avatar (Figure 4B). This behavior was not observed during the tool learning task. These differences in fact suggest the behavior in the Shared-body condition to be similar to that observed during human inter-personnel interactions, where low-impedance interactions have been shown to benefit task performance (Ganesh et al., 2014; Takagi et al., 2017; Takagi et al., 2018). Inter-personal benefits are, however, believed to be enabled by the prediction of the partner's behavior utilizing the haptic cues (Takagi, et al., 2017). Although in our task there obviously was no haptic interaction, we believe partner prediction as the reason for the straighter path of the avatar. The avatar movement in out setup was the consequence of movements made by the two dyad participants. This forced the dyad participants to cooperate, and develop an avatar trajectory together, in order to perform reaches successfully. However, this demands that the individuals predict each other's preferred avatar trajectory. We believe that the choice of the straight avatar trajectory was driven by the fact that this choice optimizes the predictability of one's partner's avatar trajectory choice. Subsequently, the lower jerk and endpoint error of the avatar reaches are probably the consequence of the straighter trajectory. Further studies are, however, required to prove this hypothesis.

Body ownership decreases when there is a mismatch between visual and motor information (Sanchez-Vives et al., 2010). This explains why in the Shared-body condition, where the avatar movement is a consequence of movements by two partners, the sense of body ownership is less than in the Solo-body condition. Interestingly, we found that the reported level of ownership in the Shared-body condition positively correlated with the hand reach deviation D in the Shared-body condition (Spearman's rank-order correlation $\rho = 0.4795$, $p = .032$; Figure 3B), and the change in the reported level of agency between the Shared-body and Solo-body conditions inversely correlates with the change in hand jerk between the conditions (Spearman's rank-order correlation $\rho = -0.5109$, $p = .023$; Figure 3D). In these results, we adopted Spearman's rank-order correlation because the data significantly deviated from normality (Shapiro-Wilk test, D^{shared}_{avatar}: $W = 0.828$, $p = .002$; Sense of agency (Shared-Solo): $W = 0.828$, $p = .002$). Although a previous study has shown the observation of an embodied limb can implicitly disturb the movements of a person (Burin et al., 2019), our results are probably the first to suggest that participants optimize the movements of the embodied limb rather than their own, which is probably also a cause of the observations in Burin et al. (2019). Pyasik, Furlanetto, and Pia (2019) propose the idea that only seeing the own body moving would be enough to activate the neurocognitive processes subserving action preparation based on the findings that the body ownership affects the sense of agency (e.g., Banakou and Slater, 2014; Kokkinara et al., 2016; Burin et al., 2019). Our results show that the low-level movement control can be systematically affected by the level of embodiment felt toward a limb. Accordingly, it might be supposed that seeing the shared body (or sense of body ownership to the shared body) can directly affect the motor control process as well as the sense of agency. A better understanding of the relation between embodiment and motor control promises new application of the shared body concept as a virtual avatar, like in our study, or as a collaborating robot.

Limitations of the Study

Although we find that the hand trajectories of the shared avatar are both straighter and less jerky than the solo hand trajectories, our results cannot clarify the causality, that is, whether the participant's goal is to have a straighter avatar trajectory, which subsequently results in less jerky hand trajectory, or, conversely, they aim for less jerk, which results in a straighter trajectory. Further studies are required to clarify this issue. However, in either case, the key goal of this work was to show that the participants are able to make straighter trajectories and better minimize the hand jerk of the shared avatar than their own.

Resource Availability

Lead Contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Takayoshi Hagiwara (takayoshi.hagiwara.18@gmail.com).

Materials Availability

This study did not generate new unique reagents.

Data and Code Availability

Original data for figures in the paper is available at Mendeley Data https://doi.org/10.17632/w9n6s2kcmc.1.

METHODS

All methods can be found in the accompanying Transparent Methods supplemental file.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.isci.2020.101732.

AUTHOR CONTRIBUTIONS

T.H. and M.K. contributed to the experimental design. T.H. performed the experiment and collected the data. T.H. analyzed the data with G.G. and M.K. T.H., G.G., and M.K. wrote the manuscript. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

Aymerich-Franch, L., and Ganesh, G. (2016). The role of functionality in the body model for self-attribution. Neurosci. Res. *104*, 31–37.

Aymerich-Franch, L., Petit, D., Ganesh, G., and Kheddar, A. (2015). Embodiment of a Humanoid Robot Is Preserved during Partial and Delayed Control (IEEE International Workshop on Advanced Robotics and its Social Impacts (ARSO)), pp. 1–5.

Aymerich-Franch, L., Petit, D., Ganesh, G., and Kheddar, A. (2016a). The second me: seeing the real body during humanoid robot embodiment produces an illusion of bi-location. Conscious. Cogn. *46*, 99–109.

Aymerich-Franch, L., Petit, D., Kheddar, A., and Ganesh, G. (2016b). Forward modelling the rubber hand: illusion of ownership modifies motor-sensory predictions by the brain. R. Soc. Open Sci. *3*, 160407.

Aymerich-Franch, L., Petit, D., Ganesh, G., and Kheddar, A. (2017). Object touch by a humanoid robot avatar induces haptic sensation in the real hand. J. Comput. Mediat. Commun. *22*, 215–230.

Banakou, D., Groten, R., and Slater, M. (2013). Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. Proc. Natl. Acad. Sci. U S A *110*, 12846–12851.

Banakou, D., and Slater, M. (2014). Body ownership causes illusory self-attribution of speaking and influences subsequent real speaking. Proc. Natl. Acad. Sci. U S A *111*, 17678–17683.

Burin, D., Kilteni, K., Rabuffetti, M., Slater, M., and Pia, L. (2019). Body ownership increases the interference between observed and executed movements. PLoS One *14*, e0209889.

Diedrichsen, J., White, O., Newman, D., and Lally, N. (2010). Use-dependent and error-based learning of motor behaviors. J. Neurosci. *30*, 5159–5166.

Dingwell, J.B., Mah, C.D., and Mussa-Ivaldi, F.A. (2002). Manipulating objects with internal degrees of freedom: evidence for model-based control. J. Neurophysiol. *88*, 222–235.

Falconer, C.J., Slater, M., Rovira, A., King, J.A., Gilbert, P., Antley, A., and Brewin, C.R. (2014). Embodying compassion: a virtual reality paradigm for overcoming excessive self-criticism. PLoS One *9*, e111933.

Falconer, C.J., Rovira, A., King, J.A., Gilbert, P., Antley, A., Fearon, P., Ralph, N., Slater, M., and Brewin, C.R. (2016). Embodying self-compassion within virtual reality and its effects on patients with depression. BJPsych Open *2*, 74–80.

Flash, T., and Hogan, N. (1985). The coordination of arm movements: an experimentally confirmed mathematical model. J. Neurosci. *5*, 1688–1703.

Franklin, D.W., and Wolpert, D.M. (2011). Computational mechanisms of sensorimotor control. Neuron *72*, 425–442.

Fribourg, R., Ogawa, N., Hoyet, L., Argelaguet, F., Narumi, T., Hirose, M., and Lécuyer, A. (2020). Virtual co-embodiment: evaluation of the sense of agency while sharing the control of a virtual body among two individuals. IEEE Trans. Vis. Comput. Graph. https://doi.org/10.1109/TVCG.2020.2999197.

Ganesh, G., and Burdet, E. (2013). Motor planning explains human behavior in tasks with multiple solutions. Rob. Auton. Syst. *61*, 362–368.

Ganesh, G., Haruno, M., Kawato, M., and Burdet, E. (2010). Motor memory and local minimization of error and effort, not global optimization, determine motor behavior. J. Neurophysiol. *104*, 382–390.

Ganesh, G., Takagi, A., Osu, R., Yoshioka, T., Kawano, M., and Burdet, E. (2014). Two is better than one: physical interactions improve motor performance in humans. Sci. Rep. *4*, 3824.

Gonzalez-Franco, M., Perez-Marcos, D., Spanlang, B., and Slater, M. (2010). The contribution of real-time mirror reflections of motor actions on virtual body ownership in an immersive virtual environment. Proc. IEEE Virtual Reality *2010*, 111–114.

Hagiwara, T., Sugimoto, M., Inami, M., and Kitazaki, M. (2019). Shared Body by Action Integration of Two Persons: Body Ownership, Sense of Agency and Task Performance (IEEE Conference on Virtual Reality and 3D User Interfaces (VR)), pp. 954–955.

Harris, C.M., and Wolpert, D.M. (1998). Signal-dependent noise determines motor planning. Nature *394*, 780–784, https://doi.org/10.1038/29528.

Kenward, M.G., and Roger, J.H. (1997). Small sample inference for fixed effects from restricted Maximum likelihood. Biometrics *53*, 983–997.

Kilteni, K., Normand, J.-M., Sanchez-Vives, M.V., and Slater, M. (2012). Extending body space in immersive virtual reality: a very long arm illusion. PLoS One *7*, e40867.

Kokkinara, E., Kilteni, K., Blom, K., and Slater, M. (2016). First person perspective of seated participants over a walking virtual body leads to illusory agency over the walking. Sci. Rep. 6, 28879.

Kondo, R., Sugimoto, M., Minamizawa, K., Hoshi, T., Inami, M., and Kitazaki, M. (2018). Illusory body ownership of an invisible body interpolated between virtual hands and feet via visual-motor synchronicity. Sci. Rep. 8, 7541.

Kondo, R., Tani, Y., Sugimoto, M., Minamizawa, K., Inami, M., and Kitazaki, M. (2020). Re-association of body parts: illusory ownership of a virtual arm associated with the contralateral real finger by visuo-motor synchrony. Front. Robotics AI 7, 26.

Peck, T.C., Seinfeld, S., Aglioti, S.M., and Slater, M. (2013). Putting yourself in the skin of a black avatar resuces implicit racial bias. Conscious. Cogn. 22, 779–787.

Pyasik, M., Furlanetto, T., and Pia, L. (2019). The role of body-related afferent signals in human sense of agency. J. Exp. Neurosci. 13, https://doi.org/10.1177/1179069519849907.

Sanchez-Vives, M.V., Spanlang, B., Frisoli, A., Bergamasco, M., and Slater, M. (2010). Virtual hand illusion induced by visuomotor correlations. PLoS One 5, e10381.

Tajadura-Jiménez, A., Banakou, D., Bianchi-Berthouze, N., and Slater, M. (2017). Embodiment in a child-like talking virtual body influences object size perception, self-identification, and subsequent real speaking. Sci. Rep. 7, 9637.

Takagi, A., Ganesh, G., Yoshioka, T., Kawato, M., and Burdet, E. (2017). Physically interacting individuals estimate the partner's goal to enhance their movements. Nat. Hum. Behav. 1, 0054.

Takagi, A., Usai, F., Ganesh, G., Sanguineti, V., and Burdet, E. (2018). Haptic communication between human is tuned by the hard or soft mechanics of interaction. PLoS Comput. Biol. 14, e1005971.

Wobbrock, J.O., Findlater, L., Gergle, D., and Higgins, J.J. (2011). The aligned rank transform for nonparametric factorial analyses using only ANOVA procedures. In Proceedings of the SIGCHI conference on human factors in computing systems, pp. 143–146.

Wolpert, D.M., Diedrichsen, J., and Flanagan, J.R. (2011). Principles of sensorimotor learning. Nat. Rev. Neurosci. 12, 739–751.

Supplemental Information

Individuals Prioritize the Reach

Straightness and Hand Jerk of a Shared

Avatar over Their Own

Takayoshi Hagiwara, Gowrishankar Ganesh, Maki Sugimoto, Masahiko Inami, and Michiteru Kitazaki
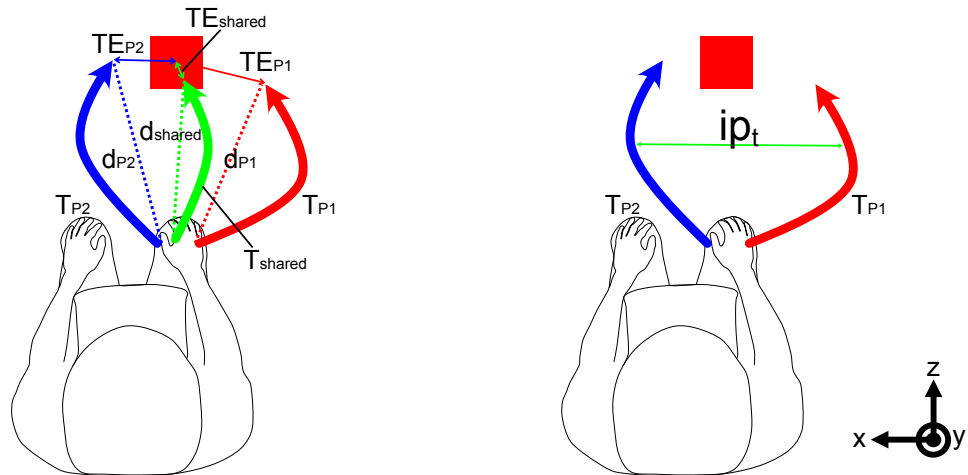
Supplemental Figures and Legends

Figure S1: Measures for reaching analysis. Related to the hand reach deviation (D), the target error (TE) and interpersonal distance (IP). Related to Figure 3A, Figure 4C, Figure 5.
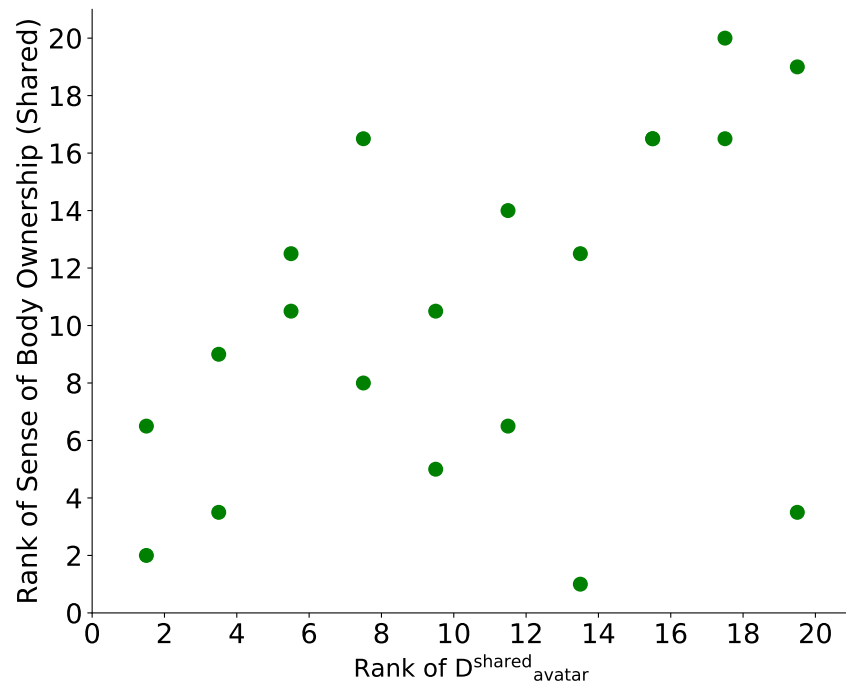

Figure S2: Data are represented as each participant's rank order in ascending order for D^{shared}_{avatar} and the sense of body ownership in the Shared-body condition. Related to Figure 3B.
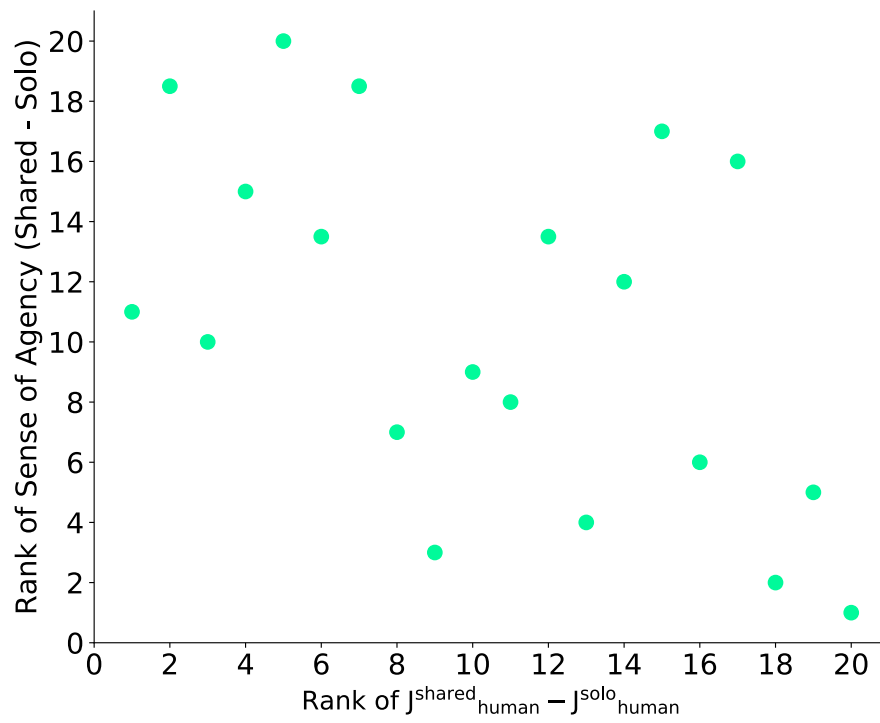
Figure S3: Data are represented as each participant's rank order in ascending order for the change in hand jerk between the Shared-body and Solo-body conditions and the change in the sense of agency between the conditions. Related to Figure 3D.

Transparent Methods

Participants

Twenty volunteers participated in the experiment (all male, mean 21.35 years old ± 1.5 standard deviation (SD)). The sample size was based on previous embodiment (Fribourg et al., 2020) and motor control (Ganesh, et al., 2014) studies involving interaction between human dyads. This number corresponds to an effect size of 0.7, alpha = 0.05, power = 0.8 using the G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007; Faul, Erdfelder, Buchner, & Lang, 2009). All participants have normal binocular vision and physical ability. They gave written informed consent before the experiment. All the experiments were approved by the Ethical Committee for Human-Subject Research at Toyohashi University of Technology and were performed in accordance with this committee's guidelines and regulations.

Setup and Apparatus

The participants took part in the experiment as dyads. They sat in chairs with their backs straight, and with their hands resting on their knees (initial posture). The movements of two participants were measured by a motion-capture system (Vicon Bonita10, 12 cameras, 1024 x 1024 pixels, 250 fps, focal length: 4-12 mm, F/1.4-CLOSE, angle of view: 26.41 x 26.41 deg), and processed in a computer (HP Z440 Workstation, OS: Windows7, CPU: Intel(R) Xeon E5-1620 v3, 3.5GHz, RAM: 32GB, GPU: NVIDIA Quadro 5000 (2560MB GDDR5)) with middle-level software (Vicon Blade 3.4.1, Vicon Pegasus 1.2.2). Two computers (PC1: DELL XPS 8930, OS: Windows10, CPU: Intel(R) Core i7-8700 3.2GHz, RAM: 16GB, GPU: NVIDIA GeForce GTX 1080 (8192MB GDDR5X), PC2: DELL Alienware Aurora, OS: Windows10, CPU: Intel(R) Core i5-6400 2.7GHz, RAM: 16GB DDR4 2667MHz, GPU: NVIDIA GeForce GTX 1080 (8192MB GDDR5X)) received the processed information of the motion capture data, and presented the virtual environment on head-mounted displays (HMD: Oculus Rift CV1, 1080 x 1200 pixels, 90 x 110 deg, 90 Hz refresh) of both participants. The virtual environment (VE) was created using Unity (2017.3.0f3).

Stimuli and conditions

A virtual three-dimensional (3D) space and a male avatar were rendered using Unity

and presented on the HMD. The height of the male avatar was 175 cm and the length of the right arm was 65.8 cm. The avatar sat on a chair in a room (4.5 m depth x 5.5 m wide x 2.5 m high), and the window was placed on the left side as seen from the avatar. A mirror (1.4 m wide x 2.2 m high) was presented in front of the avatar in the VE so that the participants could see their movement and the target object.

The movement of the avatar was a weighted sum of two participant's motions. The position and rotation of the bones of each part of the body were received from the motion capture system, and applied to the corresponding bones of the avatar. The weights reflected in the avatar was set so that the sum of the two participants was 100%. The participants looked at the avatar in the first-person perspective.

The target object was a red cube (10 x 10 x 10 cm). A burst sound was presented when the first joint of the avatar's middle finger touched the center of the object. The cube disappeared immediately after the touch, then a new cube appeared in a random position 5 s later. Participants were instructed to touch the target object while actually looking at it, rather than looking at the target object in the mirror. The target object appeared at a horizontal angle of ± 70 deg and a vertical angle of ± 45 deg from the shoulder position of the shared avatar. It appeared within a radius of 65 cm from the shoulder but did not appear less than 35 cm to the participant.

For each condition, a dyad performed the cube reaching task for 5 min, and the participants were asked to reach the cube with their right hand. The weights utilized in each condition were as follows- For the Solo-body condition: Participant 1: 100%, Participant 2: 100%, and for the Shared-body condition: Participant 1: 50%, Participant 2: 50%. The participants were not aware of the weights, and the condition order was counter-balanced with 4 repetitions. In the Solo-body condition, two participants each saw an avatar that represented their own movements.

The movements of the two participants were recorded by the motion capture system, and transferred to Unity programs in two computers. The motion data were under-sampled at 90 Hz (same timing as display refresh), and the positions of a specific parts of the participants and the avatar (head, neck, three parts in spine (divided in equal length), left shoulder, left upper arm, left forearm, left hand, right shoulder, right upper arm, right forearm, right hand, and three parts in middle finger of right hand (divided in equal

length) were extracted. We used only the positions of tip of the middle finger of the right hand.

Procedure

The participants were seated in chairs with their backs straightened, and their hands were put on their knees (initial posture). For each trial, a dyad performed the cube reaching task for 5 min, and the participants were asked to reach the cube with the right hand. After the task, the participants were asked to rate the sense of agency (Questionnaire: How much did you feel as if you controlled the avatar hand? Please give a ratio of the sense of agency between 0 and 100%. 0 is "I did not control the avatar hand at all", 100 is "I fully controlled the avatar hand"). Then, they were asked to rate the sense of body ownership (Questionnaire: I felt as if the avatar's body I saw was my body; -3 to +3; 7 level Likert scale. -3 is "I did not feel it at all", +3 is "I felt it extremely strongly"). These items were presented on a computer screen, and participants answered the sense of agency with a keyboard (0-100), and answered the sense of body ownership by choosing from the pull-down menu (-3 to +3). Two conditions (Shared-body condition and Solo-body condition) were repeated 4 times in counter-balanced order.

Measurements for reaching analysis

The participants (P1, P2) performed the experiment in dyads (see Supplementary Figure 1). They worked in two conditions. In the Solo-body condition, the participant arm movement was replicated on the avatar, while in the Shared-body condition, the avatar's arm movement was the average of the arm movements performed by the two participants in the dyad.

T_{P1}, T_{P2} and T_{shared} indicate the length of trajectory (T) of the participant P1, the participant P2, and the shared avatar (shared), respectively. t indicates the indices of the data frame collected at 90 Hz. F indicates the number of all frames in a reaching. The initial point is defined as the hand position when the target cube appears. The end point of the reach is defined as the point at which the hand velocity falls below 10% of the maximum velocity for the first time. T is calculated as follows:

$$T = \sum_{t=0}^{F} \sqrt{(x_{t+1} - x_t)^2 + (y_{t+1} - y_t)^2 + (z_{t+1} - z_t)^2}$$

d_{P1}, d_{P2} and d_{shared} indicate the direct distance of the participant P1, the participant P2, and the shared avatar, respectively from the initial hand point (x_0, y_0, z_0) to the end point $(x_{end}, y_{end}, z_{end})$ during reach. d is calculated as follows:

$$d = \sqrt{(x_{end} - x_0)^2 + (y_{end} - y_0)^2 + (z_{end} - z_0)^2}$$

Then, we calculated the difference (D) between the length of the hand movement trajectory (T) and the direct distance (d).

D^{solo}_{human1}, D^{solo}_{human2} and D^{shared}_{avatar} indicate the difference between the length of the hand movement trajectory (T_{P1}, T_{P2}, T_{shared}) and the direct distance (d_{P1}, d_{P2}, d_{shared}). D^{solo}_{human1} and D^{solo}_{human2} indicate the hand reach deviation by the participants (P1, P2) in the Solo-body condition. D^{shared}_{avatar} indicate the hand reach deviation by the shared avatar in the Shared-body condition.

$$D^{solo}_{human1} = T_{P1} - d_{P1}$$
$$D^{solo}_{human2} = T_{P2} - d_{P2}$$
$$D^{shared}_{avatar} = T_{shared} - d_{shared}$$

Target error (TE) was calculated as a performance measure.

TE_{P1}, TE_{P2} and TE_{shared} indicate the difference between the end point of the participant's reach ($x_{end}, y_{end}, z_{end}$) and the center of the target object (x_c, y_c, z_c). TE_{P1} and TE_{P2} indicate the target error (TE) of the participant P1 and P2, respectively. TE_{shared} indicate the target error (TE) of the shared avatar in the Shared-body condition. TE is calculated as follows:

$$TE = \sqrt{(x_c - x_{end})^2 + (y_c - y_{end})^2 + (z_c - z_{end})^2}$$

ip_t indicates the distance between the two participant's hand position at a frame

(Participant1: $x_{\text{P1}t}, y_{\text{P1}t}, z_{\text{P1}t}$; Participant2: $x_{\text{P2}t}, y_{\text{P2}t}, z_{\text{P2}t}$). ip is calculated as follows:

$$\text{ip}_t = \sqrt{(x_{\text{P1}t} - x_{\text{P2}t})^2 + (y_{\text{P1}t} - y_{\text{P2}t})^2 + (z_{\text{P1}t} - z_{\text{P2}t})^2}$$

$\text{IP}^{\text{solo}}_{\text{human}}$ indicate the average inter-participant distance by the participants in the Solo-body condition. $\text{IP}^{\text{shared}}_{\text{human}}$ indicate the average inter-participant distance by the same participants in the Shared-body condition. IP is calculated as follows:

$$\text{IP} = \frac{1}{F} \sum_{t=0}^{F} \text{ip}_t$$

We calculated jerk of participant's and avatar's hand reaching.

$\text{J}^{\text{solo}}_{\text{human}}$, $\text{J}^{\text{shared}}_{\text{human}}$ and $\text{J}^{\text{shared}}_{\text{avatar}}$ indicates the square root of the third order differential of the position. $\text{J}^{\text{solo}}_{\text{human}}$ indicate the jerk by the participants in the Solo-body condition. $\text{J}^{\text{shared}}_{\text{human}}$ indicate the jerk by the participants in the Shared-body condition. $\text{J}^{\text{shared}}_{\text{avatar}}$ indicate the jerk by the shared avatar in the Shared-body condition. J is calculated as follows:

$$\text{J} = \frac{1}{F} \sum_{t=0}^{F} \sqrt{\dddot{x}_t^2 + \dddot{y}_t^2 + \dddot{z}_t^2}$$

We calculated the task time (TT) and the reaction time (RT) for reaching time measures. The task time was defined as a time between the appearance of the target and the hand's touching the target. $\text{TT}^{\text{solo}}_{\text{human}}$ indicates the participant' task time in the Solo-body condition, and $\text{TT}^{\text{shared}}_{\text{avatar}}$ indicates the shared avatars' task time in the Shared-body condition. The reaction time was defined as the time between the appearance of the target and the time at which the hand velocity goes over 10% of the maximum velocity. $\text{RT}^{\text{solo}}_{\text{human}}$ indicates the participants' reaction time in the Solo-body condition, and $\text{RT}^{\text{shared}}_{\text{avatar}}$ indicates the shared avatar's reaction time in the Shared-body condition.

Analysis and statistics

All analyses were performed in RStudio and R software (Version 4.0.2, The R Project for Statistical Computing, https://www.r-project.org/) and JASP (Version 0.13.1, https://jasp-stats.org/). Aligned rank transformation (ART) procedure was performed with the "ARTool" package (https://depts.washington.edu/acelab/proj/art/index.html). All data groups were first tested for normality using the Shapiro-Wilk test before analysis. Following this, paired t-tests or repeated measures ANOVAs were utilized for the analysis of data that did not violate the assumption of normality (Shapiro-Wilk test, $p > .05$). Wilcoxon's signed-rank tests or repeated measures ANOVAs with ART were used for data that significantly deviated from the normality (Shapiro-Wilk test, $p < .05$). For correlation analysis, Spearman's rank-order correlations were used when either of both of the compared data groups significantly deviated from normality (Shapiro-Wilk test, $p < .05$).