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Improvement in the Manipulability of Remote Touch Screens Based on Peri-Personal Space Transfer

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ABSTRACT Current remote-control interfaces are difficult to operate intuitively while viewing the entire remote display and require familiarity with the operation. The space within an individual's reach, called the peri-personal space (PPS), assists them in planning their physical movements. Hence, manipulating objects outside one's PPS is more difficult than doing so inside it. Therefore, this study aimed to develop an interface that creates the illusion of an operator's finger being transferred to a remote display and transfers the PPS to the virtual finger in the display. To transfer the PPS to a manipulated object, it is necessary to enhance the user's sense of agency and ownership toward the manipulated target by ensuring it is similar in shape and motion to the user's body. Long-term input testing confirmed that by transferring the PPS to a virtual finger, there is no significant difference, as suggested by a t-test between the coefficients of the learning curves outside and inside the PPS. Furthermore, when users learned to manipulate the virtual finger outside the PPS under conditions that impaired their sense of agency, even after two weeks of learning, the PPS was not continuously transferred to the virtual finger for more than seven minutes from the start of the virtual finger operation. The experimental results demonstrated that the interface enabled the display located outside the PPS to be operated with the same degree of operability as inside the PPS from the start of the operation, even with a short learning period.

INDEX TERMS peri-personal space, sense of agency, sense of ownership, virtual finger

I. INTRODUCTION

Automated driving has been attracting attention for solving problems such as reducing traffic accidents and easing traffic congestion [1]. With the development and availability of Level-5 autonomous vehicles, users will not have to keep track of their surroundings while on the road [2]. Therefore, automobile companies are considering converting windshields and side windows into displays [3]. In addition, the car's interface requires updating to ensure that all operations can be performed from anywhere in the car. This will allow a user to not be confined to the driver's seat and, instead, be able to sit anywhere in the car.

In a similar vein, speech recognition is attracting attention as an interface that can be operated regardless of the user's location. Speech recognition can recognize standard and emotionless words with high accuracy. However, various noises, such as the sound of a running car and the air conditioner blowing, reduce the accuracy of speech recognition [4]. Furthermore, air volume and direction are difficult to recognize and require finetuning. Therefore, some of these functions are easier and more intuitive to perform through direct touch rather than relying on voice or speech recognition. Hence, even if Level-5 autonomous driving becomes available, a hand-operated interface will still be necessary.

The hand-operated interfaces used inside vehicles include touch panels, touch pads, and joysticks. Most vehicles today already come equipped with touch panels. They are intuitive to use because they operate by allowing the user to touch the desired object on the display. However, it is impossible for the users to operate a remote display using a touch panel, such as a smart phone, without also looking at their finger's position. In contrast, touch pads or joysticks are operated by moving the cursor or selection on the display to the desired position. Unlike a touch panel, the user does not need to look at their hand and can thus operate them while looking at the entire display. However, touch pads and joysticks are not used as frequently in daily life, as these interfaces require the users to be familiar and comfortable with them to perform multiple operations.

Thus, presently, there is no intuitive interface that allows users to quickly become accustomed to the operation while also enabling them to view the entire remote display. This is because such interfaces do not allow users to utilize the skills they have developed in their daily lives to manipulate a remote object in their peri-personal space (PPS) [5].

The PPS refers to the space within an individual's immediate reach, whereas the extra-personal space refers to the space outside their reach [6] [7]. The PPS assists individuals in planning the movements of their body parts while performing actions such as reaching, grasping, and manipulating objects. Additionally, presenting visual and tactile stimuli inside the PPS activates people's ventral premotor cortex and posterior parietal cortex in response. In particular, the ventral premotor cortex helps control hand movements and enables associative sensorimotor learning; therefore, manipulations outside the PPS may be more difficult because of people's inability to leverage responses that are specifically triggered within the PPS [5] [8] [9]. In addition, users are expected to require a longer learning period to become accustomed to operations occurring outside their PPS.

Therefore, as shown in Fig. 1 a new interface to solve these problems is proposed. In this interface, the user operates a virtual hand displayed on a remote panel, which helps create the illusion that the user's own hand has moved to the remote panel. Users operate the virtual touch panel on the display by touching the virtual hand. The interface provides users with the illusion of directly touching the virtual touch panel. The interface is expected to allow users to use the skills required to operate a touch panel, which they have already developed. The users are also expected to be able to transfer their PPS to the virtual hand [10] [11]. The PPS exhibits dynamic and functional plasticity. It is not only fixed around the body but also modifies itself flexibly [12] [13] [14]. Mine et al. displayed a virtual hand far away from themselves in a VR space and confirmed that PPS transfers to the virtual hand [10] [11]. Furthermore, they demonstrated that even if the real and virtual hands are not physically connected, PPS can be transferred to the virtual hand. Therefore, users are expected to be able to manipulate the interface if their PPS is transferred to the virtual hand.

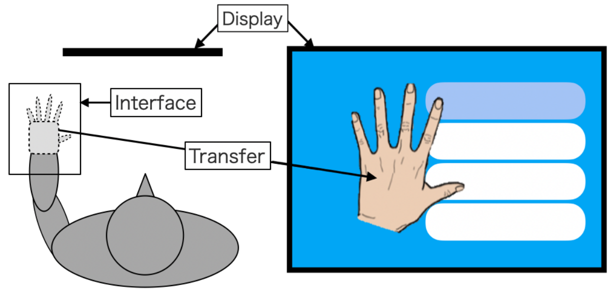

FIGURE 1. The proposed interface through which the user can transfer their PPS to a virtual finger on the display to operate the virtual finger intuitively like their own finger.

Bassolino et al. suggested that for users with long-term experience of using a mouse, their PPS simply extends around the mouse pointer merely by holding the mouse passively, even without actively moving them [15]. However, the participants had more than seven years of experience manipulating the mouse for an average of more than four hours per day. Therefore, it is unclear how long a learning time it takes for the PPS to simply extend around the mouse pointer merely by holding the mouse passively. In addition, when the mouse was grasped passively with the non-dominant hand, the PPS did not extend around the mouse pointer due to a lack of proficiency. Serino et al. suggested that if users have no long-term experience of tools, they may still be able to manipulate the tools and extend their PPS around these tools. However, after one day, the PPS that was extended returns to its original state before it was extended [16]. In contrast, if users have long-term experience of using specific tools, their PPS does not shrink; instead, it expands persistently around the tools. Thus, because the users are intimately familiar with how their hand operates, they are expected to be able to transfer their PPS to a virtual hand at the start of the remote operation regardless of the dominant hand by experiencing the virtual hand as their own.

To feel the virtual hand as if it were their own hand, the users need to enhance two senses: a sense of ownership (SoO) and a sense of agency (SoA) [15] [16]. An SoA plays a particularly important role in the expansion of the PPS [17].

An SoA is the feeling that the object being viewed is being controlled and moved by oneself [16]. It develops through a comparison between the predicted sensory feedback and sensory feedback from the actual motion [18] [19] [20]. One's SoA improves when the predicted and actual motions match. Through a subjective evaluation using questionnaires, Minohara et al. and Wen et al. confirmed that when the visual feedback for specific actions is delayed, the users' SoA decreases [21] [22]. Zopf et al. reported that people can experience an SoA even when the shape of the object does not match the shape of their body [23]. Madhur et al. demonstrated that the SoA can be experienced regardless of the distance from the object [24]. These studies suggest that to improve their SoA, users must align the manipulated objects with their predicted motion.

To transfer the PPS to a virtual hand at the start of the virtual hand operation, it was considered that when the users are introduced to the objects, they must first be able to believe that the objects belong to them. That is, the users must improve their SoO, which refers to the perception that what is being viewed is part of one's own body [15]. It has been suggested that SoO and SoA are positively correlated [25]. Thus, an increase in SoO is related to an increase in SoA, which is necessary for the transfer of the PPS. In addition, prior research has confirmed that it is easier to operate an object that resembles the shape of one's hand than to operate a pointer [26]. Therefore, an improvement in SoO would also help improve the object's operability.

Tsakiris et al. found that the SoO decreased when the shape of the rubber hand differed from that of the participant's hand, such as taking the shape of a tree branch instead of a human hand [27]. Furthermore, they confirmed that when tactile stimuli were presented to the participant's rubber right hand and their own left hand, they did not perceive the rubber right hand as their own right hand. Thus, it is necessary to ensure that the object resembles the user's own body part to improve the user's SoO.

Given this context, this research aimed to develop an interface that would transfer the PPS to the operating target outside the PPS at the start of a virtual operation, such that it would provide the same level of operability as witnessed inside the PPS, without requiring users to engage in long-term learning. Thus, a long-term study was conducted to confirm whether the operability achieved by transferring the PPS to a virtual finger outside the PPS can match that achieved inside the PPS. Moreover, whether the PPS is transferable at the start of the virtual finger operation was confirmed by conducting experiments on people with weak and strong SoA and SoO. To the best of the authors' knowledge, no studies have been conducted on the effects of long-term manipulative learning by transferring the PPS to manipulated objects. Hence, this study contributes to the literature in the following ways:

1) An interface through which a user can operate a virtual hand displayed on a remote panel to create the illusion of the user's hand moving the remote panel was proposed.
2) If the users' SoA and SoO toward a manipulated object outside the PPS are impaired, they cannot manipulate the object in the same way as they can inside the PPS at the start of the manipulation, even with long-term learning. The interface would enable the operator to operate the display outside the PPS from the start of the operation with the same degree of operability as inside the PPS, even with a short learning period.
3) A certain amount of time is required to transfer the PPS to the manipulated object when the user's SoA and SoO are impaired. The interface contributes to the transition of the PPS to the operational target from the start of the operation.
4) It was demonstrated that users can learn outside the PPS as they do inside the PPS by transferring the PPS to the manipulated object.
5) If the users' SoA and SoO toward the manipulated object are impaired, the learning period required to perform the same operations outside the PPS as inside the PPS from the start of the manipulation is confirmed to be shorter when the learning occurs inside rather than outside the PPS.

II. INTERFACE

This section describes the system configuration for an interface that provides users with the illusion of directly touching a virtual touch panel and a method for determining the size of input buttons on the virtual touch panel. The system configuration of the interface and the operational setup are shown in Fig. 2 and Fig. 3, respectively. First, the participant's finger was tracked by a motion capture camera (OptiTrack, Flex13). Motion capture has an error margin of less than 0.1 mm when reading the position of reflective markers, thus allowing for a highly accurate finger tracking. The virtual finger was manipulated using a motion-capture glove, as shown in Fig. 4a. Other reflective markers were placed on the glove between the fingertips and first joint and between the second and third joints, as shown in Fig. 4a. Three reflective markers were used to create the coordinate system at each position. The reflective markers were attached to the fingertip and right side of each finger, as shown in Fig. 4b. The x-coordinates of the fingertip and first joint were determined by the coordinates shown in Fig. 4b, point a relative to coordinate System 1. Furthermore, the y- and z-coordinates of the fingertip and the first joint were determined using the coordinates shown in Fig. 4b, points b and c relative to coordinate System 1. The coordinates of the fingertip and the first joint were determined from the relative coordinates. Similarly, the coordinates of the second and third joints were determined using the coordinates shown in Fig. 4b, points a, d, and e relative to coordinate System 2, as shown in Fig. 4c. Each coordinate was updated at an average of 108 fps and transferred to Unity3D to draw a virtual finger in real time, as shown in Fig. 5a. It took 33-41 ms for the coordinates to be measured and reflected on the monitor (BenQ, XL2546K, 144Hz). The delay is considered to have a smaller effect on the SoA and SoO than what was observed in previous studies [21] [22] [28].

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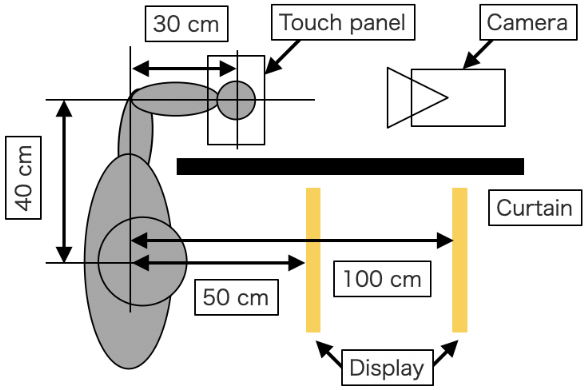

FIGURE 2. Schematic of the experiment and settings

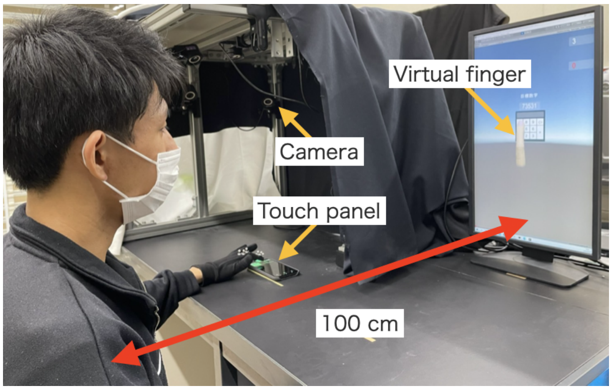

FIGURE 3. Operating environment where the display is located 100 cm from a user

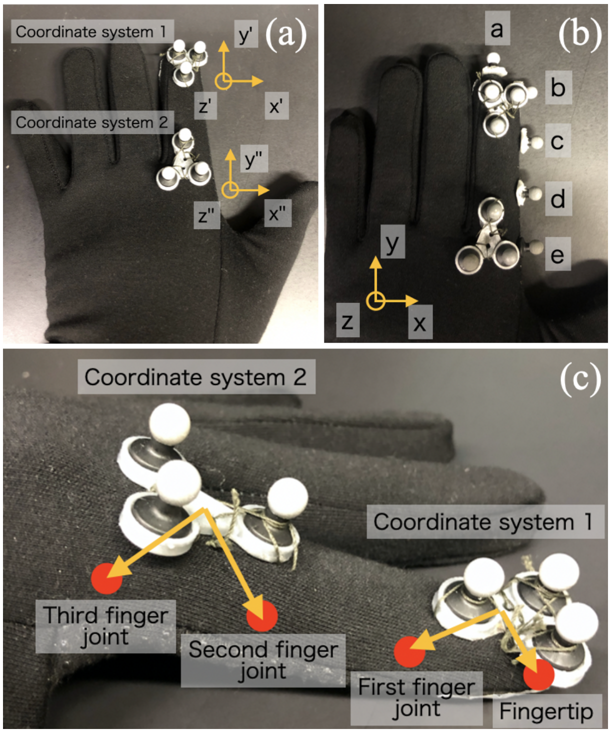

FIGURE 4. Motion capture glove and coordinate systems. (a)Positions of the reflective markers and the coordinate system created based on three reflective markers. (b)The reflective markers were placed on the sides of the fingertips and the first, second, and third finger joints. (c)The relative coordinates of the fingertips and the first through third joints as seen from each coordinate system.

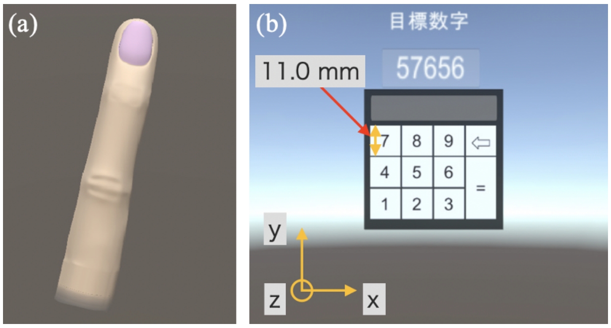

FIGURE 5. The virtual finger and virtual touch panel displayed before a participant. (a)Virtual finger. (b)Virtual touch panel.

Experiment 1 was an input task for a panel with a high density of buttons, as shown in Fig. 5b, which required highly accurate finger position control. If the fingertip of the virtual finger is placed on the button and the participant presses the touch panel (Pixel 4), the number is inputted. The touch panel communicates with the PC via UDP communication to send information via touch. When the participant pressed the touch panel, a sound was heard as feedback. The size of the buttons on the panel was designed using Fitts' law, which was extended to two dimensions.

The buttons were sized to be of a width that achieves at least a 95% success rate. The equation of Fitts' law extended to two dimensions is as follows:

$$\mathrm{W_e} = \sqrt{\frac{2\mathrm{B}}{1-\mathrm{r}^2}\sigma_x^2 + \sigma_y^2 + \sqrt{(\sigma_x^2-\sigma_y^2)^2 + 4\sigma_x^2\sigma_y^2\mathrm{r}^2}}, \quad (1)$$

$$\mathrm{H_e} = \sqrt{\frac{2\mathrm{B}}{1-\mathrm{r}^2}\sigma_x^2 + \sigma_y^2 - \sqrt{(\sigma_x^2-\sigma_y^2)^2 + 4\sigma_x^2\sigma_y^2\mathrm{r}^2}}, \quad (2)$$

$$\mathrm{B} = -2(1-\mathrm{r}^2)\log_e(1-\mathrm{A}), \quad (3)$$

where x and y are the coordinates of the point position from the center of the button; r represents the correlation coefficient between x and y; σ_x and σ_y represent the standard deviations of x and y, respectively; W_e and H_e represent the width and height of the button, respectively; and A is the success rate. The above equations are validated when σ_x is larger than σ_y. When σ_x is smaller than σ_y, the equations for W and H are reversed [29] [30]. Participants performed the input trials using a touch panel (Pixel 4) displaying the same screen as in Fig. 5b. Based on participants' input test results, the button size was set to 11 mm × 11 mm.

III. EXPERIMENT 1 - A LONG-TERM STUDY TO INVESTIGATE USERS' LEARNING CURVE BY THE LEVEL OF THEIR SOA AND SOO

Experiment 1 investigated whether 1) learning outside and inside the PPS are similar by transferring the PPS to a virtual finger outside the PPS; 2) the same operations can be performed outside and inside the PPS from the start of the operation; 3) the learning distance affects the PPS transition.

A. PARTICIPANTS

In total, 16 healthy (male) participants were recruited as paid volunteers to participate in Experiments 1 and 2. All the participants provided written informed consent before participating in the experiments. The experiments were approved by the Ethics Committee of Nagoya University.

B. EXPERIMENTAL CONDITIONS

In Experiment 1, an input task was conducted on a virtual panel. The operability of the virtual finger was evaluated by measuring the time required to input the target number of characters. Further, 14 days of training with the distance between the participant and the virtual finger set at either 50 cm (inside the PPS) or 100 cm (outside the PPS) were conducted. In addition, on day 15, the experiment was conducted at a distance opposite to that at which the learning had taken place. These experiments were conducted with weak and strong SoA and SoO toward the virtual finger. As a previous study suggested that SoA is related to the transfer of PPS, the SoA to inhibit the transfer of PPS was weakened [17]. The weak and strong SoA and SoO conditions are illustrated in Fig. 6. The weak SoA and SoO conditions were created by applying a 700 ms delay until the virtual finger moved in response to its own movement; a 700 ms delay made SoO imperceptible and reduced SoA by about 70% [21] [22] [28] [31] [32].

The size of the virtual finger at 50 cm was the same as that of the participant's finger. The size of the virtual finger at 100 cm was 1.5 × larger than the size of the participant's own finger. In general, to match the size of an object at 50 cm with the size of an object at 100 cm in the retinal image of an eye, the object at 100 cm must be twice as large as the object at 50 cm. However, the retina perceives different objects to be approximately the same size, even if the size of the retinal image in the eye changes with distance [33]. Thus, the size at which the participants perceived the virtual finger to be of the same size as their actual finger at a 100-cm distance was measured. As a result, it was 1.5 times their actual finger's size. Therefore, the size of the virtual finger at 100 cm was set to 1.5 times the size of the participant's finger. Moreover, the panel was also made 1.5 times larger at 100 cm to keep the input range constant regardless of distance.

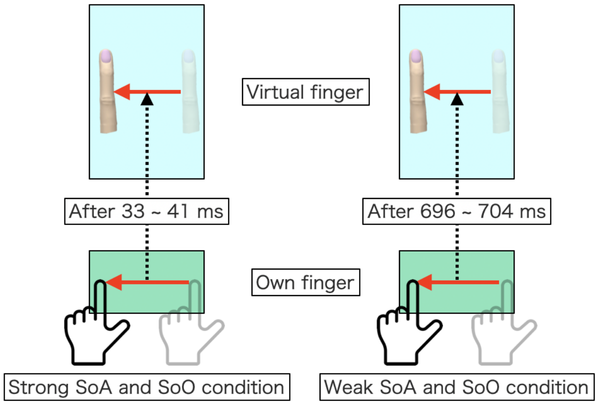

FIGURE 6. Strong and weak SoA and SoO conditions

C. PROCEDURE

Participants wore the motion capture glove shown in Fig. 4a on their left hand and placed it at the position shown in Fig. 2. Their hands were hidden by a curtain so that it was not visible during the experiment. A chair was fixed, and the participant sat with their back closely against the backrest of the chair.

Participants repeated 20 trials of typing a randomly displayed five-digit number with their left hand's index finger for a total of 100 characters. If a participant inputted an incorrect number, they input the next target number. The same number was not displayed consecutively. Participants repeated the 100-character input 10 times during each trial, with a 5-min break between trials. The experiment was repeated for 14 days, and on the 15th day, the distance was changed, and the experiment was repeated. Participants were instructed to type as quickly and accurately as possible. Four conditions were used: distance from the screen (inside the PPS, outside the PPS) × delay (with delay, without delay). Each condition had four participants who were instructed to randomly input 100 characters into the touch panel in advance. The time taken to type 100 characters was measured and the experimental groups were determined to ensure the average time matched in each condition.

D. STATISTICAL ANALYSES

The time required to input 100 characters was measured and the average input time for each participant under each condition was calculated. Additionally, operability was evaluated using the learning curve. Since the learning curve is considered the transfer function of a first-order linear system for stepwise inputs, it is drawn by a nonlinear regression using the following equation as a mathematical model of the exponential function [34]:

$$y = B3e^{-B2(x-1)} + B4(1 - e^{-B2(x-1)}), \qquad (4)$$

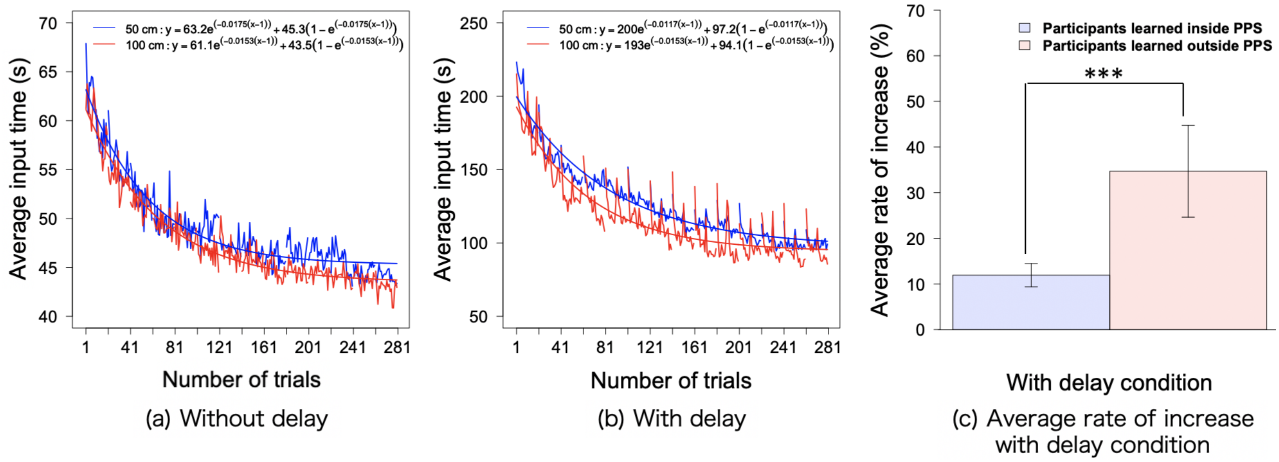

FIGURE 7. **(a) and (b) show the average input time and learning curve inside and outside the PPS, respectively, for 14 days. (a) shows the without-delay condition and (b) shows the with-delay condition. (c) shows the average rate of increase from the input time at the end of the previous day's operation to the input time at the start of the next day's operation (IR) with a delay condition for 14 days. Error bars show standard error. The blue line and bar indicate participants learning inside the PPS. The red line and bar show participants learning outside the PPS. As shown in (c), there was a significantly greater IR for participants who learned outside rather than inside the PPS. ***p < 0.001.**

where x represents the number of trials, y represents the input time, B2 is the learning rate, B3 is the initial performance ability, and B4 is the asymptote of the input time, when the number of trials is infinite.

To investigate whether the same operation was possible outside and inside the PPS from the start of the operation, the rate of increase in the input time at the end of the previous day's operation to that at the start of the next day's operation was measured. Further, the rate of increase in the input time was calculated using the following equation:

$$\mathrm{IR} = (\mathrm{ET} - \mathrm{ST})/\mathrm{ET}, \tag{5}$$

where IR is the rate of increase, ET is the input time at the end of the previous day's operation, and ST is the input time at the start of the next day's operation.

E. RESULTS

The average input time and learning curve inside and outside PPS are shown in Fig. 7a and Fig. 7b, respectively, over 14 days. The without-delay condition is depicted in Fig. 7a and the with-delay condition is shown in Fig. 7b. The average rate of increase in the input time from the end of the previous day's operation to the start of the next day's operation (IR) with delay for 14 days is shown in Fig. 7c. The blue line and bar show the participants' learning inside the PPS. The red line and bar show the participants' learning outside PPS. The input time when the distance is changed is shown in Fig. 8. The average input time on day 14, before the distance was changed, is depicted between trials 261 to 280.

Furthermore, the average input time on day 15, after changing the distance, is depicted between trials 281 to 300. The condition without delay is shown in Fig. 8a, and the condition with delay is depicted in Fig. 8b. The blue line shows the participants' learning curve inside the PPS and the red line shows the participants' learning curve outside the PPS.

The input time averaged from the first to the 10th trial and from the 11th to the 20th trial on days 14 and 15 are shown in Fig. 9. The without-delay and with-delay conditions are shown in Fig. 9a and Fig. 9b, respectively. The blue bar shows the participants learning inside the PPS, and the red bar shows the participants learning outside the PPS.

As shown in Fig. 7a, a t-test of each coefficient of the learning curve in the no-delay condition inside and outside the PPS showed no significant differences for all coefficients of B2, B3, and B4 (B2 : $t(6) = 0.08$, $p = 0.83$; B3 : $t(6) = -0.23$, $p = 0.94$; B4 : $t(6) = -0.11$, $p = 0.91$). As shown in Fig. 7a, a two-way repeated measures ANOVA (days × inside and outside the PPS) of the average rate of increase in input time from the last input time on the previous day to the start of the experiment on the following day (IR) inside and outside the PPS showed no significant difference in the no-delay condition ($F(1,103) = 0.00$, $p = 0.99$). As shown in Fig. 8a and Fig. 9a, a two-way repeated measures ANOVA (times × inside and outside the PPS) of the input times from the start of the experiment to the 10th trial and from the 11th to the 20th trial between days 14 and 15 in the no-delay condition, respectively, revealed no significant differences in either case for participants who learned inside the PPS (1 - 10 times : $F(1,79) = 0.01$, $p = 0.92$; 11 - 20 times : $F(1,79) = 0.68$, $p = 0.41$). Participants who learned outside the PPS also showed no significant differences (1 - 10 times : $F(1,79) = 0.08$, $p = 0.78$; 11 - 20 times : $F(1,79) = 0.22$, $p = 0.64$).

As shown in Fig. 7b, a t-test of each coefficient of

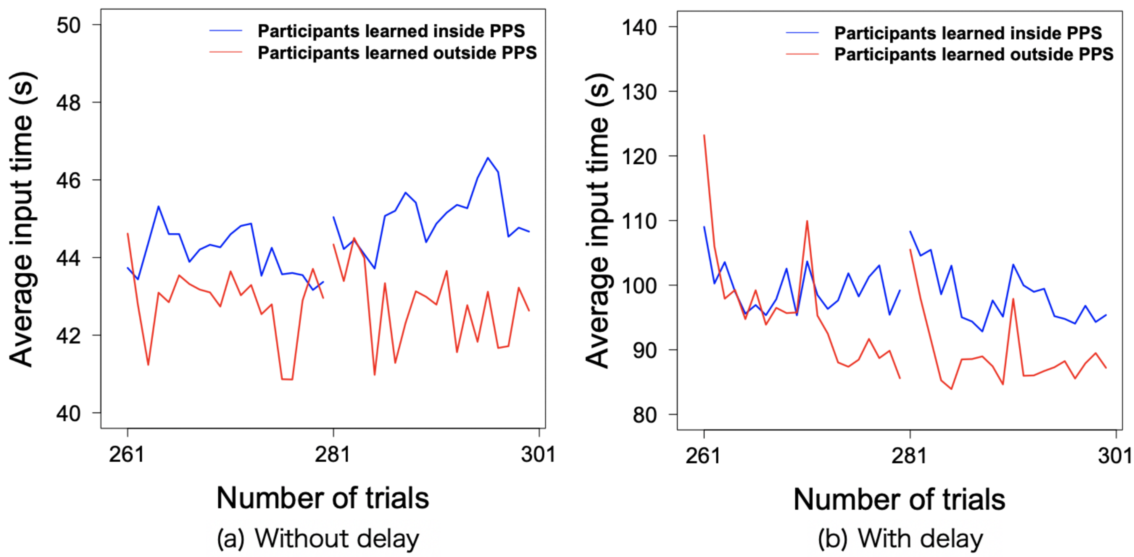

FIGURE 8. **Average input time for days 14 and 15 with delay. The average input time before and after changing the distance are shown between trials 261–280 and 281–300, respectively. (a) shows the without-delay condition and (b) shows the with-delay condition. The blue line shows the participants learning inside PPS and red line shows the participants learning outside PPS.**

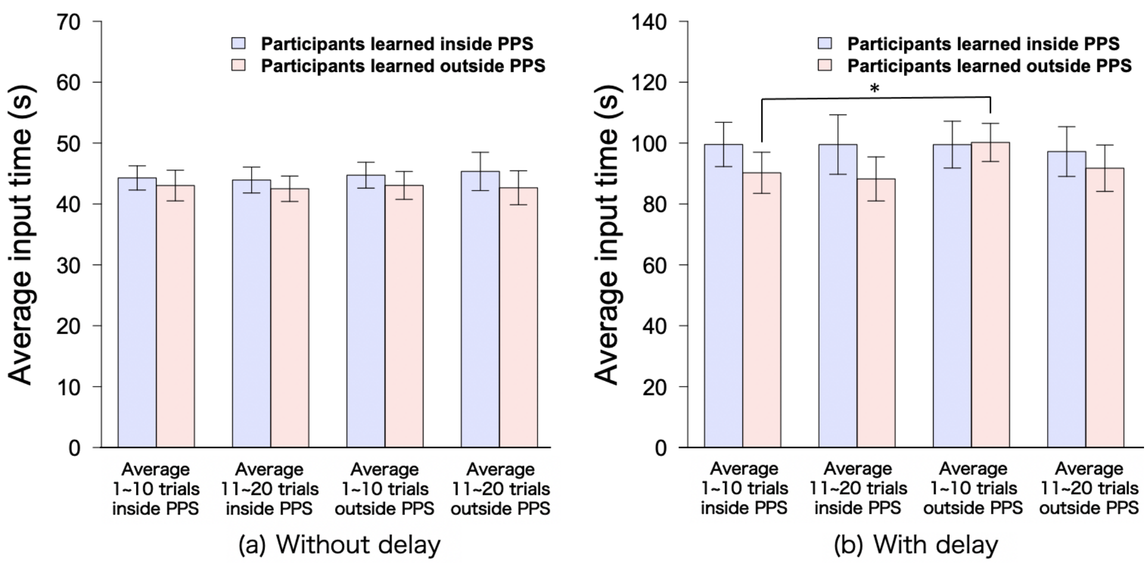

FIGURE 9. **Input time averaged from the first to the 10th trial and from the 11th to the 20th trial on days 14 and 15. (a) shows the without-delay condition and (b) shows the with-delay condition. The blue bar shows the participants' learning inside the PPS and the red bar shows their learning outside the PPS. Error bars show the standard error. As shown in (b), participants who learned outside the PPS had significantly shorter input times from the beginning of the experiment to the 10th trial when they inputted inside the PPS. *p < 0.05.**

the learning curve under the delay condition inside and outside the PPS showed no significant differences for all coefficients of B2, B3, and B4 (B2 : $t(6) = 0.24$, $p = 0.25$; B3 : $t(6) = -1.26$, $p = 0.82$; B4 : $t(6) = -0.22$, $p = 0.83$). As shown in Fig. 7c, a two-way repeated measures ANOVA (days × inside and outside the PPS) of the average IR inside and outside the PPS showed that there is significantly greater IR for participants who learned outside rather than inside the PPS in the with-delay condition($F(1,103) = 23.64$, $p < 0.001$). As shown in Fig. 8b and Fig. 9b, a two-way repeated measures ANOVA (times × inside and outside the PPS) of the input times from the start of the experiment to the 10th trial and from the 11th to the 20th trial between days 14 and 15 in the no-delay condition, respectively, revealed no significant differences in either case for participants who learned inside the PPS (1 - 10 times : $F(1,79) = 0.00$, $p = 0.99$; 11 - 20 times : $F(1,79) = 0.23$, $p = 0.63$). However, for the participants who learned outside the PPS, the input time was significantly shorter when the participants input inside the PPS from the beginning of the experiment up to the 10th time, and no significant difference was observed from the 11th to the 20th time (1-10 times : $F(1,79) = 6.46$, $p = 0.014$; 11-20 times : $F(1,79) = 1.28$, $p = 0.26$).

F. DISCUSSION

Experiment 1 aimed to investigate whether learning outside and inside the PPS are similar after transferring the PPS to a virtual finger outside the PPS; whether the operations performed inside the PPS can be performed outside the PPS from the start of the operations; and finally, whether the learned distance affects the transition of the PPS.

As shown in Fig. 7a and Fig. 7b, there were no significant differences for all the coefficients of B2, B3, and B4 in Eq. (4) between inside and outside the PPS in the no-delay and with-delay conditions. The results confirm that the learning distance has no effect on the learning of manipulation. It was considered that even with a large delay in the movement of the virtual finger, the operator felt the SoA to the extent that the PPS was transferred to the virtual finger. Several previous studies have shown that PPS transfers to manipulated targets that are disconnected from the body [10] [11]. The PPS is closely related to SoA; therefore, it was hypothesized that the PPS would not be transferred to the virtual finger in case of a delay [17]. However, in the previous studies, the targets were not constantly moved, nor were participants studied over a long period of time [21] [22]. In contrast, in Experiment 1, the virtual finger and the participant's own finger moved synchronously for a long period. In addition, the operator was able to predict the movement of the virtual finger because the delay of the virtual finger was constant. Therefore, the actual and predicted movements of the virtual fingers were considered to match, which improved the SoA of the virtual finger. Therefore, even under the conditions of delay, it is considered that the PPS could be transferred to the virtual finger outside the PPS, and the operator could have learned outside the PPS as well as inside the PPS.

As shown in Fig. 7a, in the without-delay condition, there was no significant difference in the IR between inside and outside the PPS in the no-delay condition. In contrast, in the delay condition, as shown in Fig. 7c, the IR was significantly greater outside than inside the PPS. The results suggest that the time required for the PPS transition was longer in the presence of delay than in the absence of delay. The PPS assists the body part in motion planning; therefore, when the PPS is not transferred to the virtual finger, the operation time is longer because of the participant's inability to predict the virtual finger's movement. Previous studies have reported that when there is no long-term experience with a manipulated object, the PPS that has been extended to the manipulated object reverts to the pre-extension state the next day [35]. In addition, a previous study confirmed that after a long period of experience with a manipulated object, the PPS shifts even without moving the manipulated object [36]. Therefore, the PPS is considered to be transferred to the virtual finger immediately when the virtual finger feels the same as one's own finger and which one has been using for a long period of time. This result suggests that the interface can transfer the PPS to the virtual finger outside the PPS from the start of the operation, allowing the user to operate the PPS as if it were inside the PPS from the start of the operation.

As shown in Fig. 8b and Fig. 9b, when participants who had been learning outside the PPS performed the task inside the PPS, the input time from the beginning of the operation to the 10th trial was significantly shorter in the delay condition. However, in the delay condition, there was no significant difference between the 11th and 20th trials inside the PPS. This result suggests that the PPS was transferred to the virtual finger during manipulation. In contrast, when participants who had learned inside the PPS under the delay condition performed the task outside the PPS, their manipulability did not deteriorate. In other words, the PPS was likely to have been transferred to the virtual finger from the beginning of the operation for participants who learned inside the PPS. Therefore, this finding suggests that the learning period required to immediately transfer the PPS to the virtual finger becomes shorter when the learning occurs inside rather than outside the PPS. However, further investigation is required to determine the time required for the PPS to transfer immediately to the virtual finger while learning further outside the PPS under the delay condition. In contrast, as shown in Fig. 9a, there was no change in the operation time under the without-delay condition, even if the distance was changed. This result suggests that the interface does not require the operator to learn within the PPS to transfer the PPS to the virtual finger from the start of the operation.

IV. EXPERIMENT 2 - PPS TRANSITION SURVEY

Experiment 1 confirmed that it takes time to transfer the PPS to the virtual finger under the delay condition. In addition, the experiment suggested that participants can learn to transfer the PPS to the virtual finger more quickly when they learn inside rather than outside the PPS. To investigate this possibility, in Experiment 2, the time required for the PPS to transfer to the virtual finger from the start of the virtual finger operation was examined in each delay condition.

A. PROCEDURE AND MATERIALS

A line-bisection task was used to investigate whether the PPS was transferred to the virtual finger [10] [37] [38] [39]. When bisecting a line segment within the PPS, the position of bisection is biased slightly to the left of the center of the line, whereas when bisecting a line segment

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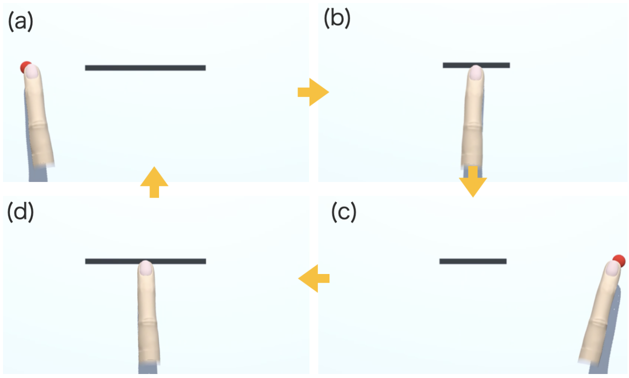

FIGURE 10. **Experimental procedure. (a)Place the virtual finger on the red point on the left. (b)Change the position and length of the line. Then move the virtual finger to the center of the line and press Enter. (c) Place the virtual finger on the red point on the right. (d) Change the position and length of the line. Move the virtual finger to the center of the line again and press Enter.**

outside the PPS, the position of bisection tends to be biased to the right of the line's center. This phenomenon, called pseudo neglect, was used to examine whether the PPS is transferred to the virtual finger [40].

The line on the display and the experimental procedure are shown in Fig. 10. The line was displayed on a white panel 130 cm above the ground, and the participant's eye height was set to 130 cm to match this. At a distance of 50 cm from the screen, the lengths of the lines were 5, 6, 7, 8, 9, and 10 cm, and the line widths were 2 mm each. The length of the line outside the PPS was increased by a factor of 1.5, so that it appeared to be the same length as that at 50-cm distance. The system configuration was the same as that used in Experiment 1.

The participant placed the virtual finger on the red point and counted down for 5 s. When the countdown reached zero, the participant placed the virtual finger at the position that bisects the line displayed on the panel at the same time as the 10-s countdown began. The participant pressed "Enter" on the keyboard with their own right hand when they felt that they had placed the virtual finger at the position that bisects the line. Subsequently, the participant placed the virtual finger on the red dot on the display. The participant continued to place the virtual finger on the red dot until the countdown reached zero. Thereafter, a 10-s countdown began, and the participant placed the virtual finger at a position that bisected the line from the red point where the finger was placed. These procedures were repeated, and participants performed the task of pointing at the position bisecting the line 60 times (10 min total). Before starting the experiment, the participants performed the task of pointing to the center of the line six times (1 min) as an exercise. The length of the line was changed each time the countdown reached zero. The red dots appeared alternately and pointed to the center of the line 30 times from left to right.

Participants who learned under the without-delay and with-delay conditions (eight participants each) were all tested using two learning distances: 50 cm (inside the PPS) and 100 cm (outside the PPS) from the panel under the same delay conditions as before (Fig. 11 and Fig. 12). The distance at which the experiment began was randomized for each participant. A one-hour interval was allowed between the distance change. As the PPS could possibly be transferred to the virtual finger after the experiment, the experiment should not be started with the PPS already transferred to the virtual finger. This experiment was designed based on the methods used in previous studies [11] [41].

B. STATISTICAL ANALYSES

The error in the position of the virtual finger from the center of the line was calculated. Negative values indicate that the point was placed to the left of the line's center. The errors for each of the six times (1 min) were averaged and the errors for each participant for each delay and distance condition were calculated.

C. RESULTS

The error inside and outside the PPS for the participants who learned inside (outside) the PPS are shown in Fig. 11 (Fig. 12). The results from the no-delay condition for the participants who learned inside (outside) the PPS with no delay are shown in Fig. 11a (Fig. 12a). The results from the delay condition for the participants who learned inside (outside) the PPS with a delay are shown in Fig. 11b (Fig. 12b). For both figures the blue and red lines show the magnitude of error inside and outside the PPS, respectively.

As shown in Fig. 11a and Fig. 12a, the results of t-tests conducted every minute inside and outside the PPS showed no significant difference at any time for the participants who learned either inside or outside the PPS in the no-delay condition. Additionally, as shown in Fig. 11b, there was no significant difference at any time for participants who learned inside the PPS under the delay condition. However, as shown in Fig. 12b, for the participants who learned with a delay and outside the PPS, significant differences were found at 1, 6, and 7 min (after 1 min: $t(6) = -3.31$, $p = 0.016$; after 6 min: $t(6) = -3.34$, $p = 0.016$; after 7 min: $t(6) = -3.56$, $p = 0.012$).

D. DISCUSSION

Experiment 2 aimed to investigate whether the time required for the PPS to transfer to the virtual finger would be longer under the delayed condition. Another purpose was to investigate whether the learning time required for the PPS to transfer to the virtual finger would be shorter if the participants learned inside the PPS.

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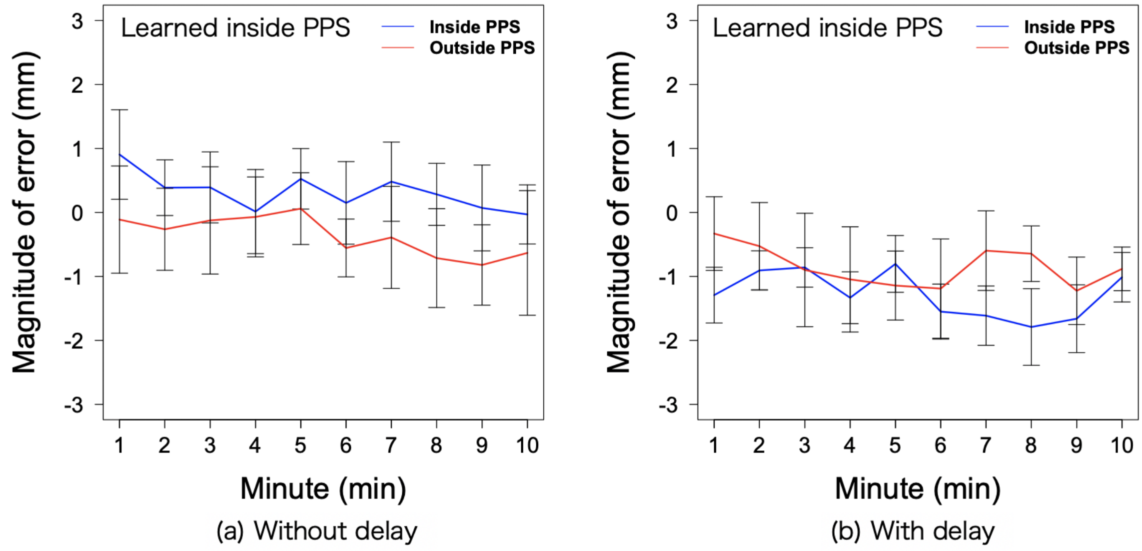

FIGURE 11. **Magnitude of error inside and outside PPS for participants who learned inside the PPS. (a) shows the without-delay condition for participants who learned inside the PPS without delay. (b) shows the with-delay condition for participants who learned inside the PPS with delay. Error bars show the standard error. The blue line shows the magnitude of error inside the PPS and the red line shows the magnitude of error outside the PPS.**

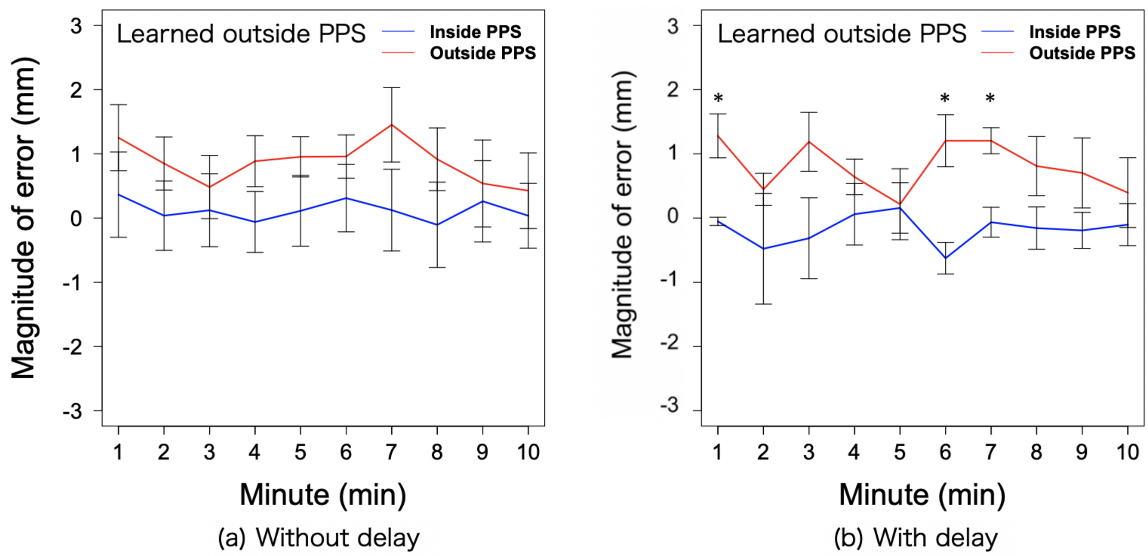

FIGURE 12. **Magnitude of error inside and outside PPS for participants who learned outside the PPS. (a) shows the without-delay condition for participants who learned outside the PPS without delay. (b) shows the with-delay condition for participants learned outside the PPS with delay. Error bars show the standard error. The blue line shows the magnitude of error inside PPS and the red line shows the magnitude of error outside the PPS. As shown in (b), the errors were significantly larger outside PPS than inside PPS, 1, 6, and 7 min after the start of the virtual finger manipulation for the participants who learned outside the PPS with delay. *$p < 0.05$.**

As shown in Fig. 11a and Fig. 12a, the experimental results of participants who learned inside and outside the PPS under the no-delay condition showed no significant difference between the errors inside and outside the PPS, respectively, from the beginning of the operation. Bjoermont et al. reported that when healthy participants bisect the line outside the PPS, the bisection position shifts significantly to the right of that inside the PPS [42]. Thus, the results confirmed that the PPS was transferred to the virtual finger from the start of the operation. Previous studies have shown that the PPS is transferred to disconnected manipulation targets, and the same result was obtained in this experiment [10] [11] [36].

In contrast, as shown in Fig. 12b, the experimental results for participants who learned outside the PPS under the delay condition showed that the errors were significantly larger outside rather than inside the PPS 1, 6, and 7 min after the start of the virtual finger manipulation. In other words, after 1, 6, and 7 min, the PPS had not transferred to the virtual finger. However, there was no significant difference in the error after 2–5 min. Therefore, the PPS transferred to and returned from the virtual finger. This result suggests that the

PPS did not continuously transfer to the virtual finger from the beginning of the operation because of the delay in the visual feedback. Thus far, previous studies have not reported that a delay in the visual feedback of the manipulated object requires some operation time to enable a PPS transfer.

However, as shown in Fig. 11b, the experimental results of the participants who learned inside the PPS under the delay condition showed no significant difference between the errors inside and outside the PPS from the start of the operation to 10 min. Hence, the PPS was transferred to the virtual finger from the start of the virtual finger operation, even if there was a delay in the visual feedback. This result confirmed that the participants who learned within the PPS could transfer the PPS to the virtual finger from the start of the virtual finger operation within a shorter learning period than those who learned outside the PPS. No prior studies have reported that learning within the PPS reduces the learning period required to immediately transfer the PPS to a manipulated target.

V. CONCLUSIONS AND DISCUSSION

A. CONCLUSIONS

This study proposed an interface that allows users to quickly become accustomed to the operation and has excellent intuitiveness for an interface that is operated while viewing the entire remote display. However, users do not show the same degree of operability outside the PPS as inside the PPS from the start of the interface operation without long-term learning because they require a longer learning time to transfer the PPS to the operated object from the start of the operation. Therefore, a long-term study was conducted with the interface to confirm whether it could achieve the same operability outside the PPS as inside the PPS by transferring the PPS to the manipulation target. Moreover, the PPS was confirmed to be immediately transferable by enhancing the user's SoA and SoO toward the manipulation target.

The following three aspects were investigated in Experiment 1: First, regardless of the degree of SoA and SoO, the same type of learning was taking place both outside and inside the PPS. The PPS was being transferred to the virtual finger outside the PPS. Second, the rate of increase from the last input time of the previous day to the input time at the start of the virtual finger operation the next day was significantly higher outside the PPS than inside it under the delay condition. Thus, the experiment suggests that some operation time is required for the PPS to transition to the virtual finger. Finally, the experiment suggests that the learning period required to immediately transfer the PPS to the virtual finger was shorter when the learning occurred insider rather than outside the PPS.

In Experiment 2, two suggestions made in Experiment 1 were investigated. The first was to investigate whether participants who learned outside the PPS under the delay condition took longer to transfer the PPS to the virtual finger. The results confirmed that the PPS was not continuously transferred to the virtual finger from the start of the operation. The second was to investigate whether participants who learned inside the PPS under the delay conditions could immediately transfer the PPS to their virtual fingers. The results confirmed that the PPS was immediately transferred to the virtual finger from the start of the operation.

The problem with the current remote-control interface is that the users need a long period of time for the PPS to immediately transfer to the manipulated object. The results of this study confirm that when the users enhanced their SoA and SoO toward the virtual fingers, they felt as if the virtual fingers were their own fingers, which they have already been using for a long time. Consequently, the PPS was immediately transferred to the virtual fingers. Thus, the proposed interface can solve the above-mentioned problem because it does not require users to learn how to transfer the PPS.

B. DISCUSSION

1) Applications of this interface

The interface proposed in this research can be applied to touch panels in public places (e.g., train ticket vending machines) in addition to automobiles. Given the current spread of COVID-19 globally, touch panels in public places are a potential source of infection because they are touched by many people. The interface can be used to connect a smartphone to the touch panels in public places and send information on touch and finger position, allowing users to teleoperate the touch panel as usual without touching the touch panel directly. Thus, the interface contributes to preventing the spread of COVID-19.

2) Shortcomings of this interface

There are two shortcomings of this interface: First, the user must wear a glove and calibrate it to track the finger. The process of putting on the glove and calibrating it each time the user gets in the car is tedious. Therefore, the interface should be improved by eliminating the requirement of wearing the glove using hand tracking to detect the position of the finger and the angles of the joints.

Second, operability is reduced due to telecommunication delays. In this interface, it takes 33-41ms from the time the user's finger moves to the time the virtual finger moves. However, according to previous research, there is a point of reduced operability ranging 24.3-44.3ms [43]. As it takes less than 10 ms to read the finger position in the environment of this interface, the time required for processing within unity is assumed to be significant. Therefore, the model in unity will be optimized to reduce the delay to less than 24.3 ms.

Participants who learned with delay and outside the PPS did not transfer the PPS to the virtual finger from the beginning of the operation, even after 14 days of learning. Therefore, future studies should investigate how much further learning is needed for participants to be able to immediately transfer the PPS to the virtual finger. In addition, future studies will include the implementation of hand-tracking without gloves and optimization of the unity model. The benefits of the interface can be further clarified by identifying the learning period required for the PPS transition in a state of impaired SoA and SoO.

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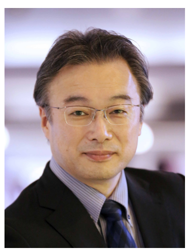

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