Spatial Positions of Operator's Finger and Operation Device Influencing Sense of Direct Manipulation and Operation Performance

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Abstract: When operating an interface using an input device (such as a mouse or trackpad,) one's fingers (referred to as the "Operating Subject"), indirectly operate a target device through a pointer displayed on the interface (referred to as the "Operation Media"). Our experiment investigated the effects of the spatial positions of the Operating Subject and Operation Media on the sense of direct manipulation and operation performance. The results showed that the sense of direct manipulation increased when the Operation Media was placed diagonally toward the left than on the front, and the operation performance was higher when the Operating Subject was placed on the right side of the body than on the front (for right-handed individuals).

1 INTRODUCTION

1.1 User Representation

When operating an interface using an input device (such as a mouse or trackpad), one's hands or fingers [hereafter referred to as "Operating Subject" (OS)] indirectly operate a target device, such as a navigation system in an automobile or an operation panel of an in-car device, through a pointer displayed on the interface [hereafter referred to as "Operation Media" (OM)]. Figure 1 shows the relationship among the OS, OM, and manipulated target device.

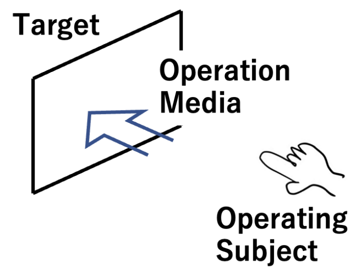

Figure 1: Relationship among the finger as an operating subject, a pointer as an operation media, and the target device for operation.

Manipulating the target device through such an OM is in contrast to manipulating a device like a tablet, which are manipulated by directly touching the device.

The OM acts as a substitute for our own bodies. In indirect manipulation, we use this substitute to touch and interact with the target device. This substitute is called "user representation," and various types of indirect operations have been discussed (Seinfeld et al., 2021). Seinfeld et al. called the space that the OS touches the "input space," and the space that the OM touches the "output space." The output space is the operating surface or interface of the target device that is manipulated by the operator.

The concept of user representation is applied to understanding interactions with various artifacts. The example discussed at the beginning of this study was an arrow-shaped mouse's cursor on a desktop; however, for on-screen avatars (Marcos et al., 2010), body parts such as arms displayed in a VR space (Rautaray and Agrawal, 2015), robots, and even drones can be included as examples of user representation.

1.2 Tacit Knowledge

In considering the issue of indirect manipulation, it is useful to refer to the concept of tacit knowledge as described by Polanyi (Polanyi, 1958).

Generally, tacit knowledge is defined as the knowledge that is used empirically but cannot be explained in words. Tacit knowledge is typically related to physical actions. Consider, for example, riding a bicycle, which requires the integrated coordination of

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multiple muscles. However, upon acquiring this physical knowledge, one can perform it unconsciously and without any difficulties. Moreover, once one learns how to ride, one never forgets. A characteristic of tacit knowledge is that it is difficult to verbalize, despite being easily operationalized. It is almost impossible to explain verbally and teach others how to ride a bicycle.

One of the most important concepts in tacit knowledge is the proximal and distal terms.

For instance, while walking down a street with a cane (see Figure 2), if an obstacle hits the tip of the cane, vibration is transmitted to the palm of the hand that is holding it. The vibration felt by the hand is the proximal term and the feeling of detecting the obstacle at the end of the cane is the distal term. We sense the vibration of the hand as the proximal term, but what we perceive is the obstacle at the end of the cane. We do not know the vibration, but we know that there is an obstacle.

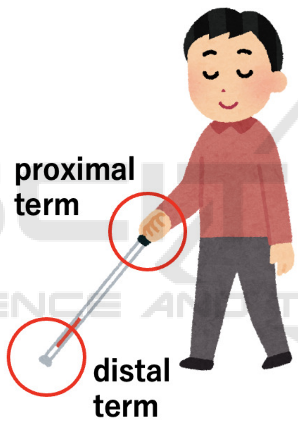


Figure 2: Proximal and distal terms.

In tacit knowledge, this phenomenon is referred to as the tacitization of the proximal term or the formation of perceptions of the distal term using the proximal term as a cue.

It is reasonable to say that the solution to various issues in indirect manipulation can be summed up as the formation of tacit knowledge, as described so far. In indirect manipulation, the proximal term emerges in the operating space that the OS directly touches (the input space), and the distal term emerges in the space that the OM touches (the output space), such as the operating surface and the interface of the operating device.

If the proximal term is not tacitly known, it is impossible to obtain a good operating experience. The key to improving the experience of direct operation is to make the proximal term tacitly known and form an awareness of the distal term.

1.3 Sense of Agency

In direct manipulation, the body touches the target device directly. In contrast, in indirect manipulation, the target device is manipulated through an OM. One of the problems that can occur with indirect manipulation in such a situation is the separation of the OS and OM. In this case, the OM is manipulated, instead of the target device; the manipulated OM interacts with the target device. In this case, the sense of directly manipulating the target device, that is, the direct manipulation sensation, is missing.

An important concept related to the sense of direct manipulation is the "sense of agency" (SoA), which is the feeling that one is the operating principal of a certain movement, controls the target, and feels responsible for the result of the movement (Limerick et al., 2014; Moore, 2016). In this study, SoA was used as an evaluation index for a good sense of operation in indirect manipulation.

SoA measurement can be divided into two methods: subjective methods rated by the operator, and objective methods. For the former, answering questions "How much your actions caused that event?" (Sato and Yasuda, 2005; Aarts et al., 2006) and "How much control you had over the actions?" (Kalckert and Ehrsson, 2012; Braun et al., 2014) in a questionnaire is the gold standard method. For the latter, a method to measure the degree of Intentional Binding using an interface called the Libet Clock is often used (Haggard et al., 2002; Limerick et al., 2014). A high SoA score indicates that the proximal term is known tacitly.

1.4 Spatial Relation Between OS and OM

In indirect manipulation, it is necessary to focus on the spatial positional relationship between the operator and the OS (which is a part of one's body), and between the operator and the OM (which touches the target device). For example, if the target device in front of the operator is manipulated with their hand facing the direction of the device (in front of their body), the spatial orientations of the OS and OM will be coincident. By contrast, when the hand is placed on the right side of the body and the device placed on the operator's left side is operated by the hand, the spatial orientations of the OS and OM will not coincide.

Researchers examined the influence of the spatial alignment of the OS' positions (in this case, the finger) and the tablet as the target device on the sense of operation in a VR experimental environment (Feuchtner and Müller, 2018). When the tablet was located above the front of the operator, the operator was required to raise their arm to reach the tablet, which aligned the OS and OM. However, with long-term use of the tablet, the physical fatigue of the arm increased. The participant gradually lowered their arm to operate the tablet in a stable position, resulting in a spatial mismatch between the OS and OM; however, the patient still reported no significant reduction in the sense of operation.

The length of the operator's arm is the distance between the operator and the OS. However, when the target device is manipulated by the hand displayed in a VR space, the length of the arm on the VR is the distance between the operator and the OM. The effect of this congruence on the feeling of manipulating the target device has been discussed (Feuchtner and Müller, 2017). In this experiment, the operator manipulated the target object in a VR space with an arm that was significantly extended in length. Even in this case, the participants reported that it was possible to have a sense of physical ownership of the long extended arm as one's own arm.

1.5 Motion-Capture Device

Recently, motion-capture devices have attracted attention as input devices (Vlasic et al., 2007). Input using motion-capture devices has many advantages from the user's perspective, including the fact that it does not require a physical manipulation device, the input location is not restricted by physical space, and various input tokens can be generated by free body movements. They hold great promise as input devices in the future.

In input using a motion-capture device, the operator can manipulate the target device by taking their hand to any location in space and pointing to the hollow. When a motion-capture device is used to manipulate a target device placed at various locations in space, the spatial positioning relationship between the operator and the OS, and between the operator and the OM becomes diverse.

1.6 Research Questions

Based on the above, this study aimed to answer the following two research questions:

Research Question 1:

In indirect manipulation using a motion-capture input device, how would the operator's sense of direct manipulation of the target device be affected by the spatial arrangement of the OS (in this case, a finger) and OM (in this case, a pointer displayed on the interface of the target device)? In this study, the spatial placement of the OM was manipulated by placement of the target device.

Research Question 2:

How would the operational performances of the target device be affected by the spatial arrangement of the OS and OM?

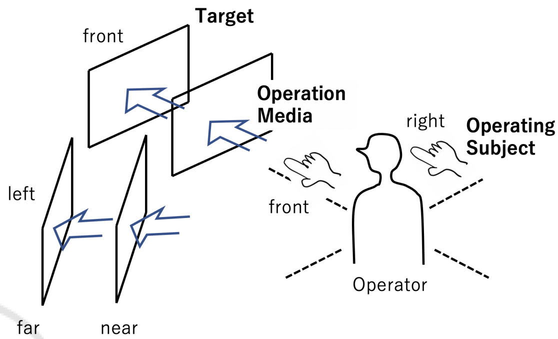


Figure 3: Framework of experimental design.

Our main aim was to investigate whether there is an interaction between the effects of OS and OM spatial placement on the sense of direct manipulation and operational performances. For example, do the effects on the sense of direct manipulation when the target device is placed in the front or the front-left of the body (OM factor) differ when manipulation is performed in the space in the front or on the right side of the body (OS factor)?

The experimental framework is shown in Figure 3.

2 EXPERIMENT

2.1 Participants

A total of 16 right-handed adults were recruited from the public.

2.2 Apparatus

In this study, a motion-capture device (Figure 4) was developed as an input device. This device could measure a participant's finger movements by attaching markers to the tip and root of the index finger of the right hand.

A display monitor was used as the target device. An overview of the experimental apparatus is shown in Figure 5.

Figure 4: Motion capture device used in experiment.

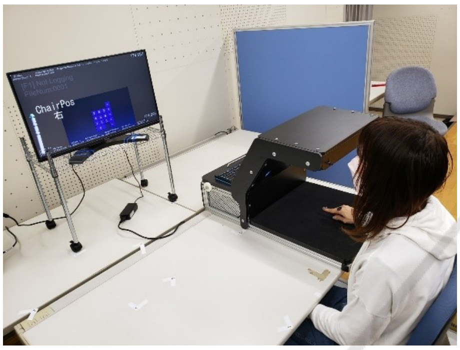


Figure 5: Scene of experimental setting.

Participants performed a pointing task by manipulating the pointer on the monitor through index finger movements performed in midair.

In this experiment, the participant's finger corresponded to the OS, the monitor on which the pointing task was displayed corresponded to the target device, and the pointer displayed on the monitor corresponded to the OM.

2.3 Experimental Design

2.3.1 Independent Variables

The three independent variables in this experiment were the input device position factor, the monitor direction factor, and the monitor distance factor, all of which were within-participant factors (Table 1).

Input Device Position Factor

The spatial position of the OS was manipulated by moving the casing of the motion-capture device. This was the input device position factor, and was composed of the front and right conditions.

Specifically, in one condition, the motion-capture device was positioned in front of the participant, and diagonally to the right of the participant in the other condition.

Monitor Direction Factor

The spatial position of the OM was manipulated by moving the position of the monitor as the target device. This was the monitor direction factor, and was composed of the front and left conditions.

Specifically, the monitor was placed either in front of the participant or a little to their left . In the latter condition, the monitor was rotated 55 degrees to the left from the participant's frontal direction.

Monitor Distance Factor

The distance between the participant and monitor was manipulated. This was the monitor distance factor, and was composed of the near and far conditions.

Specifically, in the near condition, the monitor was placed 50 cm from the participant; in the far condition, the monitor was placed 100 cm from the participant.

2.3.2 Independent Variables

Operation Performance

For each trial, task performance was measured in terms of the number of errors that indicated the number of incorrect inputs, completion time (ms), and pointer travel distance (mm).

SoA

As a subjective measure, participants' SoA was measured. Specifically, participants were asked "How well did you feel you had control over pointing?" and rated on a seven-point scale from "not at all" to "very much."

2.4 Task

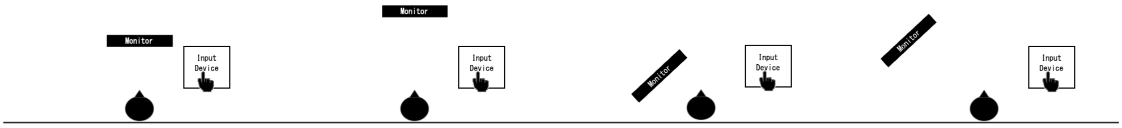
The task used in this experiment was to input mathematical expressions (such as 21-51=), using a calculator that appeared at the top of the monitor screen. The calculator was operated by a pointer that was manipulated by the participant's right-hand movements. Figure 6 shows the pointer for inputting digits for the calculator.

The participants were instructed to enter mathematical expressions as quickly and accurately as possible. When a digit was entered, its color changed from blue to orange and a sound was played to provide feedback to the participants. If the digit was entered correctly, it was displayed below the formula; if an incorrect digit was entered, it was not displayed.

Table 1: Experimental design.

Input Device Position: Front Monitor Direction: Front Monitor Distance: Near	**Input Device Position: Front Monitor Direction: Front Monitor Distance: Far**	**Input Device Position: Front Monitor Direction: Left Monitor Distance: Near**	**Input Device Position: Front Monitor Direction: Left Monitor Distance: Far**

Input Device Position: Right Monitor Direction: Front Monitor Distance: Near	**Input Device Position: Right Monitor Direction: Front Monitor Distance: Far**	**Input Device Position: Right Monitor Direction: Left Monitor Distance: Near**	**Input Device Position: Right Monitor Direction: Left Monitor Distance: Far**



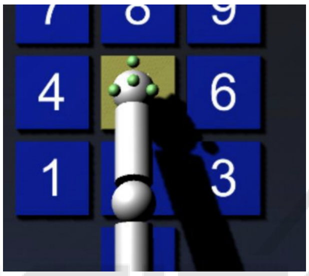


Figure 6: Pointer displayed on the monitor as target device.

2.5 Procedures

The participants first performed practice trials. In each of the eight conditions, that is, the $2 \times 2 \times 2$ conditions of the three experimental factors, they entered free formulas for one minute, and confirmed their operations before moving on to the production trials.

The production trial consisted of task and evaluation phases. For each condition, the evaluation phase was conducted after the task phase was completed. Twenty-five trials were conducted for each condition during the task phase. The order of the conditions was counterbalanced by using the Latin square method.

During the evaluation phase, the participants responded to a paper-based questionnaire for measuring the SoA.

3 RESULTS

3.1 SoA

For sense of agency, a three-factor within-participant analysis of variance (ANOVA) (2: input device position factor $\times$ 2: monitor direction factor $\times$ 2: monitor distance factor) revealed a marginal significance in the main effect of the monitor direction factor (see Figure 7). Specifically, the SoA tended to be rated higher in the left condition than in the front condition ($F(1,15) = 4.158$, $p = .060$).

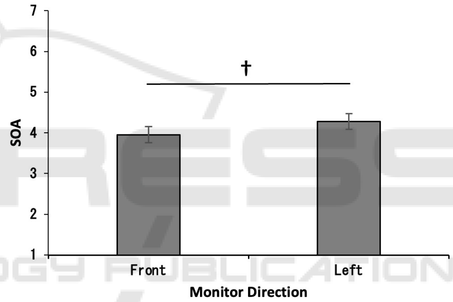


Figure 7: Result for sense of agency evaluation. Error bars show standard errors.

Neither the main effects of the input device position factor nor the monitor distance factor was significant.

None of the second-order interaction or the three first-order interactions were significant.

3.2 Operation Performances

Number of Errors

For the number of errors, the same ANOVA revealed a significant interaction between the input device position factor and the monitor distance factor ($F(1,15) = 9.401$, $p = .008$). Figure 8 shows the result for the number of errors. Simple main effect tests showed that there were significantly fewer errors in the near condition than in the far condition of the monitor distance factor when the input device was placed in front of the participants ($t(15) = 9.775$, $p = .007$), and also showed fewer errors in the right condition than in the front condition of the input device position factor when the target device was placed far from the participants ($t(15) = 10.757$, $p = .005$).

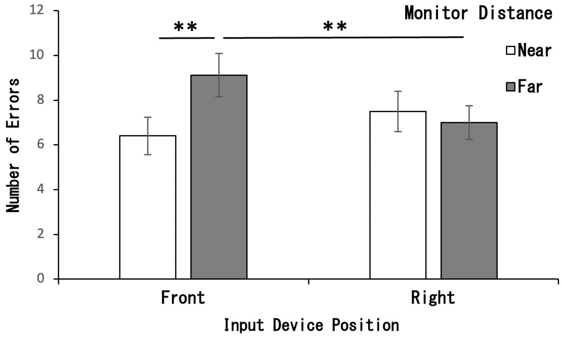


Figure 8: Result for number of errors. Error bars show standard errors.

None of the three main effects were significant.

A second-order interaction did not reach significance, and none of the first-order interactions, other than the above interaction, reached significance.

Completion Time

For the completion time, the same ANOVA showed that none of the main effects, the first-order, or the second-order interactions were significant.

Pointer Travel Distance

For the pointer travel distance, the same ANOVA showed that the main effect of the monitor distance factor was significant (Figure 9). Specifically, in the far condition, the operating distance was significantly shorter in the near condition ($F(1,15) = 11.137$, $p = .005$).

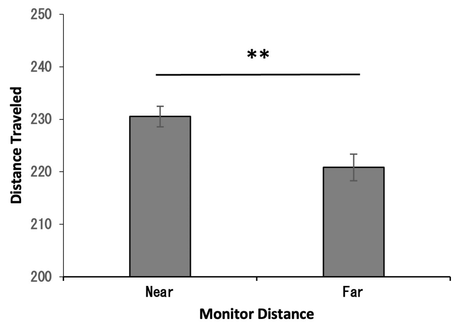


Figure 9: Result for pointer traveled distance. Error bars show standard errors.

Neither the main effects of the input device position factor nor the monitor direction factor was significant.

None of the second-order interaction or the three first-order interactions were significant.

4 DISCUSSION AND CONCLUSIONS

The SoA (or the sense of direct manipulation) was slightly higher when the target device was placed at a left oblique angle than at the front of the participants. Notably, this effect did not depend on whether the participants pointed at the front or to the right of their bodies because we did not detect the interaction effect of the monitor direction and the input device position factors.

These results suggest that the improvement in the sense of direct manipulation does not depend on the consistency of the orientation of the OS and OM; instead, assigning the OM to the front-left, regardless of the spatial arrangement of the OS, has a positive effect on the sense of direct manipulation.

A series of perceptual psychology studies have shown that humans prefer viewing objects from an angle rather than from the front (Blanz et al., 1999; Niimi and Yokosawa, 2009). This is called the three-quarter view and is often considered the canonical view. The advantage of the three-quarter view, which has been confirmed in the perceptual psychology domain, is thought to be brought about by the appearance of objects. Although the situation in those studies is different from that in the present experiment, the nature of the underlying human cognitive architecture may explain the experimental results.

There was no interaction effect of the spatial positions of the OS and OM in determining the sense of direct manipulation; however, for operational performance, the interaction effect of the input device position factor and the monitor distance factor was detected. Specifically, when the input device was placed in front of the participant (when the participant stretched their hand in front of themselves to perform the input), a decrease in performance was observed when the monitor as the target device was placed farther away. No such performance reduction was observed when the input device was placed at the right of the participant (when they performed the input on their right side).

This result indicates the advantage of performing input operations on the right side of the body for right-handed participants. This advantage may be because of the constraints of the body structure, wherein the right hand rests at the right side of the body. In the current experiment, we identified only this phenomenon. From a cognitive science perspective, we need to explain why these advantages emerge.

Finally, from the current limited experiment, we drew the following hypotheses for two design principles for indirect manipulation devices when the operation is performed by pointing with a finger:

- When an operator is right-handed, the input operation should be made on the right side of the their body (maybe on the left side of the body for left-handed).
- The target device should be placed on the left front of the operator. We do not need the consistence of direction of the target device and the space in which the finger operates.

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