Reach across the boundary: evidence of physical tool appropriation following virtual practice

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ABSTRACT

Our research explores the connection between physical and virtual tools. This work is based on research from the cognitive sciences showing that physical and virtual tool use extends our brain's representation of peripersonal space to include the tool. These findings led us to investigate if tool appropriation transfers from virtual to physical tools. The present paper reports the results of a study that revealed that manipulating a tool in the virtual space is sufficient to induce appropriation of a similar physical tool. These results have implications for interaction design in training and simulation applications.

Author Keywords

Virtual tool, physical tool, peripersonal space, motor cognition, video game, virtual avatar.

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation]: User Interfaces---*input devices and strategies, interaction styles*; J.4 [Social and Behavioral Sciences]: *Psychology*; K.8 [Personal Computing]: *Games*.

General Terms

Design, experimentation.

INTRODUCTION

We are interested in the connection between people and the tools they use, both physical and digital. Tools serve as functional extensions of the body and help people complete tasks that would be difficult or impossible to accomplish otherwise. For example, we would not be able to sink nails into wood without a hammer, or a surgeon would not be able to cut without a scalpel. Recently, the idea that tools are extensions of the body has been examined from a motor-cognition perspective. Studies have suggested that tool use extends the brain's representation of the body's peripersonal space (i.e., the space immediately surrounding the body) to incorporate the tool (e.g., [9, 5, 10]). Although most studies have examined this effect with physical tools in real space, some research has shown that the effects of virtual tool use in virtual space seems to extend our peripersonal space in a manner similar to physical tools [1, 7]. Thus, we aim to gain a better understanding of the connection between the physical and virtual tools we use. Our specific question for the present paper was whether or not the use of a virtual tool will result in the body's incorporation of a similar physical tool into its peripersonal space? In other words, does the appropriation effect transfer from virtual to physical tools?

A better understanding of our space representation and of the embodiment of virtual and physical tools is of both theoretical and practical interest. In practice, it is relevant for virtual training scenarios because it can help us understand how effectively-designed interfaces can support and enhance the transfer of skills learned in a virtual or simulated environment back to the real world. Knowledge about the extent to which people make a connection with the tools they use, and the parameters of this connection, can also help us design hybrid physical/digital tools that support their intended tasks more effectively.

A challenge for the design of virtual training systems is making the connection between a person's actions in the physical world and their effects in the virtual world in a way that is as realistic as possible. The designer needs to consider what kind of interface (both physical and virtual) is needed between a person and the virtual task. Ideally, the design would support transfer of the tool appropriation from the virtual world to the physical world. It would allow users to learn how to use a tool in the virtual space and then transfer that knowledge to its use in the physical version. Given the variety of tools, the design space for such systems is broad. Because of the variety of potential interfaces, we chose to conduct a baseline study in which participants used a traditional interface (keyboard) to control a virtual rake. We then tested whether a physical rake was appropriated into the body's peripersonal space using a conventional response time (RT) test. In this paper,

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we first provide a brief overview of the research on peripersonal space and tool use from cognitive science. Next, we describe the design of the virtual reaching game used in our study. We then describe our experiment setup and results, and discuss the implications and future directions for this work.

BACKGROUND

The term "peripersonal" space is used to describe the region of space immediately surrounding the body. It is considered a kind of interface for the body to interact with reachable objects and is characterized by a high level of multisensory integration between tactile, visual, and auditory information from the body and from the space immediately around the body [3]. A related concept is that of "body schema", which is defined as the representation of the body that the brain uses to plan and execute actions [4]. The idea that this representation is plastic and could be extended to include tools dates back at least as far as 1911, when Head and Holmes wrote: "anything which participates in the conscious movement of our bodies is added to the model of ourselves and becomes part of these schemata." [8]

More recently, cognitive and neuroscience researchers have shown increasing interest in how tools extend our bodies not only in a physical sense, but also in a perceptual sense. One seminal study was done with macaque monkeys. It was observed that, following use of a rake to retrieve distant objects, the neurons coding the space near the monkeys' hands expanded their representation to include objects near the tool's tip [9]. Notably, this expansion was observed only if the monkeys actively used the rake to perform an action, not if the rake was just held passively in their hand. Thus, the monkey did expand its peripersonal space, but only if it interacted purposefully with the tool.

This research has been very influential and subsequent studies have tried to better understand tool appropriation, and particularly whether it applies to humans as well. A number of studies conducted with brain-damaged patients have supported the idea that, with training, tools become incorporated into the body schema and extend peripersonal space (e.g., [5, 6, 2, 11]). Studies with healthy individuals have also supported tool appropriation following tool-use [12, 10]. Of these, some have used a RT approach in which visual stimuli (e.g., the illumination of LEDs) are presented on the hand or on the tool tip and people respond to these stimuli by pressing a button as quickly as possible with the other hand (e.g., [10]). These studies have shown that, even though subjects respond more quickly to visual stimuli on the hand than on a tool, only the detection of visual stimuli on the tool improves after the person has used the tool. Detection times for stimuli on the hand do not change. Thus, the RT approach is sensitive to tool appropriation. We used a similar RT approach to test whether tool appropriation transfers from virtual to physical space.

Researchers have recently demonstrated that the extension of peripersonal space happens not only by using a physical tool, but also by using a virtual tool that establishes a functional connection between the physical space of the action and the virtual space of the action goal. One study demonstrated that long-term experience with the computer mouse extends the representation of auditory peripersonal space from the near space (around the hand) to the far space (around the computer screen) [1]. Subjects sat in front of a computer screen and actively used, passively held, or did not hold a mouse. When they held or used the mouse, they responded to tactile stimuli just as quickly when sounds were presented near the computer screen as when they were presented near the hand. This was not the case if they did not hold the mouse, or if the stimuli were presented on the left hand (for right-handed subjects who do not usually hold the mouse in their left hand). Another study examined whether agency is sufficient to drive the extension of peripersonal space to the virtual tool, or whether the participant also needs to be able to control the movements of the tool [7]. Subjects were exposed to different mapping conditions between movements of the hand holding a mouse and movements of an on-screen mouse cursor (no agency, agency but no control, both agency and control), and were then tested to see how quickly they could detect the onset of mouse-cursor motion. RTs were faster after they had both agency and control of the mouse motion, suggesting that virtual tool appropriation depends on a person's ability to control the movements of the virtual tool.

The present study builds on these results and specifically considers the transfer of tool appropriation from virtual to physical tools. Participants performed a RT task in which they detected stimuli presented on the hand and a real tool before and after using a virtual tool in a video game. If virtual-to-physical tool appropriation occurs, then there should be a significant decrease in the RTs only to stimuli presented on the tool after experience using the virtual tool. If virtual-to-physical tool appropriation does not occur, then there should be no significant decrease in RTs to stimuli on the tool. RTs to stimuli on the hand should not change because the hand is already coded as part of the body.

VIRTUAL REACHING GAME

We designed a virtual reaching game that employs a virtual version of a physical tool used in many previous tool appropriation studies: the rake. The game was developed in the Unity3D engine. In the game, the player's avatar sits at a table with its right hand manipulating a small rake over the table surface to drag boxes into holes that appear on the table (see Figure 1). The boxes and holes can each appear at one of three positions. After pulling the box into the hole, the player has to return the rake to an initial position indicated by the game, which triggers the appearance of the next box. The camera remains static, looking from the avatar's perspective, but slightly off-center to have better visibility of the controlled arm. The player must use an external interface to control the avatar's rake arm. It is possible to employ different kinds of interfaces for this game. For our baseline study, we chose to use a traditional interface: the keyboard. In this case, number pad keys controlled the movements of the avatar's arm: 6 (right), 4 (left), 8 (forward), 5 (backward), 7 (up), and 9 (down).

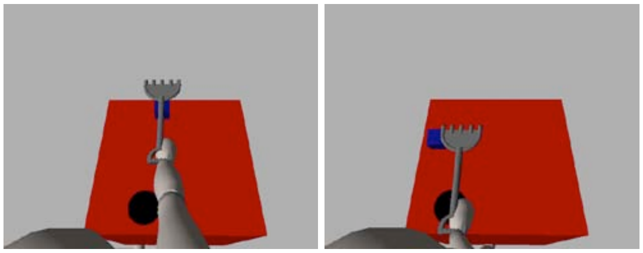

Figure 1. Virtual reaching game. Subjects use a virtual rake to drag a box from one of three possible start positions to one of three possible end positions.

EXPERIMENT DESIGN

The study investigated the appropriation of a physical tool based on virtual tool use. It consisted of three stages: 1) a pretest that assessed the participants' coding of the hand and the tool by asking participants to press a button as quickly as possible after the illumination of LEDs on the hand, the rake, or in other locations; 2) a virtual reaching game as described in the previous section; and, 3) a posttest (same as pretest). The index of tool appropriation was the change in RT to specific LEDs before (pretest) and after (posttest) virtual practice with the tool.

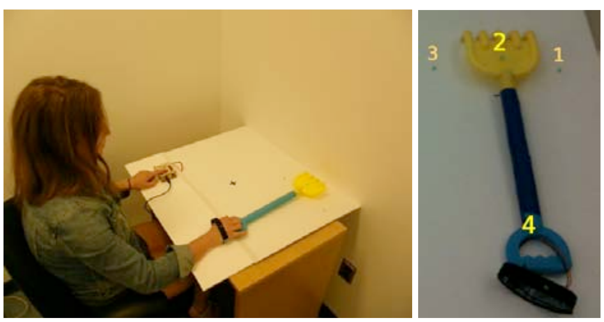

Figure 2. Subject seated for Pre/Posttest task conditions (left). Arrangement of LEDs on/around the rake (right).

Procedures

Pretest/Posttest: Participants sat in a chair at a desk and were told to grasp the rake with their right hand and place the left index finger over a response button (Figure 2, left). LEDs were located on the back of the right hand (LED 4), the end of a rake grasped in the right hand (LED 2), and on the surface of the table to the left (LED 3) and right (LED 1) of the rake (see Figure 2, right). The LEDs of key interest were those on the hand (4) and on the rake (2) because those would provide the index of the appropriation of the tool. LEDs off the rake (i.e., 1 and 3) were not of theoretical relevance, but were included to provide sufficient variation in the location of the target to prevent the participants from anticipating the target LED location on a given trial. During both pre- and posttest, participants were instructed to fixate a black central cross (located equidistant [30 cm] from the LEDs on the hand and the rake and the response button) and then press the button as quickly as possible after any of four LEDs illuminated. Each LED was presented 15 times in random order for a total of 60 responses. RT was recorded as the time interval between the LED illumination and the button press. There were no familiarization trials prior to the pre- and posttests.

Virtual Interaction: After the pretest, participants used a keyboard to interact with the virtual reaching game described above (see Figure 3). Participants received a brief (~1 minute) introduction to the interface before beginning the game. The first 10 minutes of gameplay consisted of a training period that allowed participants to become familiar with the system. After 10 minutes, the system began tracking their proficiency and participants continued until the system reported that proficiency had been reached (10 boxes placed in the target hole within 1 min).

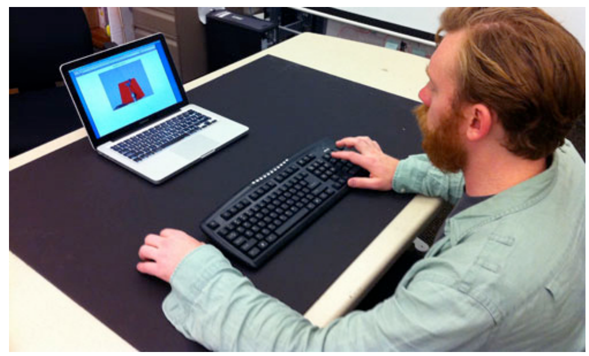

Figure 3. Subject seated using keyboard for virtual task.

Subjects

Ten naïve participants completed the study. All were adults (18-26 years old) and none had played the virtual reaching game before. Due to the equipment setup, the sample was restricted to right-hand dominant people (self-report).

RESULTS

Following established standards, RTs less than 100 ms were coded as anticipation errors and were deleted from the data set. RTs greater than 2 standard deviations above the mean for a condition were considered outliers and were deleted. In total, 11.9% of the trials were deleted. To assess pre/post differences in the RTs to LEDs on the hand and rake, mean RTs for remaining data were calculated and then submitted to separate paired-sample *t*-tests ($p<.05$). Consistent with predictions and previous research (e.g., [10]), there was no significant difference between the pre- (mean = 463 ms; SD = 137 ms) and post-training (mean = 427 ms; SD = 115 ms) RTs for the hand LED, $t(9) = 1.48$, $p>.17$. Critically, the comparison of the pre- (mean = 505 ms; SD = 149 ms) and post-training (mean = 432 ms; SD = 164 ms) RTs for the rake LED was significant, $t(9) = 2.32$, $p>.05$ (Figure 4).

Overall, these effects are consistent with the hypotheses and suggest that the coding of the real tool was modified after participants had interacted with a virtual tool.

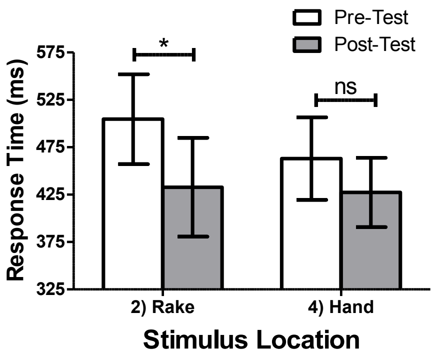

Figure 4. Mean RT (ms) as a function of LED location and experience with the training.

DISCUSSION

The results of the present experiment are consistent with and provide a valuable extension to previous work on tool appropriation through interface design. Specifically, there was a non-significant change in RTs for stimuli presented on the hand suggesting that the hand was already coded as part of the body and this coding was not affected by experience with the virtual rake (see also [10]). The slight trend toward a decrease in RTs likely occurred as the result of a generalized time or training effect associated with performing the test task a second time. The novel finding of the present study was that RTs to targets presented on the physical rake decreased after experience using a virtual representation of that rake. Based on previous work, it is suggested that this significant decrease occurred because the experience with the virtual tool altered the coding of the real tool in a way similar to experience with a real tool does. That means, that through a virtual interaction the physical rake was incorporated into the body schema.

CONCLUSION AND FUTURE DIRECTIONS

We reported on a first study that indicates a tool appropriation from the virtual to the physical domain. This effect is important for the design of interfaces meant for virtual training purposes, for example in inaccessible conditions (such as hazardous environments or emergency situations), or in the development of future tools (as seen in the medical field). This finding also reflects on the value of interfaces in general for the space perception of a user. This is important for the design of tangible interfaces that, by their very definition, combine the physical with the digital representation. A number of new questions emerged during this research. E.g., how important is the representation of an avatar vs. that of a tool? Does the level of detail affect the appropriation? In the present study, the virtual environment was relatively crude (e.g., the virtual tool was only a rough representation of the physical tool and the perspective was only approximate). It is encouraging that appropriation occurred in these conditions, but one wonders how a more realistic environment might enhance appropriation, or how poor the environment can get before transfer does not occur. Likewise, how do the relative sizes of the virtual vs. the physical rake affect appropriation? Further, do different levels of agency lead to different appropriation? The study presented here provides the first critical building block that allows future comparative tests with tangible devices to test tool appropriation in more detail.

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