Measuring Readiness-to-Hand through Differences in Attention to the Task vs. Attention to the Tool

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ABSTRACT

New interaction techniques, like multi-touch, tangible interaction, and mid-air gestures often promise to be more intuitive and natural; however, there is little work on how to measure these constructs. One way is to leverage the phenomenon of tool embodiment—when a tool becomes an extension of one's body, attention shifts to the task at hand, rather than the tool itself. In this work, we constructed a framework to measure tool embodiment by incorporating philosophical and psychological concepts. We applied this framework to design and conduct a study that uses attention to measure readiness-to-hand with both a physical tool and a virtual tool. We introduce a novel task where participants use a tool to rotate an object, while simultaneously responding to visual stimuli both near their hand and near the task. Our results showed that participants paid more attention to the task than to both kinds of tool. We also discuss how this evaluation framework can be used to investigate whether novel interaction techniques allow for this kind of tool embodiment.

Author Keywords

Embodied interaction; multi-touch; tangible user interfaces; tabletop displays; physical interaction, intuitiveness, naturalness, user centric interaction.

ACM Classification Keywords

H.5.2. [Information interfaces and presentation]: User Interfaces—Input devices and strategies.

INTRODUCTION

An important part of people's cognitive development is to interact with the physical environment [7]. This interaction continues on a daily basis throughout life. In the physical environment, many objects help us to accomplish tasks more effectively, such as paper, pencil, cooking utensils, whiteboards, and even coffee mugs. However, the tools we use to accomplish work are nowadays more and more embedded in digital environments, and our work increasingly depends on virtual artifacts, such as graphical widgets (e.g., buttons and menus) and gesture-based interaction (e.g., tapping or pinch-to-zoom on smartphones). Indeed, many of these virtual artifacts have been designed to mimic physical attributes or afford physical-like actions [10,32], and novel interactive technologies that support these physical-like actions are often referred to as natural and intuitive [44].

Although several studies have looked at ways to evaluate different types of interaction like direct touch [19], the use of the terms "natural" and "initiative" is somewhat controversial in HCI [15,41] and little work has been dedicated to understanding these constructs. On the one hand, many researchers have designed interaction with the intention of creating natural and intuitive techniques [11,13,14,16,21,25,29, 44], and techniques such as elicitation studies [28,31,46] and consideration of the "continuum of knowledge" in the design process [3] have allowed for the creation of gestures that are familiar, and therefore perhaps intuitive and natural. However, summative evaluations of these techniques have primarily used performance [18] and self-reports [12] as measures. Consequently, there is a gap in our understanding of how to measure these complex, nuanced phenomena. In our work, we focus on a more direct measure of tool embodiment using a novel measurement of attentional shift.

Our novel measurement is based on the phenomenon described by Heidegger [17], Dourish [6], and Winograd and Flores [45] that, when tool use is natural and intuitive, the tool becomes "invisible" or "transparent". When using a tool like a hammer skillfully our attention becomes focused on that task and less attention will be dedicated to the tool itself. Heidegger [17], Dourish [6], and Winograd and Flores [45] describe this phenomenon as "readiness-to-hand". While Dourish [6] discusses many different ideas of embodied interaction, there is a distinction between embodiment as a general phenomenon and being embodied with a tool or an object. In our work, we investigate how tool embodiment can be used as a direct measure of readiness-to-hand.

We developed an evaluation framework that incorporates the idea of *readiness-to-hand* from philosophy and concepts such as sensory-motor contingency [33], change blindness [34] and inattentional blindness [24] from psychology. We applied this framework to design and conduct a study using a novel task where participants were asked to use a tool,

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while their attention was tested using stimuli both near the task and near the tool's handle. Our results showed that participants' attention was focused more on the task than on the tool, suggesting that they were experiencing tool embodiment with both a virtual and physical tool. We then discuss the necessary elements required to make use of our evaluation framework for other novel interactive technologies: the presence of a tool, an action to be performed, and stimuli to measure attention both on the tool and on the task. Other researchers can use our framework and guidelines to evaluate other novel technologies for tool embodiment.

RELATED WORK

In this section, we discuss several research areas that relate to tool embodiment. Tool embodiment has often been part of philosophical and psychological research with an emphasis on how using a physical tool affects the perception of the boundaries of one's own body—the *body schema.*

Tool Embodiment

Psychologists have been concerned with tool use and object manipulation for a long time. In psychology and perception research, a key term during the 20th century was Gibson's concept of *affordances* [8]. Affordances refer to how the physical characteristics of a physical object (or the physical environment) provide information to the perceptual system about the actions that are possible with that object or the environment [9]. Because affordances are considered key in the development and use of human skills, much of the effort in the field of HCI in the last 40 years has focused on replicating the characteristics of physical objects that constitute affordances into digital objects and interfaces (e.g., [8,23,32]). For example, natural user interfaces (NUIs) use tools that resemble other tools in the physical world where skills and meaning will transfer easily from the physical world to, otherwise unfamiliar, digital tools [44]. Although the concept of affordances is still a useful lens to look at the design of digital artefacts [8], here we are concerned more with the ability of people to perform tasks rather than their ability to perceive the world or even their ability to become aware of the actions possible with a given object.

Performing a task requires a combination of visual perception and action. Several studies have labeled this the "sensory-motor contingency", and explain how interacting with physical objects results in skillful use of a tool to manipulate the environment [7,33]. For example, using a physical tool, like a pen, requires knowing specific physical properties of that pen (e.g., a rigid object) and a set of actions to use that pen in the world (e.g., used vertically, used on paper). This skillful use of a tool changes how we perceive our body schema [33]. Several studies have demonstrated updates in the body schema by extending personal space [4,26] and estimating one's arm length differently [26, 27]. In our work, we extend the concept of body schema updates to situations where a tool is used in a task. We thus concentrate our investigation on understanding how using a tool can update our body schema as we complete a task and our focus changes from the tool being used to the task at hand. We therefore looked to the phenomena of attentional and inattentional blindness—well-known effects that have been observed repeatedly in many studies—as a means to measure shifts in attention from the tool being used to the task itself.

Attention and Inattentional Blindness

The lack of attention to details in a scene or changing elements in the environment is well-known in psychology and HCI literature. Studies on lack of attention have mostly been conducted for visual perception [37]; however, some studies have considered the effects of lack of attention on haptic and auditory perception as well [2]. Change blindness (CB) occurs when people miss large changes in the scene after a visual interruption [40]. Another lack-of-attention phenomenon similar to CB is inattentional blindness (IB). CB occurs due to a failure to notice an obvious change, whereas IB is a failure to notice something unexpected while engaged in a cognitively demanding task. These effects hint at a mechanism in the brain that filters unwanted or unimportant objects in the visual scene when concentrating on a task [19].

In our work, we leverage CB and IB to measure lack of attention while a tool is being used in both physical and virtual settings. This lack of attention can be used as an indication of tool embodiment by isolating and comparing how attention can shift from the tool (and figuring out how it is to be used), to the task at hand.

Current Measures for Natural User Interfaces

Natural user interfaces [44] and tangible user interfaces [21,22] are often presented as allowing people to become embodied with the digital world by providing a bridge between the physical properties of objects and the virtual presentation of information, and have been measured in many different ways.

Performance measures of these technologies mostly consider speed and accuracy. Hardware has been evaluated by varying screen size [39] and display coordination effects on perception of 2D graphics [43]. Software has been evaluated by looking at different aspects of the presented information on the screen, including menus [11], visualizations [29], and 2D and 3D virtual object manipulation [14,25].

Other research has considered people's expectations when using interactive technology by eliciting user-defined gestures [28,31,46]. In these studies, users are shown an interaction, and then asked to select gestures to perform that task in an attempt to discover what is most natural or intuitive. Other studies have considered affect, task load, and motivation when using touch and tactile interaction [42]. This methodology uses validated scales to measure the experience of using an interactive system.

In our work, we present a new framework to investigate naturalness and intuitiveness by considering tool embodiment and leveraging readiness-to-hand.

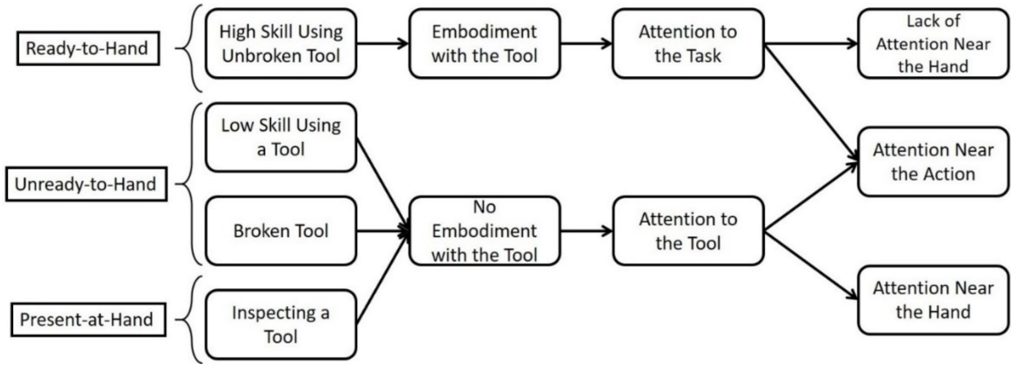


Figure 1. Tool embodiment framework that decomposes the three states of interacting with a tool as proposed by Heidegger (Ready-to-Hand, Unready-to-Hand, and Present-at-Hand).

TOOL EMBODIMENT MEASUREMENT FRAMEWORK

The aspect of forgetting a tool when skillfully using it was introduced by Heidegger in his discussion *"Being and Time"* in 1927. This characteristic of "invisibility" is often associated with technology described as "natural" and "intuitive". For example, when using a tool like a hammer skillfully, our attention becomes focused on the nail being hammered and the tool seems almost invisible. Heidegger [17], Dourish [6], and Winograd and Flores [45] describe this phenomenon as "ready-to-hand". Therefore, we propose the following definition for tool embodiment:

Tool embodiment is a characteristic of skilled action in which the attention shifts from the manipulation of the tool to the goal action itself.

Heidegger [17] described people's interactions with the world as skillful manipulation of the environment that consists of three states: ready-to-hand, unready-to-hand, and present-at-hand. Unready-to-hand describes when the tool is not functional or not working properly; attention will be focused on the tool and not the task at hand. Present-at-hand describes a state where the user observes characteristics of the tool or the object like its color or shape. Finally, ready-to-hand describes when a tool becomes "invisible" during an action. This effect of invisibility shifts the user's attention from the tool to the task at hand.

In our framework (Figure 1), we constructed a process that identifies specific elements of readiness-to-hand. We start with skillful use of a tool (Figure 1, top path), which lets the tool be integrated into the body schema, leading to *tool embodiment.* At this point, attention will be concentrated on the task, leading to a lack of attention near the hand. If a person has difficulty using a tool (e.g., due to low skill, broken tool, or tool inspection), it will not be integrated into the body schema (Figure 1, bottom paths), leading to more attention dedicated to the tool rather than the task at hand. This shift in attention is our primary indicator of tool embodiment.

To measure attentional shift, we divided the tool into two sections: near the hand and near the action. When a person is performing a skillful action with the tool (i.e., ready-to-hand), attention is directed toward the task and away from the tool. More specifically, this would lead to a lack of attention near the hand (e.g., the handle of a hammer) and more attention near the action (e.g., the nail being hammered).

Attentional shift from near the hand to near the action is central in understanding how interacting with a tool affects people's perception. Previous work [1,35,36] has reported that attention near the hand is stronger when a tool or the hand is held stationary. So, if attention is shifted from near the hand to near the action that means that the process of mastering the tool has affected how attention is allocated. Winograd and Flores [45], for example, discuss how anticipation of breakdowns is imperative in the design process, as they lead to attention shifting to the interface, rather than the task at hand. Previous work, however, has not included situations where a tool is used to manipulate other objects in the environment. Our work concentrates primarily on how attention is affected during skillful use of the tool, which could indicate a ready-to-hand state as proposed by Heidegger [17], Dourish [6], and Winograd and Flores [45].

To verify the effects of tool embodiment and to test our framework we conducted a study using two main tool types: physical and virtual. We considered readiness-to-hand as a main indicator of tool embodiment where attention is shifted from near the hand to near the action.

STUDY DESIGN

In this study, we explore the effect of attentional shift when using both physical and virtual tools. More specifically, we concentrate on the difference between near-hand attention and near-action attention, as described in the tool embodiment framework (Figure 1).

Apparatus

For this study, we wanted to be able to compare two similar tools, and so created a physical and virtual version of a "wrench" tool and a "bolt" to be twisted, which were both usable on a two-dimensional surface.

Physical Tool. The physical tool consists of several layers of cardboard foam (Figure 2b) and is similar in appearance to a monkey wrench (gas grips), but is not adjustable. The tool had two holes for the index finger and thumb to be able to move and rotate the "wrench" to fit over a square piece of

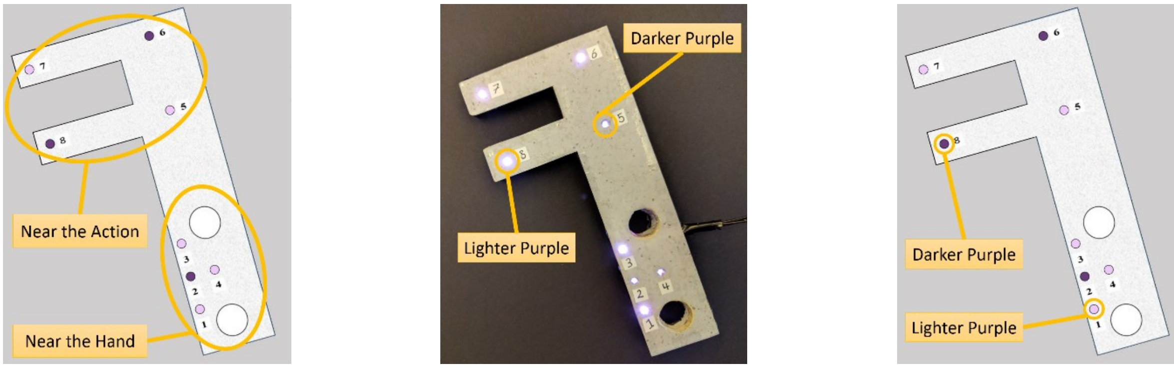


Figure 2. (a) The secondary task stimuli: near the hand and near the action, on (b) the physical tool, and (c) the virtual tool.

cardboard on a pin that allows it to swivel (Figure 3), which represented a bolt.

As shown in Figure 4, two screens were used in both conditions. In the physical setup, we created a mock screen from cardboard foam that was firmly situated on top of a regular screen. In order to present stimuli on the tool, wired lights (Flora RGB Smart NeoPixel v2) and wires were placed in the middle layer of the tool and controlled by an Arduino board.

Virtual Tool. In the virtual setup (Figure 2c), we mirrored the physical setup as closely as possible, using white circles to represent the holes for the index finger and thumb, which could be used to move and rotate the tool to fit over a virtual white square representing the "bolt" that could only rotate. The virtual tool and object were developed in Processing using Java. Procesing2D was used as a physics engine to take touch input and simulate movements of the tool and the object. The Simple Multitouch Toolkit[1] was used to record touch points and enable touch interactions.

Screen Setup. Two 21 inch screens were placed on a 120 cm × 60 cm table (Figure 4). The table's surface was 65 cm above the floor. Participants were seated on a chair where it was most comfortable for them to interact with screen 1 (Figure 4, a and c). Screen 1 was used to interact with either a physical or virtual tool and screen 2 provided feedback about the task. Screen 1 was placed horizontally and screen 2 was placed vertically. A keyboard was also available on the table for participants to provide input.

Task

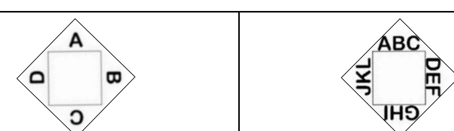
We introduced a novel task of using either a virtual or physical tool in nearly similar conditions. Participants were asked to complete a primary spelling task and a secondary stimulus task during the experiment. The primary task was intended to be the focus of attention, with the secondary task as a means to measure shifts in attention.

Primary Spelling Task. Participants were asked to use either a virtual (Figure 2b) or physical (Figure 2c) tool to rotate a square "bolt" object (Figure 3) until a target letter was facing upward (only clockwise rotations were allowed). In the *easy* condition, the square object had 4 letters located on each corner (Figure 3a) and participants were always asked to go to the "next" letter (i.e., one clockwise rotation). In the *hard* condition, the object had 12 letters, 3 on each corner (Figure 3b), and participants were asked to spell a four-letter word, so the next letter was determined by the next letter in that word. After each letter, participants would return to the starting position. Thus, as shown in Figure 5, to complete an easy task the sequence was: *Position 1*, *Position 2*, *Position 3*, and return to *Position 1* (starting point). To complete a hard task, the sequence always started in *Position 1*, then had one or more repetitions of *Position 2*, *Position 3* (to get to the right letter), before returning to *Position 1* (to indicate that letter was selected).

The second (vertical) screen showed the target letter/word and, in the hard condition, a green dot was used to indicate the current letter (Figure 4b). This feedback was initiated by the experimenter, who would press a button to advance when the participant returned to *position 1*. In the hard task, when the required letter was already facing up (e.g., when going from "A" to "B" in "ABLE"), participants were asked to make a full rotation of the object (4 rotations). The words used in the study were: ache, bail, bike, chef, dice, file, gild, held, idle, leak (physical condition); and able, back, bide, cage, deal, face, glad, half, idea, lack (virtual condition).

Participants were instructed to complete as many spelling tasks (letters/words) as they could in a 432 second interval.

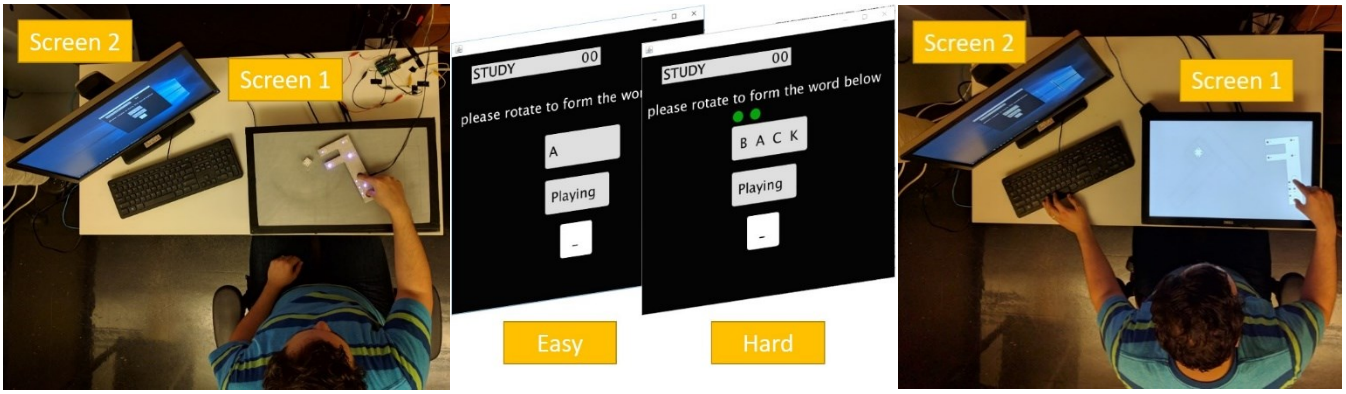
Secondary Stimulus Task. Participants had to report any change that occurred on the tool (Figure 2) while completing the primary task. Both tools had 8 coloured circles/lights divided into near-the-hand and near-the-action sections (Figure 2a)—this division was not known to participants. Participants were instructed to report any changes on the tool re-



a. Easy "bolt" object | **b. Hard "bolt" object**

Figure 3. Object of manipulation "bolt"

[1] (http://vialab.science.uoit.ca/smt/)



(a) (b) (c)

Figure 4. (a) The physical study setup with a participant holding the physical tool. (b) The second screen for the primary task. (c) The virtual study set up with the participants holding a virtual tool.

gardless of location. Half of the circles/lights (randomly selected) were a lighter purple colour and the other half a darker purple colour. The experimental system creates a change by shifting the colour from lighter to darker or vice versa. Changes took place 6 seconds apart, and only one change happened at a time. Participants were only aware that changes would occur (not how many, when, or where), and they were instructed to report changes that they noticed as soon as possible by pressing the space bar and then typing the number of the changed light and then "enter" to resume the letter/word completion task. In each condition, 36 near-hand stimuli and 36 near-task stimuli were changed (2 × 36 × 6 seconds = 432 seconds). Pressing space to report the change also paused the primary task timer.

Procedure

The experiment follows a within-participants design with two factors: tool type (physical vs. virtual) and task difficulty (easy vs. hard). We counterbalanced first by tool type, then by difficulty and so participants were assigned to one of four orders and either performed all physical trials first (both easy and hard), or all virtual trials first (both easy and hard). Figure 6 shows one of four orders used by participants. A third random factor of location was also used in our analysis, but not controlled for in the study procedure.

Start (S). After participants were seated, study details were explained. Participants were reminded of the procedure after finishing each condition and wherever they needed help.

Ishihara Color Blindness Test (I). Participants then completed the Ishihara Color Blindness Test [20].

Tool Training (ToT). Participants were then given 10 minutes to interact with a physical (Figure 2b) or virtual tool (Figure 2c). Each participant was instructed to use their thumb and index fingers in the holes on the wrench-like tool (Figure 2) to rotate a square bolt-like object (Figure 3).

Task Training (TT). Participants were given 2 minutes to use the tool and practice the main task (VE, VH, PE, PH).

Virtual Condition (VE and VH). Participants interacted with a virtual tool (Figure 2c) to accomplish either an easy (VE) or hard (VH) task.

	Virtual						Physical				
		Easy		Hard				Easy		Hard	
S/I	ToT	TT	VE	TT	VH	B	ToT	TT	PE	TT	PH

Figure 6. The order of trials was counterbalanced first by tool type (virtual/physical) and then by difficulty (easy/hard). This figure shows the order (1 of 4) with virtual-easy (VE) first, and the actual tasks are highlighted in orange (VE, VH, PE, PH).

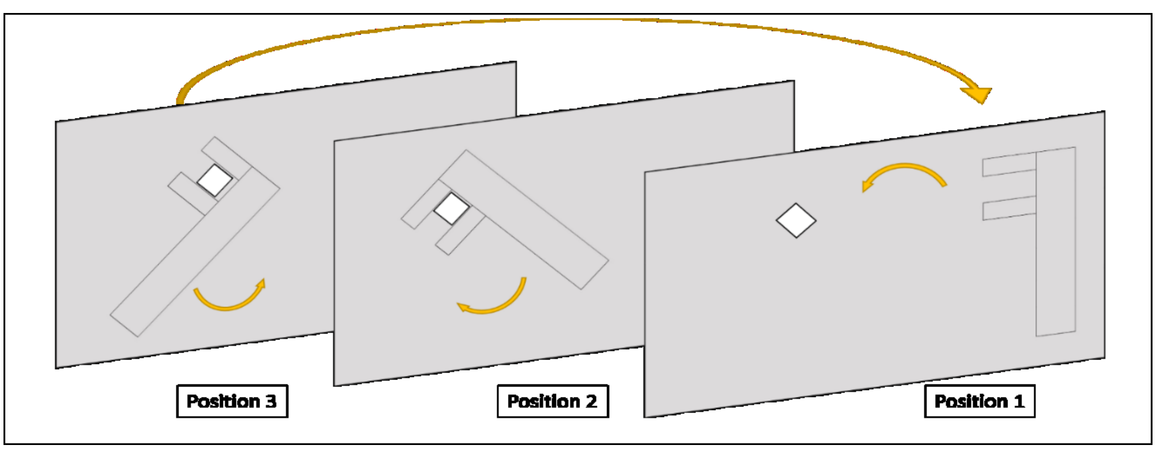


Figure 5. Rotation task by participants in the study. Position 1 is the starting position; positions 2 and 3 show object rotation.

Physical Condition (PE and PH). Participants were asked to interact with a physical tool (Figure 2b) to accomplish either an easy (PE) task or a hard (PH) task.

Break (B). Participants were asked if they needed a break. Although breaks at any time were allowed, longer breaks were more common (3-5 min) for a few participants.

Participants

Thirty-two participants (16 female) aged 18 to 31 (*Mdn* = 22) took part in our study. Participants were screened for handedness (all reported to be right-handed), color-blindness (all passed the Ishihara Color Blindness Test [20]), and English proficiency (self-rating from 1-10; *M*=8.7). Participants were recruited via on-campus mailing lists, and given $15 gift certificates to a local coffee establishment.

Measures

For the primary spelling task, the experimenter manually recorded task completion time and number of tasks completed. The number of rotations required to complete the task was computed using the letter sequence. For the secondary stimulus task, attentional shift was measured based on reported changes noticed by participants. A percentage of missed stimuli was used for study analysis (recorded separately for near the hand and near the action). We also recorded the timing between stimuli presentation and space bar presses.

Hypotheses

Our study is designed to identify an attentional shift from the tool being used toward the task being done, and so our primary hypothesis is as follows:

H1: Participants will experience tool embodiment with both physical and virtual tools, which will lead to attentional shift in the secondary task from stimuli presented near the hand to stimuli presented near the primary task (the action). This effect will lead to more missed stimuli and longer reaction times in the secondary task for stimuli near the hand.

Based on this attentional shift, we can further investigate the degree of embodiment by looking at the size of the difference between what happens near the hand vs. near the action. Thus, our secondary hypotheses relate to the size of this *attentional shift*, measured by the difference in number of lights missed and reaction times near the hand vs. action:

H2: As difficulty of the primary (spelling) task increases, participants will become more embodied with the tool, and therefore have a larger attentional shift. We expect the shift in this direction because the difficulty is cognitive and requires focus on the task, and no complex manipulations (e.g., as might be seen in skilled use of a musical instrument).

H3: Due to its tangible, physical nature, participants will be more embodied with the physical tool and therefore have a larger attentional shift with the physical tool than the virtual.

We also had a hypothesis for our primary task measure:

H4: Due to being tangible/physical, we expect performance to be better when using the physical tool than the virtual one.

Study Design Decisions

As this is a first attempt to operationalize tool embodiment, a number of study design decisions we made could be adjusted or tweaked in future studies that build on our work.

In particular, our definition of tool embodiment relies on skilled use of a tool, which is difficult to replicate in a lab. We intentionally chose a wrench-like tool as we expected it to be familiar for participants so that minimal practice could lead to skilled use. We were required to make some modifications to make it work in 2D for a touch-based interface, but these modifications were intended to mimic physical-like interaction to again be familiar. Similarly, in order to provide visual stimuli, we needed to augment and tether the physical tool, but made efforts to minimize any discomfort by having the cord be mostly hidden and lightweight. This also had the consequence that visual stimuli “near the action” were still on the tool itself, but we were careful to make stimuli at this part of the tool always be *closer* to the action, and therefore more likely to lead to measurable attentional shift.

RESULTS & DISCUSSION

Because the measure of primary interest in our study was the comparison between what happened near the hand and near the action in the secondary stimulus task, we report these findings first. We then report findings of the primary spelling task, followed by a correlational analysis between the number of rotations in the primary task and the overall number of missed lights in each task.

Secondary Stimulus Task

For secondary task measures (missed changes, reaction time), we performed a repeated-measures ANOVA with tool type (physical vs. virtual), difficulty (easy vs. hard), and location (near hand vs. near action) as within-participants factors. We also included order as a between participants factor to enable further investigation of order effects. Bonferroni corrections were used in all post-hoc analyses.

Missed Changes

There was a significant main effect of location ($F_{1,28}$ = 22.9, p < .001, η_p^2 = .45), with participants missing more near the hand (M = 60.7%, SE = 3.7%), than near the action (M = 50.4%, SE = 3.1%). This finding supports the presence of attentional shift throughout all conditions (H1).

There was a significant interaction between tool type and location ($F_{1,28}$ = 8.1, p = .008, η_p^2 = .23). Post-hoc analyses revealed pairwise significant differences between missed changes near the hand and near the action for both tool types (p < .05); inspection reveals that the difference was smaller for the physical tool (7%) than the virtual one (13%), which runs *contrary* to H3 (Figure 7). However, there was a significant tool type × difficulty × location interaction ($F_{1,28}$ = 5.9, p = .02, η_p^2 = .17) which helps shed light on this finding (Figure 8). Post-hoc analyses revealed pairwise significant differences between missed lights near the hand and near the action (p < .05) for all except for the physical easy condition (p = .18). Thus, for the hard task, both physical and virtual

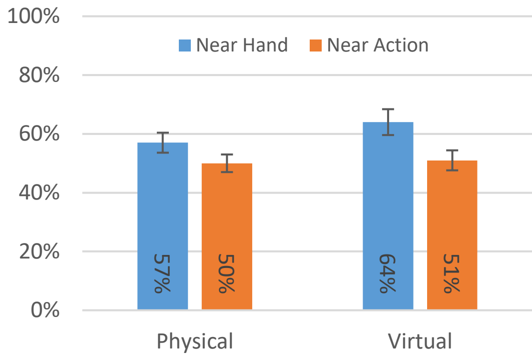


Figure 7. Tool type × location interaction for missed lights. This result indicates the strength of the attentional shift.

had similar-sized attentional shifts (i.e., differences between near-hand and near-action means), and the change in attentional shift is only larger for the virtual tool in the easy condition. We expect this is because the virtual tool generally required more effort, and so even in the easy condition, participants were more embodied with the tool (i.e., had to pay more attention to the primary task). Nonetheless, we cannot confirm H3 (larger attentional shift for physical), but this finding does provide partial support for H2 (larger attentional shift for difficult primary tasks).

There was also a significant main effect of difficulty ($F_{1,28} = 26.1$, $p < .001$, $\eta_p^2 = .48$), with participants missing fewer stimuli in easy ($M = 52.3\%$, $SE = 3.4\%$) than in hard tasks ($M = 58.8\%$, $SE = 3.2\%$). This finding is unsurprising given the pattern of missed changes in the 3-way interaction, but may indicate that cognitive load was lower, leading to fewer missed lights. There were no other significant main effects or interactions. In particular, there was no main effect of order, nor interactions that involved the order factor.

Reaction Time

There was a significant main effect of location ($F_{1,27} = 7.2$, $p = .01$, $\eta_p^2 = .21$), as participants were slower to report changes that occurred near the hand ($M = 2.16$ s, $SE = 0.09$ s) than near the action ($M = 1.93$ s, $SE = 0.09$ s). This finding again supports the presence of attentional shift (H1).

There was also a significant main effect of tool type ($F_{1,27} = 6.7$, $p = .02$, $\eta_p^2 = .20$), with participants taking longer to report the stimuli in the virtual condition ($M = 2.17$ s, $SE = 0.09$ s) than in the physical condition ($M = 1.92$ s, $SE = 0.10$ s). This may again indicate that there was higher cognitive load in the virtual condition, but there were no other significant main effects or interactions (except with order, discussed below), and so this increased reaction time did not depend on whether the lights were near the hand or near the action, and thus there is no support for H2 or H3 from the reaction time analysis.

There was a significant interaction between tool type and order ($F_{3,27} = 3.4$, $p = .03$, $\eta_p^2 = .27$). Pairwise comparisons revealed that, with the virtual tool, orders 2 ($M = 2.5$ s, $SE = 0.2$ s) and 3 ($M = 2.6$ s, $SE = 0.2$ s) had significantly higher reaction times than orders 1 and 4 ($p < .05$), but no

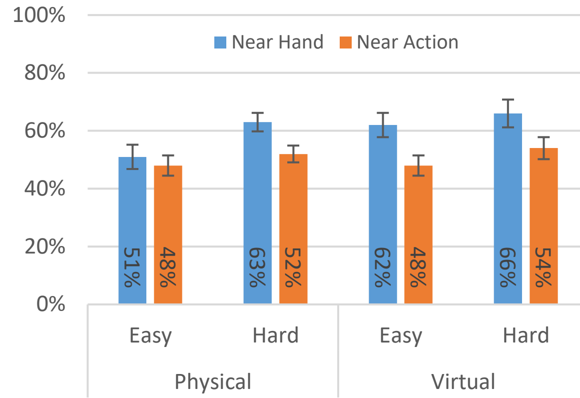


Figure 8. Tool type × difficulty × location interaction for missed lights. Participants missed more lights near the hand in all but the physical-easy (PE) condition.

other pairs of orders were different ($p > .99$). Moreover, orders 1 and 4 in the virtual condition and all orders in the physical condition were in the range 1.8 s-2.0 s, and so it is likely orders 2 and 3 which were anomalous, and only for virtual-tool reaction times. The only pattern we can discern for these two orders is that order 2 began with virtual-hard and order 3 ended with virtual-hard, and so this particular condition may have had higher reaction times due to being either first or last. We don't expect that this effect influenced our findings about location differences, but may influence reaction time findings regarding tool type, although these were already inconclusive (H2 and H3 are still not supported).

Primary Spelling Task

We also analyzed measures from our primary spelling task using the same RM-ANOVA, without the location factor. Since participants completed as many tasks as they could in a fixed time, the number of tasks completed and task completion time are perfectly correlated. Consequently, we present findings for number of tasks only. Bonferroni corrections were used for post-hoc analyses.

Number of Tasks Completed

There was a significant main effect of tool type ($F_{1,28} = 220.7$, $p < .001$, $\eta_p^2 = .89$), with participants in the virtual condition completing fewer tasks ($M = 26.7$, $SE = 1.1$) than in the physical condition ($M = 57.2$, $SE = 2.7$), suggesting higher performance in the physical condition (H4). The main effect of difficulty was also unsurprisingly significant ($F_{1,28} = 316.1$, $p < .001$, $\eta_p^2 = .92$), with participants completing more tasks in the easy condition ($M = 57.1$, $SE = 2.5$) than in the hard condition ($M = 26.8$, $SE = 1.1$). There was a significant interaction between tool type and difficulty ($F_{1,28} = 144.0$, $p < .001$, $\eta_p^2 = .84$). Post-hoc analyses revealed pairwise significant differences between number of tasks for easy and hard conditions for both tool types ($p < .05$); inspection (Figure 8) reveals that the difference was smaller for the virtual tool (18) than the physical one (42). This interaction also suggests that performance was better in the physical condition (H4).

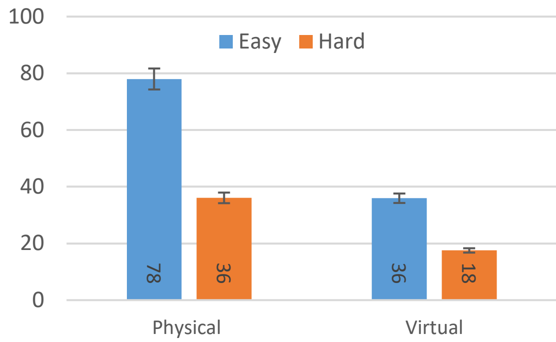


Figure 8. Tool type × difficulty for number of tasks.

There was a significant interaction between difficulty and order ($F_{1,28} = 11.8$, $p < .001$, $\eta_p^2 = .56$). Post-hoc analysis revealed that the only pairwise differences were between orders 1 and 4 in the easy condition (p = .048) and orders 2 and 3 in the hard condition (p = .04). This effect again seems to be related to when the virtual condition occurs, with the differences being exacerbated when the virtual easy is first (order 1) vs. last (order 4) or when the virtual hard is first (order 2) vs. last (order 3). This order effect is consistent with our hypothesis that people would perform better in the physical condition, and does not interfere with our main findings.

Object Rotation Analysis

Due to the nature of our task, the number of tasks completed can be further dissected into the number of rotations performed *within* each task (i.e., to get to the subsequent sequence of letters—1 rotation per easy task, $M = 9$ rotations per hard task). Since the conditions were time-limited, the total number of rotations performed over the duration of each condition is an indication of how engaged participants were with the task. We suspected that this would be related more directly to how embodied they were with the tool, so we conducted a further correlational analysis using number of rotations as a measure, and compared this to the number of lights missed *overall* in the secondary task to see if there was a connection between this measure and attention. There was a positive correlation between object rotations ($M = 248.4$, $SD = 55.7$) and total missed changes ($M = 160.0$, $SD = 15.5$), $r = .52$, $p = .002$, $n = 32$, as shown in Figure 9.

This relationship indicates that participants tend to miss more lights as the number of rotations they complete in the primary task increases (note that there were exactly 288 light changes for each participant, as these happened at regular intervals in a fixed time interval). Because the number of rotations only relates to the primary task, it is not possible to identify a relationship between increased rotations and lights missed specifically near the hand (to indicate attentional *shift*); however, this finding does suggest that higher engagement may be related to attentional changes in general.

GENERAL DISCUSSION

A summary of our findings is as follows:

- Overall, there were more missed lights and reaction times were higher near the hand than near the action for both virtual and physical tools, indicating an attentional shift predicted by our framework (H1).
- We expected difficult tasks to lead to a greater shift in attention (H2); however, only the physical tool followed this pattern.
- We expected the physical tool to lead to a greater attentional shift (H3); however, this hypothesis was completely unsupported, and instead, the difficulty imposed by the virtual tool led to more attentional shift even in the easy condition.
- Participants performed (expectedly) better with the physical tool than the virtual one.
- There was a correlation between number of rotations (as a measure of engagement) and the number of lights missed, indicating a connection between engagement/performance and attention.

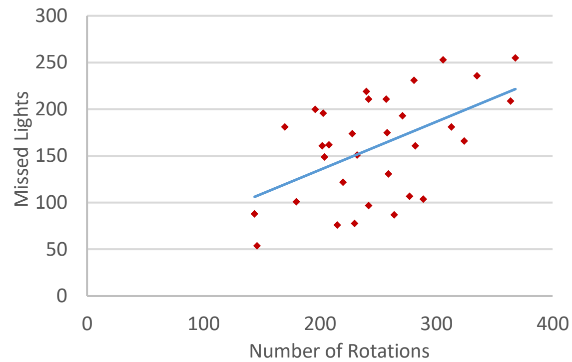


Figure 9. A positive correlation between the number of rotations and missed lights. This result indicates how engaged participants were with the task.

Our study provides support for the framework we have described in this paper, which we believe can be used as a new measure of tool embodiment. In particular, the paradigm we have described in this study of having a primary task with a secondary attention task can allow for the measurement of attentional shift in novel interaction techniques.

Of particular note is that our study indicated a clear performance difference between physical and virtual tools, and without our additional attentional shift measure, an experimenter may be tempted to conclude that the virtual tool is less "intuitive" or "natural". Our attentional shift measure can therefore augment these findings, and provides evidence that tool embodiment occurs with both. Furthermore, interactions between tool type × difficulty × location can help elucidate these performance findings and demonstrates a more nuanced story that can help explain that the virtual tool requires more cognitive resources, despite still providing a high level of tool embodiment.

To our knowledge, this work is the first to directly measure attention as evidence of Heidegger's readiness-to-hand phenomenon using both physical and virtual tools. Other studies have identified Heidegger's readiness-to-hand phenomenon using a mouse [5], in which the mouse controls a pointer on the screen, but failed to link the tool directly to the person interacting with it. Our results show a direct link between tool use and being ready-to-hand, where attentional shift was observed in both physical and virtual tools.

Framework Implications for HCI

Our framework can be used to compare interactive technologies as a measure of readiness-to-hand. In our study, we used direct touch and tangible interaction to manipulate the tool, but other interactive technologies could be tested in a similar way. In particular, our framework can be applied as a measure with the following elements:

- The tool: a tool is an essential part of our framework. In our framework, this tool must act as an intermediary between a person and the task in some way (e.g., a wrench, hammer, etc.)
- The action: just holding a tool in one's hand will not affect attentional shift. A tool must be used skillfully to measure attentional shift.
- The stimuli: visual stimuli on the tool and near the action are also required. We recommend augmenting the tool with these stimuli in clearly separate locations, but a similar setup could also augment the "bolt" in our study with stimuli to determine attention near the action.

Limitations and Future Work

While our study provides some of the first evidence that tool embodiment can be measured independently from task performance, we present only two instances of a tool. Further studies could help to corroborate these findings and support more nuanced analysis involving differences in attentional shift between vastly different tool types. Moreover, tools could be tested under different circumstances, such as intentional tool malfunctioning, to paint a more complete picture of measures of *unreadiness*-to-hand and present-at-hand.

The wrench-like tool used in our study was specifically designed to target our definition of tool embodiment—a decision we took to demonstrate the utility of our framework—but future work should look at existing digital interaction techniques that leverage tools, such as pen interaction, wearable/spatial interaction [16], multi-touch techniques [13,14] or menus [11,25]. Even with direct manipulation (e.g., pinch-to-zoom on a map), it may be worth considering attentional shift between the points of contact and the point of interest. Similarly, our protocol currently requires that a tool be augmented with stimuli (e.g., lights), which may prove difficult for small tools, so future work could consider other measures, such as eye tracking, to measure attention. This measure would also avoid any issues of occlusion, which in our study was not possible to measure, though we intentionally placed lights to avoid occlusion, and the experimenter did not observe any specific instances of occlusion.

As mentioned above, our framework also relies on skilled use, which can be difficult to replicate in a lab setting. While our work focused on already-familiar wrench-like interaction, future work could explore more longitudinal use.

CONCLUSION

This paper presented a study that measures readiness-to-hand with different tools (physical and virtual). Results showed that participants' attention shifts from the tool to the task at hand, indicating that they experienced tool embodiment using both. We highlight how this tool embodiment framework can be applied to different technologies moving forward.

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