Quantitative Measurement of Virtual vs. Physical Object Embodiment through Kinesthetic Figural After Effects

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ABSTRACT

Over the past decade, multi-touch surfaces have become commonplace, with many researchers and practitioners describing the benefits of their natural, physical-like interactions. We present a pair of studies that empirically investigates the psychophysical effects of direct interaction with both physical and virtual artefacts. We use the phenomenon of Kinesthetic Figural After Effects—a change in understanding of the physical size of an object after a period of exposure to an object of different size. Our studies show that, while this effect is robustly reproducible when using physical artefacts, this same effect does not manifest when manipulating virtual artefacts on a direct, multi-touch tabletop display. We contribute quantitative evidence suggesting a psychophysical difference in our response to physical vs. virtual objects, and discuss future research directions to explore measurable phenomena to evaluate the presence of physical-like changes from virtual on-screen objects.

Author Keywords

Embodied interaction; multi-touch; tangible user interfaces; tabletop displays; physical interaction.

ACM Classification Keywords

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

INTRODUCTION

Most of the emerging paradigms in input-output since the invention of the mouse try to enable more direct relationships between the human body and digital objects. For example, Ishii and colleague's Tangible Computing and Radical Atoms visions [37,18] provide physical proxies for digital information that can be manipulated as physical objects; multi-touch interaction allows people to spatially overlap their physical input (finger touch) with the visual representation of the virtual objects [6,15]; and much of the work in on-air volume sensing aims to enable more natural body interactions with virtual objects (e.g., work with the Kinect [3] and Leap Motion [10]).

A common mantra for these new technologies is that they allow us to become more embodied with the digital world and better leverage the natural motor and body skills of humans for digital information manipulation. While we have begun to have a firm grasp on the philosophical implications of these advances (e.g., [10]), we don't yet have a good understanding of the psychological phenomena and mechanisms at work. Moreover, there is very little quantitative evidence from HCI that these more "direct" modes of interaction actually result in interaction that is more similar to real-world physical object manipulations. As a result, we are still missing important evidence that would allow us to answer questions such as the following:

- How do virtual artefacts affect human psychology when manipulated through direct touch?
- Is there a quantitative difference between interaction with technology through a physical object (tangible computing) and through screen touch?
- Is there any psychophysical advantage to the separation of the digital and the physical, or an advantage to input "indirectness"?

There is a large amount of research from Psychology that, although not directly able to answer these questions, has investigated the connection between the physical body and physical and virtual objects, both for physical tools [7,17,20,24,32] as well as for "virtual" embodiments [4,7,11,26].

In this work, we attempt to break ground in finding quantitative evidence regarding the relationship between interaction with physical objects and interaction with virtual objects in a psychophysical sense. This evidence can be useful for the design and evaluation of input systems. As a first step, we take the phenomenon of figural after effects—changes in human perception resulting from grasping or holding physical artefacts, well studied in psychology—and use a controlled laboratory experiment to observe whether the effect applies to virtual object representations accessed through multi-touch screens.

Our results show that the psychophysical effects of virtual touch are not comparable to those of holding a physical object. The findings indicate a measurable qualitative difference between virtual and physical artefacts that has important consequences for the design of interactive systems. We highlight several consequences of this finding, including both psychophysical advantages of tangible interfaces over virtual ones, as well as potential benefits of virtual interfaces due to reduced perceptual interference.

EMBODIMENT AND FIGURAL AFTER EFFECTS

The concepts of embodiment and embodied interaction have been discussed in the HCI and psychology literature with different meanings and different goals. In this section, we start by framing our work in terms of those meanings, and then present relevant results from the psychology literature. We then discuss different types of figural after effect.

Embodiment in HCI and Philosophy

The most comprehensive work about embodiment in HCI is Dourish's "Where the Action Is" monography [10]. Here 'embodiment' takes a very general meaning drawing from multiple philosophical currents that applies, not only to objects or people, but also to phenomena in its most general sense. We do not aspire to quantify this general meaning of embodiment or enter into the phenomenological discussion, but we can still use one of his more restrictive definitions of embodiment: "Embodiment means possessing and acting through a physical manifestation in the world" [10, p. 100]. Our work therefore applies to the relationship between information and physical objects that Dourish also discusses with respect to tangible computing in his Chapter 2 [10,37]. For our limited purposes, an object can be embodied in at least two different ways: through a physical presence (physical embodiment) or through a visual representation in a display (visual embodiment). Although we focus on the embodiment of objects, the HCI literature has also discussed embodiment of people, for example, when represented in the virtual world [2], or when parts of their bodies are extended into displays [27,36].

Embodiment in Psychology

According to Arzy and colleagues [1], embodiment is the innate ability to perceive the localization of one's body within one's body outlines. This property is often extended beyond the body and includes other physical objects in contact with our body, such as clothes, tools, or prosthetic limbs. De Vignemont [38] posits that an object becomes embodied only when its properties are processed in the same way as one's body or, in other words, when an object becomes part of our body schema [17]. There are multiple studies that test variants of how embodied an object is in this sense. For example, several studies have measured that using a tool extends one's own 'personal space' [7,24], and that the length of one's arm is overestimated after using a prosthesis or a grasping tool [7,26]. The famous 'rubber hand' illusion also illustrates how people can be made to believe that an artificial object is part of one's body, both by using tactile [4] and purely visual stimulation [11].

Although the haptic and limbic systems are mostly credited with maintaining the sense of proprioception, it is remarkable that visual manipulations such as the rubber hand illusion [11], or the mere lack of visual feedback [20] can produce systematic distortions in proprioception. From these phenomena we could therefore conceive of the possibility that embodiment is created, not only through the haptic properties of its physicality, but also through visual representations. Perhaps visuals and simpler tactual experiences (e.g., those from touch screens) could be perceptually equivalent to physical embodiment.

To see if this is possible we took a perceptual approach to embodiment: if we can find a measurable perceptual phenomenon that appears with physical objects and not with virtual ones, we could assert that these two embodiment modalities have different psychophysical effects. This would be a step in decoding the fundamental differences between interaction paradigms based on physicality, haptics, and visuals.

After searching the literature for an adequate effect and following several false starts, we decided to investigate Kinesthetic Figural After Effects (KFAE).

Figural After Effect

The phenomenon of figural after effects (FAE) was first discovered by the great visual perception pioneer James J. Gibson and refers to alterations of the perception of certain visual patterns after seeing other patterns [12,13,14]. FAE refers mostly to the visual effects of visual patterns; however, following Gibson's work, Kohler and Dinnerstein [22] conducted several experiments to observe the after effect in touch, which we refer to as Kinesthetic Figural After Effects (KFAE). Participants were blindfolded and instructed to hold a long cardboard piece between their thumb and fingers and run their hand alongside it for some time. Then they were asked to report the width of a different (wider or narrower) test cardboard piece by touch. Kohler found that people overestimated the testing object if it was the narrower test cardboard and underestimated the wider test cardboard. This over- and underestimation did not take place for a control group who never touched the initial object in the first place, providing evidence that the touch of a previous object affects subsequent touches.

FAE is a very reliable phenomenon, and it has since been replicated many times [8,16,31] and used to correlate with and validate a wide range of psychological phenomena, including pain resistance [29], gender differences [30] and personality variables [21]. We make use of this reliable phenomenon in our comparisons of interaction with physical and virtual (i.e., on-screen, multi-touch) artefacts.

STUDYING EMBODIED INTERACTION

While there is an abundance of literature in psychology that explores the idea of embodiment, we focused our attention on the kinesthetic figural after effect for several reasons. First, this effect suggests a psychophysical response from direct interaction with physical artifacts. Thus, it seems in line with the notion in existing HCI literature, since, if we argue that direct interaction can make virtual objects seem more physical, we should expect them to have similar effects on human perception. Second, the FAE phenomenon is linked to touching objects, which is something that we can reproduce with hands and fingers on a multi-touch device. Third, we experimented with a variety of alternatives from the literature, and had little success reproducing effects from the published work. The FAE experiment has been reproduced in the literature many times, and our pilot studies revealed we could indeed reproduce these results.

Thus, in order to begin to understand the effects of direct touch interaction on one's physiology, we ran a pair of experiments. The first experiment's purpose was to confirm that we could reproduce the FAE phenomenon from previous work and provide a baseline measure for the effect. In the second experiment, we replicated the physical setup of the first study as closely as we could using a digital table and a virtual object in place of the physical table and physical object, in order to determine whether this effect transferred to the digital space.

EXPERIMENT 1: VERIFYING FIGURAL AFTER EFFECTS

In this study, we adopted procedures from Petrie [29], with some modifications, to verify that we could reproduce the figural after effect found in previous work. The essence of the experiment is the same as in Kohler and Dinnerstein's study [22] described before: we asked participants to estimate the width of wooden blocks with and without a previous exploration of another physical block. The expected result was that being primed with this exploration would result in different perceived widths than not being exposed.

Participants

Nineteen right-handed participants (6 female) between the ages of 22 and 37 (*Mdn* = 26) participated in this experiment. Participants were recruited from on-campus graduate mailing lists, and paid with $10 gift certificates to a local coffee establishment.

Task and Procedure

The study involved an interleaving of two phase types: *inspection phases* and *measurement phases*. In inspection phases, participants were asked to tactually explore a physical block of wood. The expectation was that this inspection would lead to perceptual changes over time. In the measurement phase, participants were asked to determine the width of a physical block of different size, having either been primed with an inspection phase, or not. The expectation in this phase was that their measurement of the block would be biased by the inspection phase. The order of trials was as shown in Figure 1.

R	M	I_{90}	M	I_{90}	M	I_{120}	M	R	M	I_{90}	M	I_{90}	M	I_{120}	M
Condition 1								Condition 2							

Figure 1. Each participant performed this trial sequence. R = rest, M = measurement, I_x = x-second inspection.

Rest Period (R). After the participant was seated and blindfolded, they were asked to keep their hand in an upward position, wherever it was comfortable for them to keep for ten minutes. They repeated this rest period before the second condition and block of trials.

Inspection Phase (I). In this phase, participants were given a specific time to inspect the object through touch. During this time, participants were instructed to move their left hand and feel the full length of a long block (the inspection block, see Figure 2) laid parallel to the long straight end of semi-circular table. The right hand was not used in this phase and participants were asked to hold their hand comfortably, without touching anything else with their fingers. To feel the full length of the block they needed to walk back and forth parallel to the length of the table.

As shown in Figure 1, inspection phases occurred after the first measurement phase and before each subsequent measurement phase. The first measurement phase was therefore always free from the influence of an inspection phase. The time allowed for inspecting the object was 90 s for the first inspection phase, 90 s for the second, and 120 s for the last phase. Participants were blindfolded.

Measurement Phase (M). In this phase participants were still blindfolded and were asked to compare the test block—a wooden block similar to the inspection block of the inspection phase but with a different width—to a measuring block. The measuring block, unlike the inspection and test blocks has different widths along its length (notches), which change width gradually in steps (see details in the Apparatus section), and is laid on a symmetrical table to the participants' right. Participants move between two tables holding the test block with their left hand and the measuring block with the right (Figure 3). The participant is then asked to walk between the tables (Figure 4), sliding their fingers along both the test block and the measuring block until they feel that the widths of both sides are equivalent.

Figure 2. The 3 cm (top) and 7 cm (bottom) blocks used in the inspection phase.

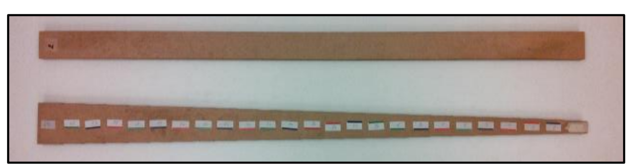
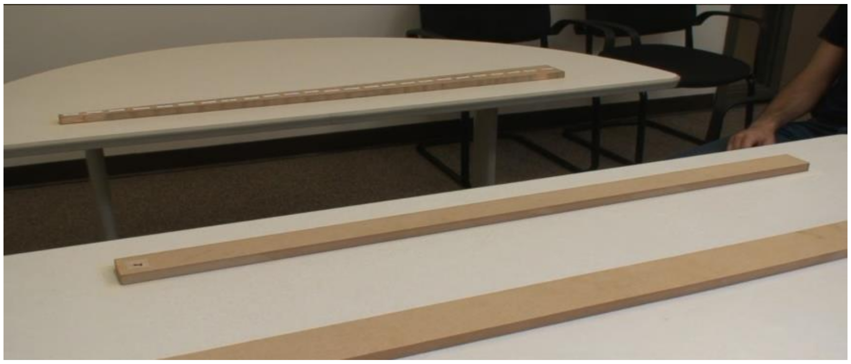


Figure 3. The 5 cm (top) and notched measuring (bottom) blocks used in the measurement phase.



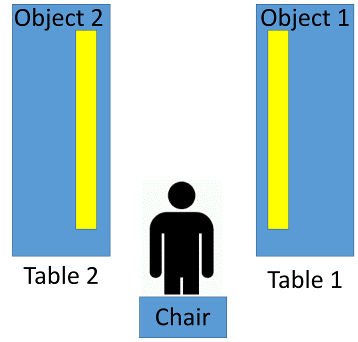


Figure 4. The setup in Experiment 1. Participants inspected blocks on their left (left image: near table) and measured the block with the measurement tool on their right (left image: far table).

Each measurement phase took between 300 s and 450 s. Because participants were blindfolded, the experimenter helped them to start a trial by standing up with their hand held in an upward position, in order not to touch anything with their fingers. The investigator then took the participant's left hand and placed it on the test block, and then their right hand holding onto the measuring block. Participants were instructed to feel the full length of both blocks (which required walking from one end of the tables to the other) using exclusively their thumb and index finger before settling on a judgment (a particular notch). For each trial, the participant provided the estimated width four times. After settling on a particular notch in the measurement device, participants had to again feel the full length of the block and make another judgment for a total of four measurements per phase. This was done to increase the reliability of the measurements.

As shown in Figure 1, there were four measurement phases in each condition, the first being the control, with three following inspection phases. Participants performed two consecutive blocks of these phases, one with a small inspection block, and one with a large inspection block.

Apparatus

The two parallel tables were placed approximately 55 cm apart to allow participants to move freely between them (Figure 4). A chair was placed at the end of one side of the tables for the rest phases. The tables were 120 cm long on the participant's edge and 77 cm tall.

Inspection and Test Blocks

We used Kohler and Dinnerstein's configuration [22] for our physical blocks, with the exception that our blocks were made from medium-density fiberboard, not cardboard. Two inspections blocks were used with 3 cm and 7 cm widths. The test block used in test phases was always 5cm wide. Each block was 1 m in length and 1 cm tall (Figure 2).

Measuring Block

The measuring block is a notched measuring device that varied in width by an average of 2.22 mm at each notch (Figure 3) starting at 2.28 cm, for 25 notches. After cutting the measuring block we mapped the widths of each step using callipers (Table 2). This was necessary because the manufacturing technology does not allow for extremely precise widths. The distance between each step was 4 cm. The material is smooth enough that participants could not sense irregularities in any of the blocks to use as landmarks. The measuring block was again 1 m long and 1 cm tall, and each step was annotated to allow the experimenter to easily record the width measured by the participant.

Factors and Design

We used a within-participants design and varied only the inspection phase. Specifically, we compared measurements after the inspection of a *small* block (3 cm) to those after the inspection of a *large* block (7 cm). We thus used a 4 (measurement phase) × 2 (size) within-participants design. We counterbalanced the size factor and the distribution of participants was as shown in Table 1.

Participants (N)	Condition 1	Condition 2
10	Small (3cm)	Large (7cm)
9	Large (7cm)	Small (3cm)

Table 1. Participants across conditions in Experiment 1.

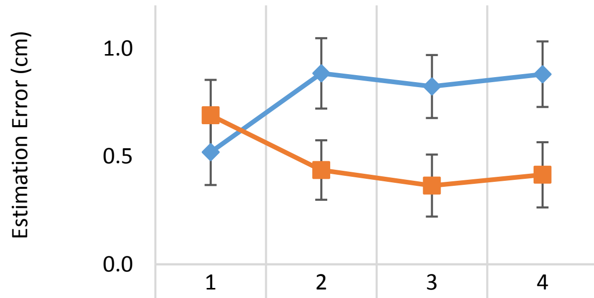
The differences in size between each of the inspection blocks and the test block were the same as what Koehler and Dinnerstein [22] used in their experiment. We thus predicted an overestimation of the test block width after inspecting the small 3 cm wide block, and an underestimation of the test block after inspecting the large 7 cm wide block.

Measures

The measure used was the difference between the recorded size and the actual size (5 cm). Thus, positive values indi-

Notch	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Width (cm)	2.28	2.62	2.85	3.07	3.29	3.52	3.72	4.00	4.25	4.48	4.69	4.89	5.11	5.35	5.55	5.75	5.94	6.16	6.35	6.56	6.75	6.95	7.14	7.40	7.61

Table 2. The measured widths of the notches on the measurement tool, using callipers.



	1	2	3	4
small	0.52	0.89	0.82	0.88
large	0.69	0.44	0.37	0.42

Figure 5. Interaction between size and measurement phase.

cate overestimation, negative values underestimation, and zero a perfectly accurate measurement.

Relation to Previous Work

Our study differed from Petrie [24] in the resting period, length of inspection phase, number of measurements taken, use of the wooden blocks instead of cardboard, and different widths of the physical objects. The length of the inspection phase increases to compensate for after effects from measurement phases.

EXPERIMENT 1 RESULTS

A repeated-measures ANOVA with measurement phase and size as within-participants factors and order as a between-participants factor was performed. Bonferroni corrections were used in post-hoc analyses. There was a significant main effect of size ($F_{1,17} = 15.7, p = .001, \eta_p^2 = .48$), with participants estimating higher after small inspections (*M* = 0.78 cm, *SE* = 0.15 cm) than after large inspections (*M* = 0.48 cm, *SE* = 0.14 cm). Note that these means include both the control phase and the subsequent measurements, and are therefore better interpreted as an interaction.

Estimation Compared to Control

There was a significant interaction between size and measurement phase ($F_{3.51} = 11.4, p < .001, \eta_p^2 = .40$). Figure 5 shows that the pattern of over- and underestimation relative to the control (phase 1) was as expected. Pairwise comparisons revealed that, when participants inspected the small block (blue diamonds in Figure 5), their estimation in phase 1 was significantly smaller ($p < .02$) than all three subsequent measurement phases (indicating overestimation). Phases 2-4 were not significantly different from each other ($p > .999$). When participants inspected the large block (orange squares in Figure 5), their estimation in the control phase was not significantly different from the other three phases ($p > .15$), nor were the subsequent three phases significantly different from each other ($p > .84$). Nonetheless, the means in the large condition demonstrate the expected pattern of underestimation relative to the control measurement phase; however, these estimates were unexpectedly overestimates (positive), rather than underestimates.

The main effect of measurement phase was not significant ($F_{3,51} = 0.5, p = .65, \eta_p^2 = .03$). There was also no significant interaction between size and order ($F_{1,17} = 0.2, p = .68, \eta_p^2 = .01$), nor between size, block, and order ($F_{3,51} = 1.8, p = .17, \eta_p^2 = .09$).

Order Effect and Between-Participants Analysis

There was a main effect of order ($F_{1,17} = 8.5$, $p = .01$, $\eta_p^2 = .33$), with participants inspecting small blocks first measuring blocks in all conditions higher (*M* = 1.02 cm, *SE* = 0.19 cm) and participants inspecting large blocks first measuring blocks in all conditions lower (*M* = 0.23 cm, *SE* = 0.20 cm). This order effect suggests that thechanges that resulted from inspection in the first condition may have carried over to the second.

We thus performed a second repeated-measures ANOVA with size as a between-participants factor (discarding data from the second condition) and measurement phase as a within-participants factor. This analysis revealed the same significant effect of size ($F_{1,17} = 17.4, p = .001, \eta_p^2 = .51$) and significant interaction between size and measurement phase ($F_{3.51} = 6.4, p = .001, \eta_p^2 = .27$). Though, with significantly reduced power, the post-hoc comparisons only revealed significant differences between the control phase and the second phase ($p = .04$) for the participants who inspected small blocks, with all other pairwise differences being not significant ($p > .08$). The main effect of measurement phase was again not significant ($F_{3,51} = 1.2, p = .31, \eta_p^2 = .07$).

EXPERIMENT 1 DISCUSSION

The results of this study show that the figural after effect can be reproduced, but that this effect was more easily reproduced with a small inspection phase leading to overestimations. Specifically, we found that the pattern of overestimation was as predicted for small block inspection, with size estimation prior to this inspection being more accurate than after inspection, and estimates after inspection being significantly higher than this baseline. Additionally, we also identified an order effect that suggests that inspections in the first part of the experiment may impact estimations in the second, despite participants having a rest period in between these conditions. Thus, a between-participants design may be more appropriate for this type of study.

The results of this study were used for two purposes. First, we got assurance that the chosen effect was reproducible with our own setup. Although this might seem trivial, we recommend HCI researchers to take this approach first, since not all phenomena from the psychology literature is equally easy to reproduce, and sometimes the modifications required to test it for an HCI application can make the effect disappear. Second, the results directly informed the design of the second study, which involved a comparison of this physical phenomenon to the inspection of physical blocks without blindfolding participants and virtual blocks on a multi-touch table. For example, due to the effect being

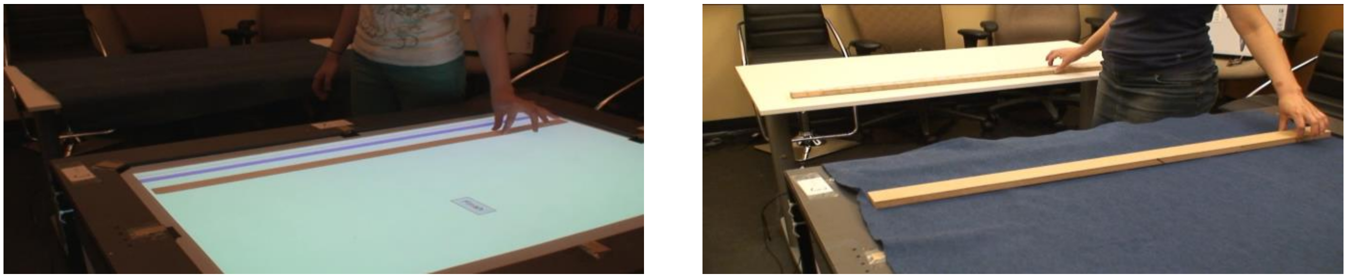


Figure 6. The setup in experiment 2. Participants inspected blocks on their left (near table in the image) and measured block with the measurement tool on their right (far table).

more obvious for the small blocks, we decided to only test small blocks in the second experiment. Although we expected that a within-participants design may again lead to cross-over effects in the second phase, we opted to again use a within-participants design, as the collection of this data was straightforward, and a between-participants analysis was still possible by discarding data from the second half of the study.

EXPERIMENT 2: PHYSICAL VS. VIRTUAL

The second experiment approximately replicated the physical setup of Experiment 1 using a digital table and a virtual object instead of the physical table and the physical object. Note that, in the studies that we modelled Experiment 1 after, participants were blindfolded. Since interaction on a multi-touch screen would not provide awareness of a virtual object without the visual sense, we also used our second study to verify that figural after effects would occur when participants were not blindfolded in the inspection phase of the procedure.

Participants

Twenty-one participants (12 female) between the ages of 21 and 28 (*Mdn* = 24), 17 of whom were right-handed, participated in this experiment. Participants were recruited and paid as in Experiment 1. All except one were naive to the experiment, as this one participant had taken part in the first. Due to the time period between the two experiments (6 weeks) and the low-level nature of the effects being measured, we chose to include this participant's data in our analysis, and don't believe that it impacted the results.

Task and Procedure

The task and procedure used in this experiment mirror exactly what was done in Experiment 1, with the following exceptions. In the inspection phase, instead of varying the size of blocks, we varied whether they were presented in the physical world (i.e., as in Experiment 1) or on a digital table. The inspection phase *(I)* with the physical block mimics Experiment 1 with the difference that participants were not blindfolded and were instructed to look at the object repeatedly when necessary. The inspection phase *(I)* with the virtual object was performed in the same manner (participants were not blind folded). The reason that the inspection phases were not blindfolded is to reproduce situations in the physical world, where objects are simultaneously grasped and seen. Additionally, it would not be possible for people to perceive the virtual blocks without the visual sense. Although this represents a departure from previous studies, in which participants were blindfolded throughout the whole experiment, it is still a valid manipulation, because both conditions included the visual sense, and provides a more ecologically valid task. Participants were still blindfolded in the measurement phase *(M)*, which was thus identical to Experiment 1.

Apparatus

The distance between tables in the second experiment was again 55 cm. However, the dimensions of the table were slightly different at 120 cm long, 80 cm wide, and 88 cm tall. In the second experiment, one of the two tables was a multi-touch digital table (Figure 6), so that the inspection phase could be done with virtual objects. We used a 1920 × 1080 pixel rear-projected screen that could detect touches by detecting reflections from diffuse laser infrared illumination, with a Sony PS3 camera. Camera data were processed using CCV and sent using the TUIO protocol to a Java program described below. In the physical condition in the second experiment, the table was covered with cloth.

Virtual Inspection Block

Only one virtual object was used that mimics the 3 cm physical block. The object was developed in Processing [33] and presented on the laser table. The virtual block was designed to appear with the same length (1 m) and width (1 cm) as the 3 cm long inspection block that we used in the Experiment 1, and in the other condition of this experiment. Participants were asked to not touch anything on the touch table except the digital block and were shown a 3D representation of the block before starting the inspection (Figure 8). The investigator was able to rotate the block on its long

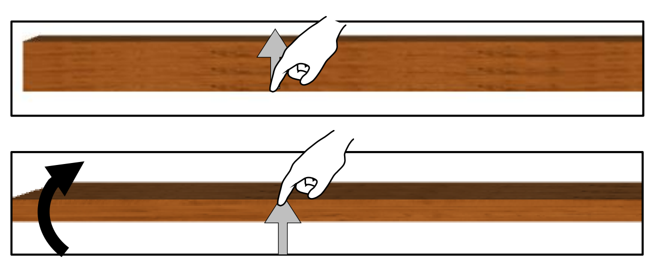


Figure 7. A screen capture of one end of the virtual block before (top) and after (bottom) rotation. The experimenter rotated the block before inspection phases to show its 3D shape.

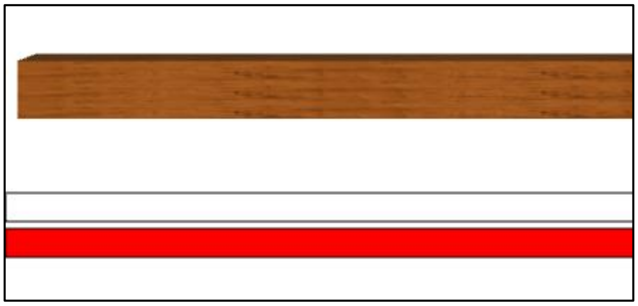


Figure 8. A screen capture of one end of the virtual block during the inspection phase. The bottom red bar indicates that the participant is not touching both sides of the block. This switches to the top bar turning blue when they are.

axis to show participants the edges of the block; this was important because participants were not able to rotate the block themselves. Visual feedback was provided through two lines: a *blue* line indicated that the object was being "held" by the participant for the inspection, otherwise an adjacent *red* line was visible (Figure 8). These lines were the same length as and separated from the virtual block, so that the visual appearance of the block did not change, and the feedback did not require looking too far from the virtual block itself.

Factors and Design

We again used a within-participants design and varied only the inspection phase. However, in this experiment, we compared measurements after the inspection of a small *physical* block (3 cm) to those after the inspection of a small *digital* block (also 3 cm). We thus used a 4 (measurement phase) × 2 (interaction type) within-participants design. We counterbalanced interaction type and the distribution of participants was as shown in Table 3.

Participants (N)	Condition 1	Condition 2
11	Physical (3cm)	Virtual (3cm)
10	Virtual (3cm)	Physical (3cm)

Table 3. Participants across conditions in Experiment 2.

We expected again to see an overestimation of width after inspection of small physical blocks. We hoped to also answer two questions: would looking at the object during the inspection period result in a KFAE, and would the virtual object reproduce the same error in judgment after inspecting it?

EXPERIMENT 2 RESULTS

A repeated-measures ANOVA with measurement phase and interaction type as within-participants factors and order as a between-participants factor was performed. Bonferroni corrections were again used in post-hoc analyses. The main effect of interaction type was not significant ($F_{1,19} = 0.3, p = .57, \eta_p^2 = .02$), nor was the interaction between interaction type and measurement phase ($F_{3,57} = 2.3$, $p = .08$, $\eta_p^2 = .11$). There was a significant main effect of measurement phase ($F_{3,57} = 4.5$, $p = .01$, $\eta_p^2 = .19$); however, post-hoc analyses did not reveal any pairwise significant differences between these phases ($p > .13$).

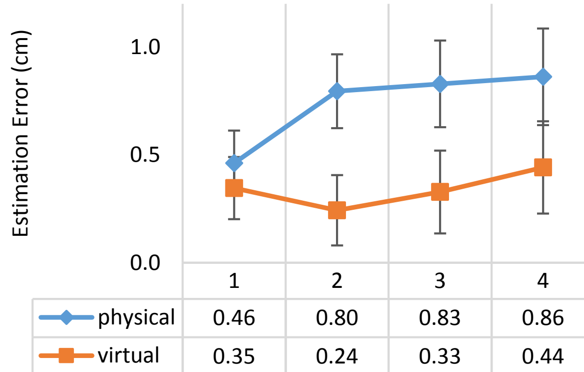


Figure 9. Interaction between interaction type and measurement phase.

Order Effect

There was, however, a significant interaction between order and interaction type ($F_{1,19} = 8.6$, $p = .01$, $\eta_p^2 = .31$). Post-hoc pairwise comparisons revealed that, in the virtual condition, participants who inspected virtual blocks in the first phase estimated more accurately (M = 0.34 cm, SE = 0.17 cm) than when they had already inspected physical blocks (M = 0.87 cm, SE = 0.18 cm), and this difference was significant (p = .046). Participants overestimated when inspecting physical blocks, and the order did not significantly affect this overestimation (p = .41). Thus, again, the overestimation due to physical block inspection may have carried over into the virtual condition.

Between-Participants Analysis

Thus, we again performed a second ANOVA of only the first phase of the study, with interaction type as a between-participants measure, and measurement phase as a within-participants factor. This analysis revealed a main effect of measurement phase ($F_{3,57} = 3.8$, $p = .02$, $\eta_p^2 = .17$), but again, post-hoc comparisons revealed no pairwise significant differences between measurement phases ($p > .09$).

However, there was a significant interaction between measurement phase and interaction type ($F_{3,57} = 3.3$, $p = .03$, $\eta_p^2 = .15$). Figure 9 shows that the pattern of overestimation relative to the control (phase 1) was as expected for the physical block, and mirrored results from Experiment 1, but did not appear to manifest for the virtual condition. Pairwise comparisons revealed that, in the physical condition, the control phase (phase 1) was significantly smaller than phase 2 (p = .04) and phase 4 (p = .049), and marginally smaller than phase 3 (p = .051), and that phases 2-4 were not significantly different from each other (p > .999). For the virtual condition, no pairwise differences between measurement phases were significant (p > .26).

EXPERIMENT 2 DISCUSSION

The results of this second experiment reveal that the kinesthetic figural after effect from the physical condition does not manifest in the virtual environment. Specifically, while the inspection of physical blocks again led to overestimation in measurement phases 2-4, this same overestimation did not occur after inspection of virtual blocks, and instead resulted in very close to accurate estimations.

We must highlight that the KFAE was present for the physical condition even though in Experiment 2, unlike in Experiment 1, the task was bimodal (visual in addition tactual). This demonstrates that the tactual aspect can have an effect for tasks that include a visual component.

DISCUSSION

The results of the experiments above show that the kinesthetic figural after effects, a psychophysical phenomenon that has been replicated multiple times in the context of the perception of tactual physical objects by psychologists, does not appear (or is attenuated to be too small to measure) when the grasping of the physical object is replaced by its equivalent in a multi-touch interface. In this section, we discuss the implications of this finding for the design of interfaces and for further research in psychophysics, as well as the methodological contributions of our studies, their limitations, and future directions of research that follow from our findings.

Implications for HCI and Interface Design

The results of our experiments show that there is at least one fundamental difference between the experiences of touching a physical object and interacting with a similar virtual object through a multi-touch interface. Because this effect takes place at a basic perceptual level, it will likely be consistent across many situations and most people. In essence, this provides quantitative empirical evidence that the tangible interfaces paradigm [37] and the multi-touch interfaces paradigm [6] (each represented by the two conditions of Experiment 2) are fundamentally different from each other—the two combinations of embodiments provided by the two paradigms are not perceptually equivalent.

At the very least, interaction designers should be cautious to assume, for example, that an interface implemented with tangibles (e.g., [19]), is going to have the same impact as a similar interface implemented within the limits of a multi-touch interface [34]. A designer of touch screen interfaces should consider that interactions in the physical world will have different psychophysical responses, and the act of touching a screen may not be sufficient to provide the physical-like response we may expect.

Because perceptual processes underlie and modulate motor control (e.g., [25]) this could be a source of differences at higher levels of interaction, which in turn can have practical relevance to HCI and interaction/experience design. For example, basic perceptual differences could result in differences in motor and semantic memory, or even emotional effects of interacting with artifacts. Although we are still far from being able to provide solid empirical evidence (and what follows is mostly speculative), our experiments might be a first step towards explaining, for example, the anecdotally reported preference of many people for physical books against e-books because of "how they feel in the hand", or the initial findings reporting that paper documents have different memorability than digital documents [28].

There is, however, a practical implication for the design of interfaces that can already be derived from our study. Since the KFAE represents a distortion of our actual perception of objects, interfaces that require or can benefit from accurate perception of the dimensions of 3D objects (e.g., CAD applications) might benefit from the KFAE-free perceptions with a multi-touch interface.

Implications for Psychology

To our knowledge, the experiments reported in this paper are the first to show that the KFAE can be present in tasks that include a visual component. This is relevant for two reasons. First, it contributes to the body of knowledge in multi-modal perceptual effects and how different modalities integrate and compete with each other, showing that, unlike in other cases (see Arzy et al. [39]), the visual aspects of the task do not necessarily override other senses completely (in this case, the tactual).

Second, because the KFAE still appears when visual information of the task is available, this makes the previous literature in KFAE relevant to a wider set of practical situations that are far more common than tactile-only ones. Assuming that the KFAE is strictly tactual and will not appear in the presence of visual information seems to unnecessarily constrain its relevance to people with severe visual impairments or for scenarios where visual attention needs to be engaged elsewhere (e.g., drivers and pilots).

Methodological Implications for HCI

The results that we report above are a small but important step towards a better understanding of the differences between different interaction paradigms. We believe that it is important to uncover the foundations of existing interactive paradigms to be able to explain their differences and to predict in which circumstances to best apply them (or not), but also to find new paradigms. To do this we cannot ignore previous knowledge from disciplines like psychology that, although usually less applied than HCI, provide a rich set of methodologies, results, and understanding that are applicable to interaction and its problems. Our approach is similar to other efforts in related areas, such as the efforts to quantify presence in terms of its measurable physiological side effects [35], or suggested new ways to quantify agency [9].

Using effects or illusions to measure and differentiate conditions is not uncommon in the psychology literature, and we believe that, although laborious and indirect, it might provide the key to other constructs important for HCI.

In addition, we think that preliminary replication of previous psychology studies should be a separate first step for HCI research of this kind. We have a few years' (unpublished) experience in investigating candidate phenomena, and would like to encourage researchers to replicate first, and not to assume that effects shown in studies from psychology will be reliable or reproducible in conditions that are relevant for HCI scenarios. This replication-first approach has the potential to save researchers much time in two ways: it can expose early which effects or illusions are likely to lead to fruitful research in HCI contexts, and it will allow researchers to tune the experiment and reduce sources of experimental noise before the HCI-relevant experiment is executed—most experiments will need to be somewhat tweaked before they can be applicable to HCI questions.

Limitations and Future Work

Our study looks at the comparison of only two of multiple types of object embodiment. There are multiple other types of embodiment (e.g., binocular, haptic) that correspond to other interaction paradigms (VR, augmented reality, assistive technologies) and are worth exploring.

Additionally, although we have provided some of the first quantitative evidence of differences in our perception of the embodiments supported by physical vs. virtual artefacts, further experiments are required to eliminate alternative hypotheses of the causes of the differences observed, even when considering exclusively the two interaction paradigms that we have compared (tangible and multi-touch). Research into virtual embodiment is by no means complete, and it is likely that other after effects or psychophysical measures would manifest differently.

In the future, we intend to explore other configurations of virtual representations of objects, including virtual objects rendered with a physics engine and objects that can be further manipulated (e.g., moved and rotated) through the inspection phase.

CONCLUSION

In this paper, we have presented a sequence of studies that first verifies the existence of psychophysical changes that result from handling physical artefacts (specifically, a figural after effect), and then show that these changes do not manifest in the virtual world. We discuss the implications of this finding to our understanding of multi-touch interaction and its ability to provide embodied interaction with virtual artefacts on a large display—we provide some of the first evidence that suggests that the psychophysical effect of interacting with virtual artefacts is different than interaction with physical objects, despite the ability to directly interact similarly with both. We also highlight the potential benefit that digital interfaces can provide as a mechanism for interacting with precise information, without biasing our perceptions of the world. We expect this study can provide a small piece of a larger understanding of the role of embodied interaction through multi-touch devices.

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