Understanding Visual Feedback in Large-Display Touchless Interactions: An Exploratory Study

Debaleena Chattopadhyay* & Davide Bolchini

To cite this version:

Chattopadhyay, D., & Bolchini, D. (2014). Understanding Visual Feedback in Large-Display Touchless Interactions: An Exploratory Study. [Research Report] IUPUI Scholar Works, Indiana University.

Submitted on November 3, 2014 – p. 1- 26

***Correspondence:**
Debaleena Chattopadhyay
School of Informatics and Computing, Indiana University
535 West Michigan Street, Indianapolis, IN 46202 USA
debchatt@iupui.edu

Acknowledgements: We would like to thank our study participants for their time and feedback, Wei Pan, who assisted in data collection for the experimental study, and UITS AVL for the use of their facilities. This work was partially supported by an IUPUI Research Support Funds Grant (RSFG).

Understanding Visual Feedback in Large-Display Touchless Interactions: An Exploratory Study

Debaleena Chattopadhyay & Davide Bolchini

Abstract: Touchless interactions synthesize input and output from physically disconnected motor and display spaces without any haptic feedback. In the absence of any haptic feedback, touchless interactions primarily rely on visual cues, but properties of visual feedback remain unexplored. This paper systematically investigates how large-display touchless interactions are affected by (1) types of visual feedback—discrete, partial, and continuous; (2) alternative forms of touchless cursors; (3) approaches to visualize target-selection; and (4) persistent visual cues to support out-of-range and drag-and-drop gestures. Results suggest that continuous was more effective than partial visual feedback; users disliked opaque cursors, and efficiency did not increase when cursors were larger than display artifacts' size. Semantic visual feedback located at the display border improved users' efficiency to return within the display range; however, the path of movement echoed in drag-and-drop operations decreased efficiency. Our findings contribute key ingredients to design suitable visual feedback for large-display touchless environments.

Keywords: visual feedback; touchless interaction; large displays; visuomotor transformation

1. Introduction

Touchless interfaces can foster device-less interaction at different distances from a display, thus becoming crucial for “beyond the desktop” large-display environments. Touchless gestures relieve users from acquiring and interacting with an additional *medium* (such as a tablet or a smartphone)—while supporting intermittent and spontaneous interactions. For example, large-display touchless interactions are particularly suitable in the absence of an interaction device (such as community spaces, Valkanova, Walter, Vande Moere, & Müller, 2014), in sterile environments (such as surgery rooms, O'Hara et al., 2014), in browsing multimedia information (such as interactive TVs, Morris, 2012), or in collaborative brainstorming (such as information visualization, Dostal, Hinrichs, Kristensson, & Quigley, 2014).

In spite of the abundant enthusiasm about more “natural” forms of interaction, the lack of feedback in touchless scenarios raises important usability concerns (Nancel, Wagner, Pietriga, Chapuis, & Mackay, 2011; Norman, 2010). In fact, unlike the mouse or touch-based interactions, touchless synthesizes input and output from physically disconnected motor and display spaces, and without any haptic feedback. This lack of haptic guidance reduces users’ efficiency and effectiveness, because users are excessively dependent on other forms of sensory feedback, such as visual, auditory, or proprioception (Nancel et al., 2011; Markussen, Jakobsen, & Hornbæk, 2014). Researchers have tried to compensate this lack of haptic feedback using visual and auditory feedback (Vogel & Balakrishnan, 2005; Kajastila & Lokki, 2013), or tactile feedback (Gupta, Morris, Patel, & Tan, 2013; Sodhi, Poupyrev, Glisson, & Israr, 2013). Specifically, visual feedback has been used to improve the learnability of touchless gestures (Walter, Bailly, & Müller, 2013), to identify multiple users (O'Hara et al., 2014), to communicate gesture ambiguity (Vogel & Balakrishnan, 2005), and to represent clicking and swiping gestures (Vogel & Balakrishnan, 2005; Markussen et al., 2014). Although visual feedback is being actively used in touchless interaction, a systematic exploration of its properties still remains unexplored.

Visual feedback in touchless interactions should guide users’ movement effectively. It should also be salient among an array of artifacts on a large display. The role of visual feedback in acquiring and learning movements has been extensively studied in human motor science (Saunders & Knill, 2004; Sigrist, Rauter, Riener, & Wolf, 2013). Similarly, attributes of display artifacts have been widely explored in the visual search literature (Wolfe, 1998; Wolfe & Horowitz, 2004). But these findings have not been significantly adopted to guide the design of visual feedback in touchless interactions. Designers simply consider representing users’ position and their actions: “where the user is” (e.g., with an open hand) and “what the user is doing” (e.g., a grab posture). To help users learn, retain, and perform touchless gestures effectively, we are faced with the challenge of designing visual feedback as a salient yet non-distracting aide.

The main contribution of this paper is to explore visual feedback in large-display touchless interactions—using six controlled experiments—along four aspects: (1) types of visual feedback; (2) alternative forms of touchless cursors; (3) alternative approaches to visualize target-selection; and (4) persistent visual feedback for two common user actions: *drag-and-drop* and when users *land out of the display range*. Our approach to explore visual feedback is informed by the motor science and the visual perception literature. A successful design of visual feedback have the potential to augment users’ proprioception, and somewhat compensate the lack of haptic feedback in touchless interactions. Our work makes the following contribution:

- We discuss related work about visual feedback from the motor science and the visual perception literature—such as timing, attributes, and semantics—that can inform future research on designing appropriate visual feedback for different touchless interactions (sections 2.3, 2.4).

- We provide empirical results from six controlled experiments that explore types of visual feedback, shape, size, color and opacity of touchless cursors, different approaches to visualize target selection, and persistent visual feedback in touchless interactions (section 3).
- Grounded in our empirical results, we provide practical guidelines for designing visual feedback in large-display touchless environments (section 4). Finally, we illustrate our guidelines by designing a visual feedback routine for drag-and-drop operations across a touchless system's three interaction states—idle, active, and engaged.

How visual perception regulates attention and controls movement is complex and being extensively studied. Still, our work is a first step toward adopting some existing results and rethinking the design of visual feedback in touchless interactions. Our findings can facilitate the development of a visual feedback language for large-display touchless interfaces.

2. Related Work

Our work builds upon three research areas: large-display touchless interactions, the role of visual feedback in motor responses, and visual attributes guiding attention.

2.1. Large-Display Touchless Interactions

Large displays are being extensively built, deployed and evaluated in HCI settings (surveyed in Ni et al., 2006). They have been found to improve task productivity (Czerwinski et al., 2003), spatial performance (Tan, Gergle, Scupelli, & Pausch, 2006), collaborative sensemaking (Vogt et al., 2011), difficult data manipulation (Liu, Chapuis, Beaudouin-Lafon, Lecolinet, & Mackay, 2014), collocated brainstorming (Bragdon, DeLine, Hinckley, & Morris, 2011), and 'beyond the desktop' visualization (Dostal et al., 2014). Real-world deployments have also shown the potential of large displays for collaborating in multi-user environments (Jagodic, Renambot, Johnson, Leigh, & Deshpande, 2011) and interacting with large datasets (Beaudouin-Lafon et al., 2012). To interact up and close with large displays, multitouch interactions have been investigated (Jakobsen, & HornbÆk, 2014); to interact from a distance, both device-based (Nancel et al., 2013) and device-less interaction techniques have been studied (Bailly, Walter, Müller, Ning, & Lecolinet, 2011; Chattopadhyay & Bolchini, 2014). Empirical studies have shown that due to the lack of haptic guidance, device-less touchless gestures are less efficient and more fatiguing than device-based gestures (Nancel et al., 2011). However, in the absence of any interacting device, touchless interaction with large displays becomes suitable for certain scenarios. For example:

- *Public spaces*: Users in public spaces, such as airports, shopping malls, or urban streets, interact with large displays for a brief amount of time; they may not spend the time and the effort required to connect to an intermediate device (Walter et al., 2013; Valkanova et al., 2014).
- *Surgery*: Surgeons need to browse and manipulate images in sterile operating rooms; touchless interactions provide them direct control without the assistance of an intermediary nurse (O'Hara et al., 2014).
- *Consumer Electronics*: Touchless interactions can support the sporadic browsing of multimedia in interactive televisions (Bailly et al., 2011; Morris, 2012), or facilitate interaction with omni-directional videos (Rovelo Ruiz, Vanacken, Luyten, Abad, & Camahort, 2014).

- *Brainstorming and visualization*: During co-located collaboration—when users co-share a central display—touchless gestures can support interaction from different distances; thus allowing unrestricted physical navigation (Bragdon et al., 2011; Dostal et al., 2014).

2.2. Visual Feedback in Motor Responses

Visual feedback plays a twofold role in motor responses: motor control and motor learning. Hence the impact of visual feedback on movement is widely studied in rehabilitation, sports training, and minimally invasive surgery. Two aspects that mediate the role of visual feedback in motor responses are task complexity and feedback visualization.

2.2.1. Motor control. While proprioception estimates the initial body posture and selects a motor command, pointing movements are continually corrected by the visual feedback of the hand (Scheidt, Conditt, Secco, & Mussa-Ivaldi, 2005). Processing of visual feedback while pointing movements can be quire short (e.g., 100 ms, Zelaznik et al., 1983), and thus facilitate the accuracy of rapid movements. In dynamic environments, where closed-loop control (sensory feedback of the users' action) is possible, visual feedback informing motion pattern and position coordinates significantly affects hand movements—in both early and later stages of the movement (Saunders & Knill, 2004).

2.2.2. Motor learning. In any desktop environment, transfer functions (or gain factors) define how amplitudes of hand and cursor movements relate to each other; these are a type of visuomotor transformation that we can easily master due to our sensorimotor abilities (Verwey & Heuer, 2007). In general, when users need to retain mastery of visuomotor transformations, the type of visual feedback during the practice plays a key role: While terminal visual feedback (at the end of the movement) facilitates simple tasks, such as aiming movements using a mouse, continuous visual feedback helps complex tasks, such as inter-limb coordination skills (Sülzenbrück, 2012; Sigrist et al., 2013). Even the frequency of visual feedback—when decreased with decreasing task complexity—further facilitates motor learning. Touchless interactions in large-display environments range from bimanual gestures for data manipulation to static gestures for mode switching. Visual feedback, if appropriately used, can augment learnability of such visuomotor transformations.

2.2.3. Visualization. Visual feedback designs are effective when they enable parallel processing of the visual and the kinesthetic information about the ongoing movement (Sigrist et al., 2013). In motor learning, they range from abstract (lines, bars, curves, Lissajous figures) to natural visualizations (virtual avatars, 3D animations). Studies indicate that it is very important to provide feedback about only the relevant key features of the task (Huegel, Celik, Israr, & O'Malley, 2009). While it is common to provide user information in large-display touchless interactions using a skeleton representation, rethinking our visual feedback designs may facilitate user performance.

2.3. Visual Attributes Guiding Attention

Design-dimensions of display artifacts have been widely explored in visual search literature (Smith and Thomas, 1964; Wolfe, 1998; Wolfe & Horowitz, 2004). But these findings have not been significantly adopted to guide the design of visual feedback in touchless interactions. For example, research suggests that color coding leads to efficient visual search (Carter, 1982), but in a dense display efficiency is retained only if the distractors and the targets are widely separated in color space (D'Zmura, 1991). Although debatable, the topological property of a "hole" or the number of line terminators are often considered as features that guide attention in visual search (Wolfe & Horowitz, 2004). Relative size of a target item and how densely packed it is (spatial density) compared to other display artifacts also plays a role in guiding attention (Wolfe, 1998). Empirical studies suggest that attention can be efficiently guided to opaque targets among transparent objects, but it is more difficult to find one transparent item among all opaque items. Interestingly, the effect of opacity is explained by the human tendency to combine multiple cues—namely motion, luminance and structural features (Wolfe, Birnkrant, Kunar, & Horowitz, 2005).

With the absence of haptic feedback in touchless interactions, we are faced with the challenge of designing visual feedback that can help users control and learn touchless gestures effectively. Inspired by the role of visual perception in motor responses and visual search, our work is a first step to investigate the effects of visual feedback in large-display touchless interactions.

3. General Method

3.1. Overview

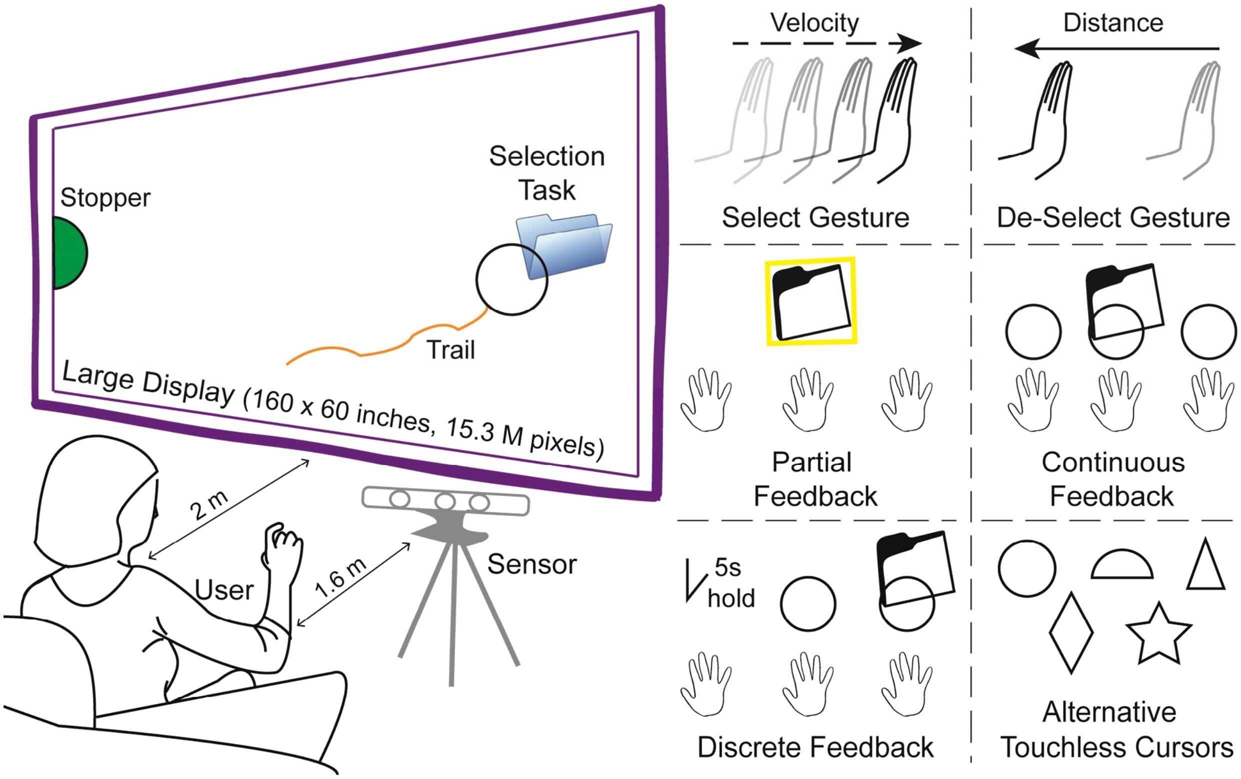


Figure 1. We conducted six controlled experiments to understand how visual feedback affects user experience in large-display touchless interactions. (Left) In our experiment, participants used touchless gestures to select display objects while sitting away from a large display. (Right) They used a velocity-based *select* and a distance-based *de-select* gesture. We evaluated three types of visual feedback (partial, continuous, and discrete) and alternative touchless cursors. (Left) We also designed and evaluated *Stoppers*—semantic visual feedback informing users when they are out of the display range, and *Trail*— persistent visual feedback echoing the path of movement during drag-and-drop operations.

We conducted six within-subject experiments to understand how the following four aspects of visual feedback affect large-display touchless interactions: (1) types of visual feedback (discrete, partial, and continuous); (2) alternative forms of touchless cursors; (3) alternative approaches to visualize *target-selection*; and (4) persistent visual feedback for *drag-and-drop* operation and when users *land out of the display range* (Figure 1). Findings from these empirical studies can facilitate the development of a visual feedback language for future touchless interfaces.

3.2. Apparatus

Our experiments were conducted using a high-resolution large display that comprises of eight 50–inch projection cubes laid out in a 4 x 2 matrix. The large display is driven by a single computer. Each of these

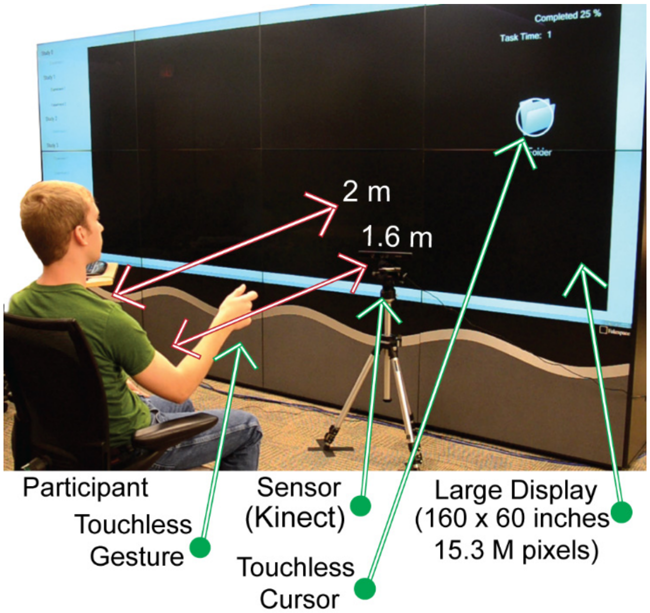


Figure 2. Our experiments were conducted using a 160 x 60 inches large display with a resolution of 15.3 M pixels. We used Microsoft's Kinect sensor for motion tracking, and across all six experiments participants sat in a chair 2 meters away from the large display.

cubes has a 1600 x 1200 pixel resolution, resulting in a 160 inches wide and 60 inches high display with over 15.3 million pixels (Figure 2). For motion tracking, we used a Kinect™ (for Windows) sensor. All experiments were written in C# running on Windows 7, and were implemented with OpenNI 1.4 SDK and PrimeSense's NiTE 1.5 middleware.

3.3. Participants A total of 37 right-handed participants with no color-blindness were recruited from an urban university campus; experiments were conducted in two rounds (December, 2012 and August, 2013). 18 participants (9 females, 13 familiar with touchless gestures) took part in the first five experiments (first round), and 19 participants (8 females, 11 familiar with touchless gestures) took part in the sixth experiment (second round). 15/18 and 15/19 participants were below 30 years of age. Participants were randomly recruited by sending out emails using the university's mailing list. The study was approved by the university's Office of Research Administration (IRB Study No. 1210009814 and 1303010855), and participants were compensated with a $20 gift card for two hours of participation.

3.4. Gesture Primitives

To explore visual feedback in large-display touchless interactions, we designed two gesture primitives: *select* and *de-select*. A select gesture was defined as a forward movement of the hand with a certain velocity (350 mm/s), and a de-select gesture was defined as a backward movement of the hand by a certain distance (100 mm, Figure 1). Using these two gestures, participants performed two basic actions: *point-and-select*— point to an object, select and de-select, and *drag-and-drop*— point to an object, select it, drag it to a specified location, and de-select.

3.5. Procedure

Across all five experiments, participants sat in a chair 2 m away from the large display, and took about two hours to complete all trials. They were situated 1.6 m away from the sensor, and the chair-seat was 53 cm high. The sensor was 89 cm from the ground with a horizontal field of view of 57 degrees, and a vertical field of view of 43 degrees. (In the second round, for experiment 6, participants sat in a couch 2.25 m away from the display and 1 m away from the sensor, and the couch-seat was 44 cm high.) In the XY plane (parallel to the display), hand movements were mapped from real space to display space as 1: 2.4 (when a participant moved 1 cm in real space, the cursor moved 2.4 cm in the display space). Before the experiment, all participants spent about 10 – 15 minutes practicing *select* and *de-select* gestures while solving a picture puzzle on the large display (see Figure A1 in Appendix A). Each block of experiment began by selecting a 'Start' circle. Each trial began with a blue folder appearing on the display with a black background (Figure 2). To successfully complete a trial, participants either performed a point-and-select or a drag-and-drop operation on the folder. Participants were required to take at least a 10–second break in between each block. (For experiments 1 – 4, 20 trials constituted a block.) Trials were recorded using a video camera capturing users' gestures and the display. In the first round, across the five experiments, randomized partial counterbalancing was used to control order effects.

3.6. Measures

User experience was operationalized as efficiency (performance time), effectiveness (selection and de-selection error rates), and user satisfaction (users' ranking of experimental conditions and qualitative comments). We also logged the location where selection and de-selection errors occurred. Time was measured from when a folder (target) appeared on the display to when users successfully selected the folder, or moved the folder to a specified location. To ensure that participants do not spend too long on any particular trial, and could complete the entire experiment, point-and-select trials were skipped after 20 seconds and drag-and-drop trials were skipped after 40 seconds. Data were analyzed only for successfully completed trials.

4. Experiment 1: Different Types of Visual Feedback

In WIMP-based interfaces, the mouse pointer provides visual feedback for two input states—tracking and engaged. In direct-touch paradigm, visual feedback is usually available for the engaged state (e.g., user tapping on an icon, or pinching to zoom). Touchless systems are typically one-state input devices, where users are always being tracked (Wigdor and Wixon, 2011). What kind of visual feedback should be available for touchless interactions? In this experiment we studied three different types of visual feedback—discrete, partial, and continuous (Figure 1). Discrete feedback required users' explicit invocation by holding their hand stationary for 5 seconds in front of the sensor. Once discrete feedback was invoked, the touchless cursor was continually visible on the display. It would disappear after a certain period of user's inactivity. Partial feedback only visualized the target's response to user input, but did not provide any visual feedback otherwise (This condition was inspired by terminal feedback in motor learning). For example, when users' hand hovered over a folder, the folder got highlighted. Though user's hand was continually tracked, no visual feedback was available at any other time. Continuous feedback did not require any explicit invocation. A touchless cursor was always visible as long as the user's hand was within the display range. Overall, continuous feedback operated similar to the mouse pointer, partial feedback operated similar to tapping an on-screen object in touch-based systems, and discrete feedback provided strict user control on the system's behavior.

4.1. Method

The experimental target-selection task was adapted from Fitts' 1D reciprocal task (Fitts, 1954). For each consecutive trial, a folder appeared at a certain amplitude (1100 pixels in display space, 29 cm in control space) left or right of the previous trial position. Experimental conditions were randomly counterbalanced. The size of the white-bordered touchless cursor was equal to the size of the target folder (256 pixels, or 163 mm). In summary, the study design was as followed:

3 types of feedback (condition)
x 4 trials
x 18 participants
= 216 trials

For discrete feedback, participants needed to invoke the touchless cursor for each trial. The invocation time was not considered as part of their performance time. We did not evaluate dismissal of discrete feedback. The time threshold for discrete feedback was informed by our pilot studies. When previous work used lower time-out thresholds (e.g., 1 second) for selection by dwelling (Hespanhol, Tomitsch, Grace, Collins, & Kay, 2012), authors reported that users found it too sensitive, and even after considerable training users could not avoid unintentional triggering. However, we do not argue that our time-out threshold is an optimal choice. We simply wanted to measure the user experience, when participants perceived an explicit invocation of visual feedback.

4.2. Results and Discussion

Shaprio-Wilk test of normality showed that performance time was normally distributed, but error rates were not. A repeated measures ANOVA found that performance time was significantly affected by the type of feedback, $N = 72$, $F(2, 12) = 5.09$, $p < .05$, $\eta^2 = .46$ (Figure 3, left). Only successful selections were considered for data analysis; participants were unsuccessful with 51% of the trials in discrete, 75% in partial, and 21% in continuous feedback condition. Unsuccessful trials were treated as data missing completely at random (MCAR). Planned contrasts showed that participants were significantly efficient with continuous feedback ($M = 4.30$ s, $SD = .83$) compared with discrete feedback ($M = 7.17$ s, $SD = 1.61$), $p < .01$, $d = 2.24$.

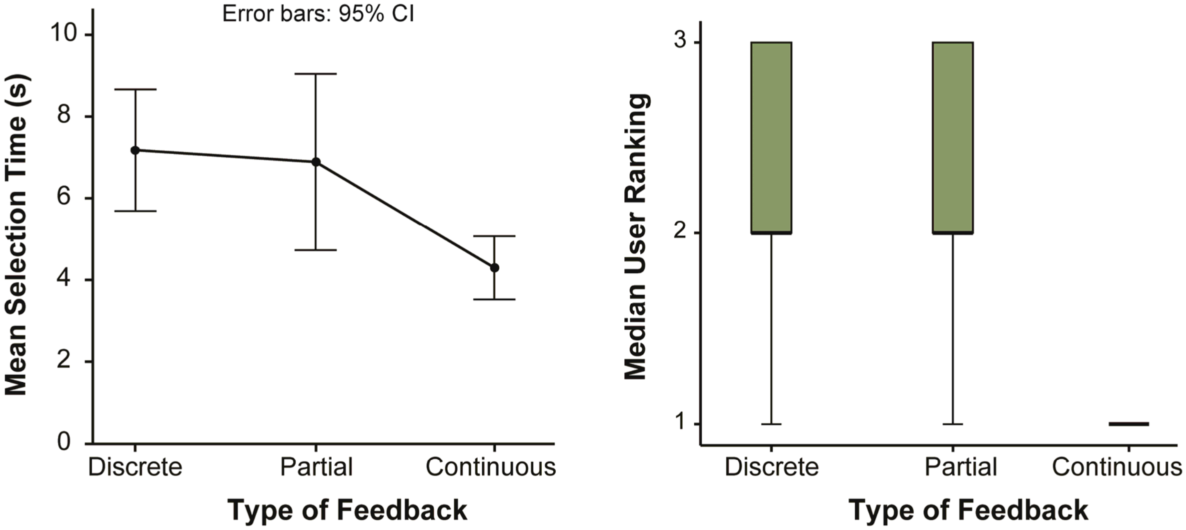


Figure 3. Types of feedback (discrete, partial, and continuous) significantly affected selection time and user preference. Continuous feedback was most efficient and most preferred by users.

A Friedman test showed significant effects of the type of feedback on error rates, $\chi^2(2, n = 19) = 16.00$, $p < .001$. Follow-up pairwise comparisons were conducted using a Wilcoxon test and Type I error was controlled using *Bonferroni-Holm* correction. Error rates were significantly more in partial feedback condition ($Mdn = 0\%$, $IQR = 50$) than both in continuous feedback (*no errors*), $Z = 2.83$, $r = .65$, and discrete feedback condition (*no errors*), $Z = 2.83$, $r = .65$, ps $< .01$.

Each participant was asked to rank the three types of feedback according to their order of preference. A Friedman's ANOVA showed a significant effect of the type of feedback on user preference, $\chi^2(2, N = 18) = 17.56$, $p < .001$ (Figure 3, right). Follow-up Wilcoxon tests showed that users significantly preferred continuous feedback over discrete feedback, $Z = 3.23$, $r = .76$, and partial feedback, $Z = 2.99$, $r = .70$, ps $< .01$.

Among the three conditions, continuous feedback provided the best user experience, thus confirming the critical role of visual feedback in controlling touchless interactions. Although discrete feedback differed from continuous feedback only in invocation, users were less efficient with the former. Holding their hand stationary not only made users dislike discrete feedback, but also affected their efficiency. This suggests that simply holding the hand stationary may not be an ideal candidate for mode switching.

However, in a touchless system, this effect would only be articulated in the first task following the mode switching. For partial feedback 7 out of 18 participants mentioned that they guessed where to point, which explains the significant decrease in their efficiency and effectiveness. This suggests that in device-less touchless interactions, point-and-select tasks on a large display cannot be guided sufficiently with proprioception.

5. Experiment 2: Alternative Shapes, Sizes, and Colors of the Touchless Cursor

Mouse pointer is an icon from a semiotic perspective (Pierce, 1931-58). By default, it resembles an arrow and signifies the concept of pointing. It may also take up other forms, such as an hour clock (to signify that the user needs to *wait* for a computer response) or a blinking vertical line (to signify the possibility of *text* input). The mouse pointer provides visual feedback for point-and-click interactions. Similarly, in touchless systems, the touchless cursor could change its form (e.g., shape, size) to provide necessary visual feedback on the ongoing status of the interaction. In this experiment, we studied three different properties of the touchless cursor—shape, size and color. But why can't we simply replicate the existing representations of the mouse pointer? Because the lack of kinesthetic feedback in touchless interactions and the inherent ambiguity with hand-gesture input requires unobtrusive yet effective visual feedback at many instances—unwarranted in point-and-click interactions (e.g., see Vogel & Balakrishnan, 2005). This makes our investigation of visual feedback in large-display touchless interactions pertinent.

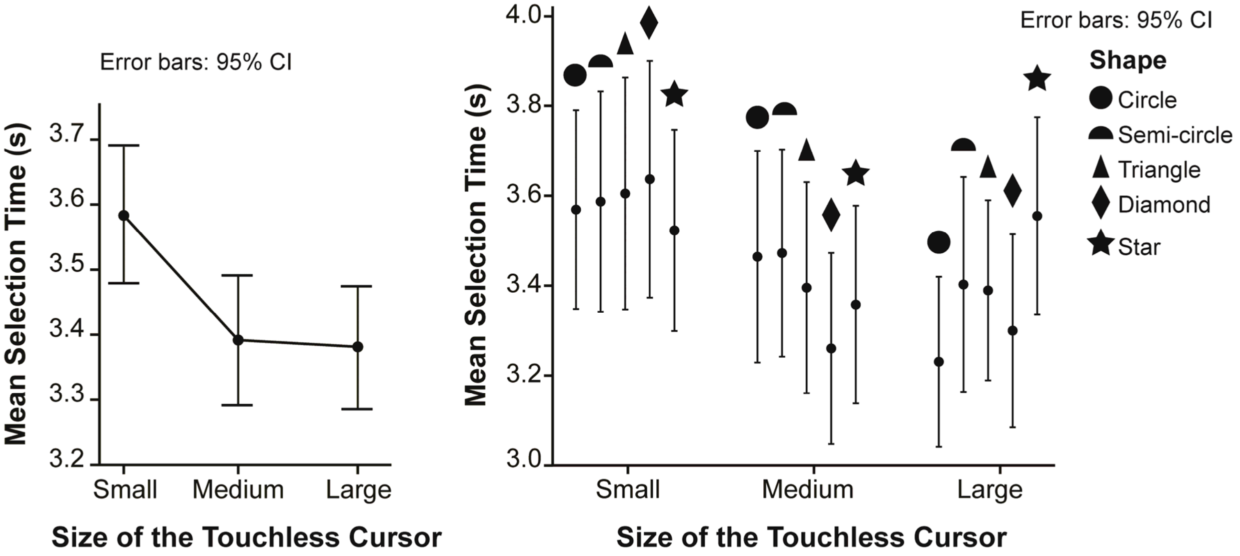


Figure 4. (Left) Selection time was significantly correlated with the size of the touchless cursor, $r = -.10$, $p < .01$. (Right) We found an interaction effect of shape x size on selection time. Increase in number of corners did not increase efficiency across all sizes of touchless cursors.

We studied five shapes: circle, semi-circle, triangle, diamond, and star; three sizes: small, medium, and large; and five outline colors: green, blue, white, red and yellow. Searching the mouse pointer on a traditional desktop screen is not a pressing problem, but it is often reported that users lose track of the cursor in very large displays and multi-monitor configurations (e.g., see Baudisch, Cutrell, & Robertson, 2003). On the other hand, large displays are suited for visualizing and manipulating large datasets (Beaudouin-Lafon, 2012). Hence, it is crucial that a touchless cursor can easily be searched while interacting with information-dense displays. Our shape and color coding dimensions were inspired by a class counting study (most common visual search task) by Smith and Thomas (1964). The shapes used in this experiment are geometric forms with vertices ranging from 0-5. We conducted a pilot study to confirm the user perception of the five Munsell colors (Fig.1, p. 139, Smith and Thomas, 1964) when converted to RGB space (see Appendix B for conversion details). Seven observers classified each color on the large display. Fleiss' kappa was used to measure the reliability of their agreement. All observers substantially agreed on all colors ($\kappa > .75$) except white ($\kappa = .30$). Following the analysis, we changed the white color to be described by its hex color code, FFFFFF. Small-sized cursors were bounded by a square of 128 pixels (81 mm), medium by 256 pixels (163 mm), and large by 512 pixels (325 mm). Overall, the cursors were 50%, 100% or 200% of the display object (256 x 256 pixels) that required to be selected during the point-and-select task.

5.1. Method

For this experiment, we used the same target-selection task as experiment 1. Visual feedback was continuously present. The touchless cursor was not filled with any solid color. All experimental conditions were randomized across trials. In summary, the study design was as followed:

5 shapes
x 3 sizes
x 5 colors
x 4 trials
x 18 participants
= 5400 trials

5.2. Results and Discussion

Among the three independent variables (shape, size, and color), we only found a significant correlation between the size of the touchless cursor and performance time, $r = -.10$, $p < .01$ (Figure 4, left). No main effect of shape, size, or color was found on participants' efficiency or effectiveness. We only found an interaction effect of shape x size, $F(8, 184) = 2.15$, $p < .05$, $\eta^2 = .09$. Increase in number of corners did not increase efficiency across all sizes, which explains the interaction effect (Figure 4, right). No significant performance benefit of the large-sized cursor was found over the medium-sized cursor, but 10/18 participants reported preference for large-sized cursors. Nine out of 18 participants preferred circular cursors. No color preference was reported.

Our results suggest that a touchless cursor of size equivalent to display objects (equal bounding areas) provides an optimal user experience, and an increase in cursor size do not improve user performance. We did not find any significant effect of shape or color coding of the touchless cursors. Overall, participants reported their preference for symmetrical shapes. A limitation of this study was the simplicity of the selection task, and a non-distracting background. Future research on the effects of shape and color of touchless cursors should investigate complex scenarios, where the display already contains artifacts of different shapes and colors.

6. Experiment 3: Alternative Levels of Transparency of the Touchless Cursor

Researchers have found that different levels of transparency of user interface elements, such as a tool palette, affect users' selection time (Harrison, Kurtenbach, & Vicente, 1995). In this experiment, we investigated user experience for different levels of transparency (100%, 50%, 25%, and 0%) of the touchless cursor. The level of transparency affected the fill of the touchless cursor, but not its outline.

6.1. Method

We used the selection task from experiment 2. The touchless cursor always had a white outline, and was equal to the size of the target folder (256 pixels, or 163 mm). Different transparency levels with the base color white were randomized across trials. In summary, the study design was as followed:

4 transparency levels
x 4 trials
x 18 participants
= 288 trials

6.2. Results and Discussion

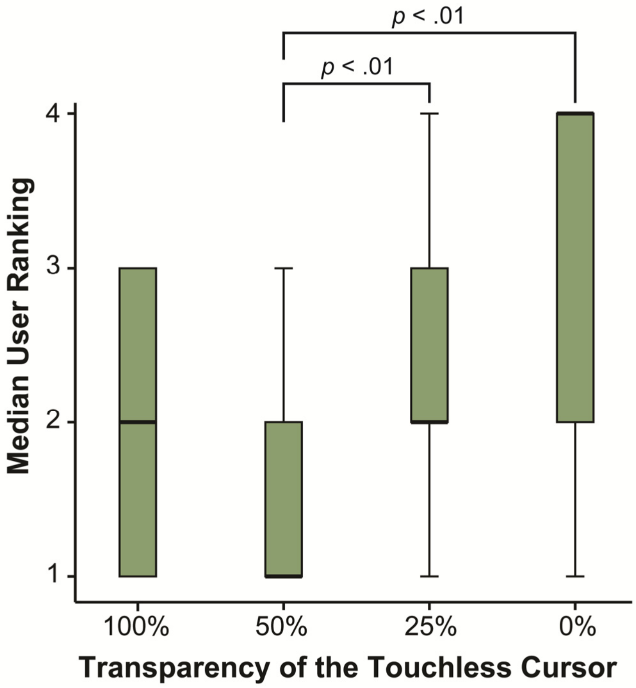


Figure 5. User preference of touchless cursors was significantly affected by their level of transparency. Participants significantly preferred medium transparency (50%), both over low transparency (25%) and opaque touchless cursors.

Performance time or error rates were not significantly affected by levels of transparency, *p*s > .05; but user preference was significantly affected (Figure 5). Each participant was asked to rank the four types of touchless cursors according to their order of preference. A Friedman's ANOVA showed a significant effect of transparency on user preference, $\chi^2(3, N = 18) = 18.17$, $p < .001$. Follow-up Wilcoxon tests showed that users significantly preferred medium transparency (50%) over low-transparent (25%), $Z = 3.56$, $r = .84$ and opaque touchless cursors, $Z = 3.06$, $r = .76$, *p*s < .01.

Participants mentioned that they disliked the opaque touchless cursor because it obstructed the view of the display object, but a 50% transparent touchless cursor was equally preferred as a completely transparent touchless cursor (with only an outline). This is an important finding since we are used to an opaque mouse pointer in desktop environments, but the mouse pointer is significantly smaller than the icons, thus not producing the obstruction problem that participants faced in this experiment. As we found in experiment 2, having a touchless cursor smaller than the display icon reduces user's selection efficiency.

7. Experiment 4: Alternative Approaches to Represent Selection

The touchless cursor should not only inform users where they are on the display, but also what they are doing. How can we represent operations (e.g., selection, de-selection) using the touchless cursor as a 'sign vehicle'? This is particularly important because of the absence of any kinesthetic feedback in touchless interactions that is conveniently available with a mouse or on a touch surface. In this experiment, we investigated different approaches to represent target-selection: change in the cursor's shape (circle to semi-circle, semi-circle to triangle, triangle to diamond, and diamond to star), change in depth (sphere to circle, and circle to sphere), and change in transparency (0% to 100%, 100% to 0%, 50% to 25%, and 25% to 50%). For example, when hovering over a folder, a user would see a circular touchless cursor, a successful select gesture would transform the cursor into a semi-circle, and a successful de-select gesture would convert the cursor back to a circle.

7.1. Method

We used the selection task from experiment 2. The touchless cursor always had a white outline (except for depth changes, where the cursor was filled white), and was equal to the size of the target folder (256 pixels, or 163 mm). In summary, the study design was as followed:

10 cursor transitions
x 4 trials
x 18 participants
= 720 trials

7.2. Results and Discussion

Performance time or error rates were not significantly affected by different cursor transitions, *p*s > .05. Although most participants could not report clear ranking preferences for the 10 cursor transitions, overall they reported that a change of opacity was more informative and less distracting than change in shape or depth. Ten out of 18 participants liked cursor transitions to represent target-selection. One participant commented, *"I felt I am accomplishing something. It made me feel good."*

8. Experiment 5: Persistent Visual Feedback for *Drag-and-Drop* Operations

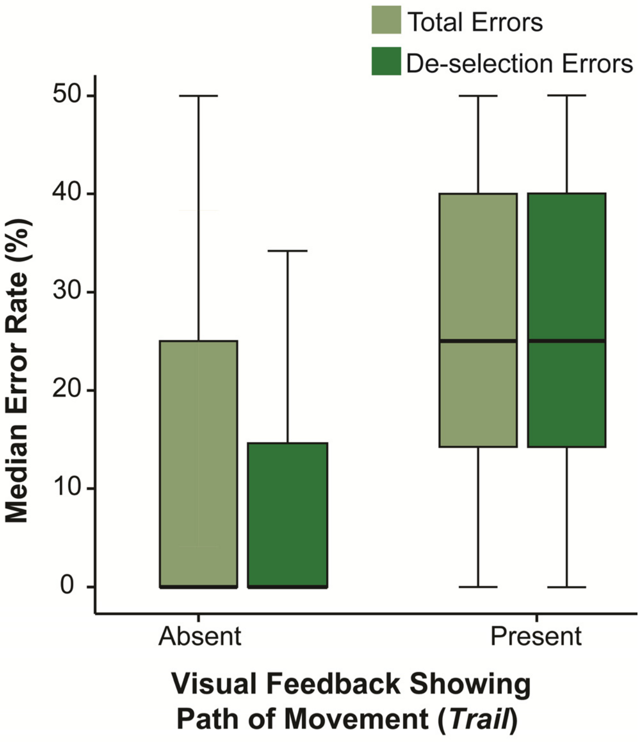


Figure 6. Participants made significantly more errors when Trail was present compared with no Trail condition, $p < .05$, $r = .50$.

All interactive systems are affected by some amount of lag: a delay between users' input and the visualized response. Working with multitouch systems, Wigdor et al. (2009) reported that such lag reduces users' perception of reactivity of the system, and designed a *trail* visualization that renders behind a finger as its contact point moves from one position to another. Large-display touchless interactions are device-less. With no surface friction of any device, the user moves faster, and with a larger screen the delayed reactivity of the system becomes a significant problem. Moreover, without any tactile feedback, the user solely depends on proprioception to perceive their path of movement. Since continuous visual feedback controls motor responses (see section 2.3.1), this lack of immediate visual feedback can affect operations where users are dragging an object on the display. In this experiment, we evaluated *trail* – persistent visual feedback that echoes the immediate history of user's hand positions (for a pre-defined time window). A trail was visualized as a Bézier spline (using cubic Bézier curves) along 10 previously tracked hand positions.

8.1. Method

The experimental task was a drag-and-drop operation. For each trial, participants moved a folder across the display (2000 pixels in display space, 53 cm in control space) to the left or to the right. The white-bordered touchless cursor (equal to the size of the target folder, 256 pixels) was filled with solid white, when a successful select gesture was interpreted; and the trail was visualized as a yellow line (Figure 1). In summary, the study design was as followed:

2 directions
x 3 blocks of repetitions
x 18 participants
= 108 trials

Before this experiment, participants practiced drag-and-drop operations in 8 compass directions (1100 pixels in display space, 29 cm in control space) for 3 blocks of repetition (Figure 9 shows the de-selection errors during those practice sessions).

8.2. Results and Discussion

Shaprio-Wilk test of normality showed that neither performance time, nor error rates were normally distributed. The presence of trail did not significantly affect performance time; but error rates were significantly more with trail present (*Mdn* = 25%, *IQR* = .28) than without trail (*Mdn* = 0%, *IQR* = .29), *n* = 17, *Z* = —2.08, *p* < .05, *r* = .50 (Figure 6). Specifically, trail did not affect error rates for selection, but de-selection errors were more with trail present (*Mdn* = 25%, *IQR* = .33) than without trail (*Mdn* = 0%, *IQR* = .14), *n* = 17, *Z* = —2.20, *p* < .05, *r* = .53. Participants commented that the continuous updating of the trail was distracting and exacerbated the natural tremor in hand motions.

Unlike in device-based interactions (such as with touch), hand movements in mid-air are rarely smooth—they frequently create a convoluted trail, thus distracting rather than supporting the user's task at hand. Moreover, the echo feedback provided information not entirely relevant to users' task at hand. Our results suggest that a trail significantly affected participants' effectiveness, mainly while dropping objects on the display (de-selection errors). Why selection was not equally affected by trail may be explained by the inherent difficulty of the de-select gesture (for details see additional observations, Figure 9). Based on participants' comments, video recordings, and logged data, we re-designed trail: A straight line joining the initially selected position to the user's current hand position (Figure 10, bottom-left).

9. Experiment 6: Persistent Visual Feedback for Out-of-Range Events

In large-display touchless interactions, when the sensor's tracking range does not match with the system's display range, a gap is created between the system's behavior and the user's mental model. This happens when users perform a gesture that erroneously steps out of the display range. During our pilot studies in the first round of experiments, we observed that when participants' gestures go off the display and the touchless cursor becomes unavailable, participants stop and get disoriented. They do not further attempt to move their hands and return within the display range. In the absence of any visual feedback, users fail to perceive that they are still being tracked by the sensors. From our observations, we hypothesized that participants halted because they perceived a lack of feedback as an error, and their reaction to an error was to slow down, a well-known phenomenon called post-error slowing (Notebaert et al., 2009).

Based on our hypothesis, we iteratively developed and tested *Stoppers* (Figure. 1), a type of semantic feedback (p. 83, Wigdor & Wixon, 2011) that uses the metaphor of stoppers (or plugs) to inform users that the system is still tracking their gesture, thus giving them the opportunity to instantly step back within the display's range. Stoppers support this action by providing visual feedforward (direction to move) and visual feedback (user's current position). When users gesture within a display range, a touchless cursor (such as a circle) is available. When users go off the display range, a semi-circle appears at the last-recorded within-display position of their gesture. In our current visualization of *Stoppers*, the change in feedback from a circle to a semi-circle subtly informs users that they are out of the display range and need to retrace their way back (see Figures C1 and C2 in Appendix C for a detailed visualization). Stoppers disappear as soon as the user is back within the display range. During pilot studies in the first round of experiments, users found *Stoppers* intuitive and helpful (Chattopadhyay, Pan & Bolchini, 2013) (video link provided in Appendix C). In the second round, we systematically investigated the effect of stoppers on user's efficiency in returning within the display range.

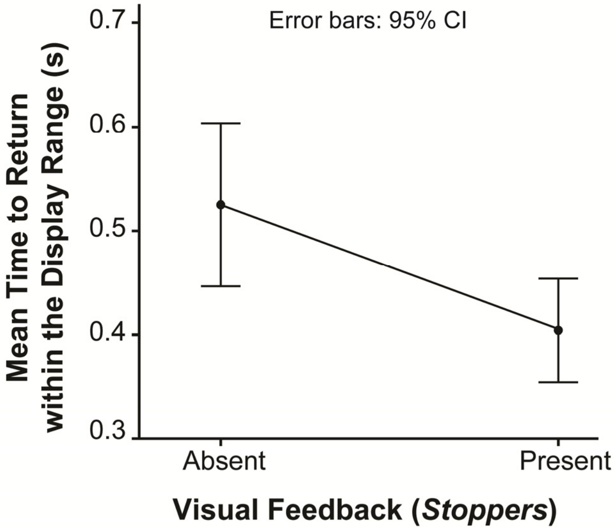


Figure 7. Participants were significantly faster in returning within the display range with Stoppers present than without Stoppers, *p* < .01, *d* = .87.

9.1. Method

For this experiment, participants pointed to a target object (a text label or a display icon of size 256 pixels) appearing randomly at certain positions at the top, left or bottom border of the display (see Figure C3 in Appendix C for a description of the experimental task). Because of the difficulties of our de-select gesture in the previous round of experiments, we decided to use a pointing task. To successfully complete a trial, participants pointed to the target object with a white-bordered touchless cursor (sized equal to the target). In summary, the study design was as followed:

14 target positions
x 5 blocks
x 19 participants
= 1330 trials

9.2. Results and Discussion

Participants were significantly faster in returning within the display range with stoppers present (*M* = 411 ms, *SD* = 104) than without stoppers (*M* = 533 ms, *SD* =169), *t*(18) = 2.97 , *p* < .01, *d* = .87 (Figure 7). Participants also reported stoppers as a non-distracting, helpful guide to keep them within the display's range, and to help them retrace their steps back.

Our results from experiments 5 and 6 confirm that the type of visualization plays a key role in visual feedback: relevant and semantic visual feedback seems to be more effective than echo feedback in large-display touchless interactions.

10. Additional Qualitative Findings and Observations on the Touchless User Experience

Apart from our six controlled studies we made two interesting observations: one throughout the first round of the experiment, and another during the drag-and-drop practice sessions. Since our gesture primitives and hand tracking algorithm was agnostic of participants' hand poses, we encouraged participants to user their preferred hand pose. Across all experiments, we observed a rich paradigm of spontaneous gesture variations that participants created to perform touchless selection (Figure 8).

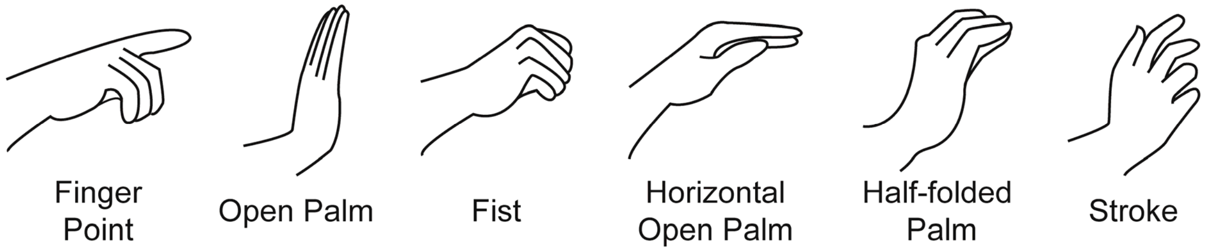


Figure 8. While using the select gesture, participants spontaneously created and used a rich range of hand poses.

Throughout our first five experiments, we used two gesture primitives: *select* and *de-select*. While a select gesture was defined as a forward movement of the hand with a certain velocity, a de-select gesture was defined as a backward movement of the hand by a certain distance (Figure 1). During the drag-and-drop practice sessions (prior to experiment 5), participants performed de-selection at 8 different locations of the display. We observed an interesting phenomenon: While participants intended to move backward from the sensor (in Z-direction), they actually moved *down* vertically (during de-selecting objects in northern regions, such as NW, N, or NE) or moved *up* vertically (during de-selecting objects in southern regions, such as SW, S, or SE) (Figure 9). Overall, there was a strong trend among participants to bring their hand closest to the center of their torso, probably for energy conservation. An inverse, but related phenomenon was reported by researchers while using push-to-select gestures on large displays (Hespanhol et al., 2012): While translating from one position on the display to another (parallel to the display), users often moved their hands forward (orthogonal to the display), and accidentally invoked the select gesture.

11. General Discussion

11.1. Overview

We conducted six controlled experiments to explore four different aspects of visual feedback in large-display touchless interactions. Specifically, we investigated: types of feedback, alternative forms of touchless cursors, alternative approaches to visualize target-selection, and persistent visual feedback for drag-and-drop operations and out-of-range events. Although we studied visual feedback using a point-and-select task, our findings are applicable beyond our experimental tasks. In the following sections, we discuss how our findings can be extended to inform the design of visual feedback for touchless interactions with large displays. To frame our discussion properly, it is important to note two different kinds of large-display touchless interactions: An interaction that happens in the context of a display object (e.g., using a marking menu to operate on an icon, Bailly et al., 2011), and an interaction that is object-agnostic (e.g., making a *teapot* gesture to create an avatar; Walter et al., 2013). Our findings and design guidelines are relevant to object-oriented touchless interactions that require users to point to a display object prior to any gesture invocation.

11.2. Design Implications

First, our findings suggest that *continuous* visualization of users' current position on the display—independent of an application's response to user input—is crucial for touchless interactions. The designer may choose to represent tracking information corresponding to one or more body parts depending upon the interaction vocabulary in use. For example, a touchless system allowing two-hand manipulations would require visual feedback for both hands; a system allowing foot interactions should further represent tracking information of users' feet. Visual feedback of an application's response does not provide enough feedback to users prior to any successful gesture registration, or during gesture relaxation (Wu, Shen, Ryall, Forlines, & Balakrishnan, 2006). For example, an application allowing users to rotate 3D images bimanually in a sterile environment should show the hand positions in addition to the rotation of the object as a result of users' hand movements (similar to Rosa & Elizondo, 2014).

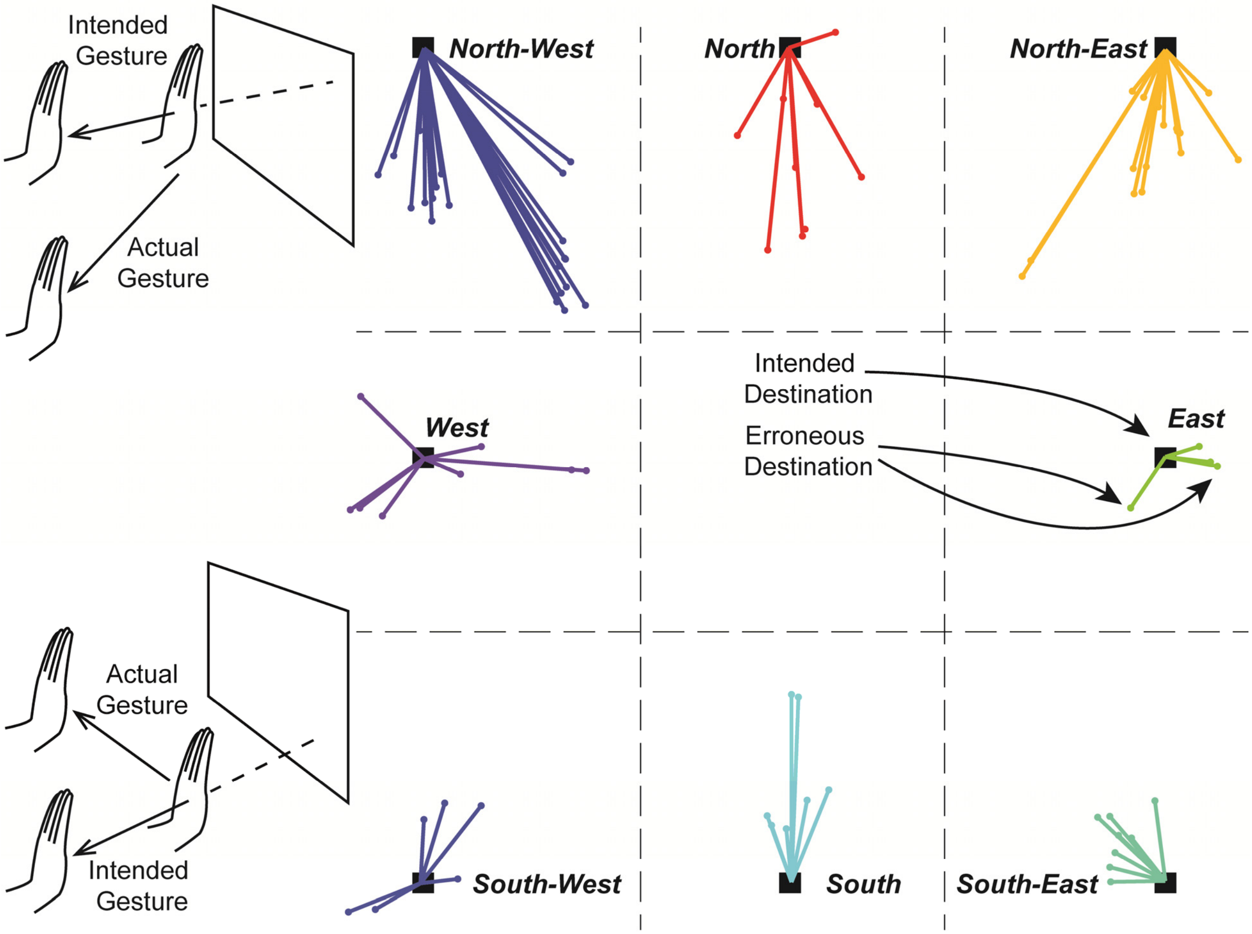


Figure 9. During drag-and-drop practice sessions, participants moved display objects in 8 directions (N, S, W, E, SW, SE, NE, and NW). We found an interesting pattern in the de-selection errors across different positions of the display: While moving backward from the sensor (in Z-direction), participants often moved down vertically (during de-selecting objects in northern regions, such as NW, N, or NE) or moved up vertically (during de-selecting objects in southern regions, such as SW, S, or SE). Overall, there was a strong trend among participants to bring their hand closest to the center of their torso, probably for energy conservation.

Second, a touchless cursor can be efficiently used as a 'sign vehicle' to represent many critical aspects of touchless interactions, such as when a user is engaged in an on-going interaction or when multiple users are collaborating synchronously. Our results suggest that shape or color coding of touchless cursors do not significantly affect user experience in large-display touchless interactions. Yet users informally commented on their preference toward symmetrical shapes. Hence, colors may be used to distinguish multiple users interacting at a time, while shapes may be used to represent different interaction states (e.g., when the user is clutching instead of interacting).

We found that a touchless cursor of size equivalent to a display object is significantly more efficient than a smaller cursor (50% of the display object), but not significantly less efficient than a larger cursor (200% of the display object). While using a cursor equivalent to the size of a display object, users disliked an opaque cursor, but significantly preferred a slightly transparent touchless cursor (50% opacity). The applicability of our results on the size of the touchless cursor may be limited by our gesture primitives. Nevertheless, similar to shape coding, our results on transparency can be applied to represent a touchless cursor during interaction. For example, multiple users reported envisioning a scenario where during touchless selection the cursor would transform from an outline to a transparent fill to represent a successful select gesture, and revert back to its default outline when deselected. Although we explored different transitions of the touchless cursor to represent touchless selection (experiment 4), no particular condition emerged as significantly more efficient or effective. Still users reported preference for transparency changes, and mentioned that shape transitions were distracting.

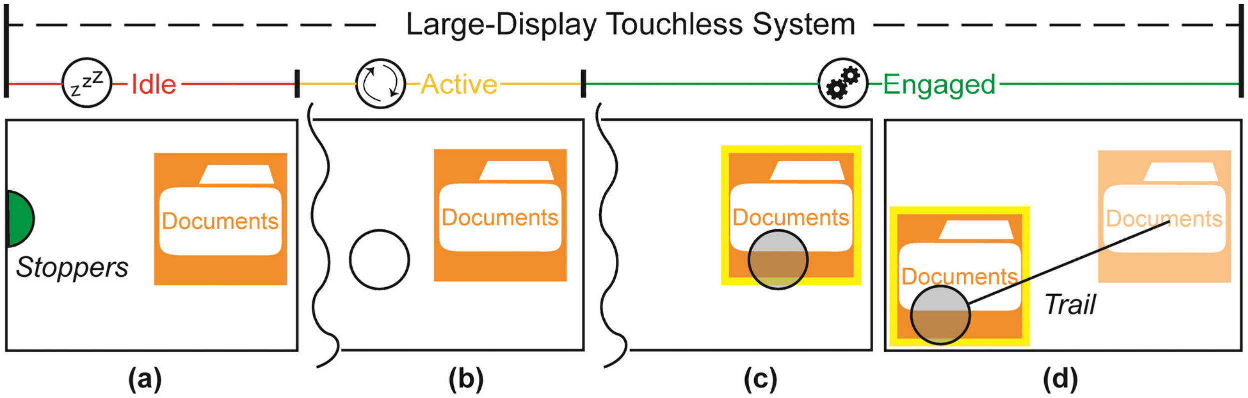
Most current systems use the icon of an open hand as a touchless cursor, and transform the icon to a closed hand or corresponding poses (such as finger counts) on successful pose recognition (Microsoft, 2013). This visual feedback technique may not be scalable for a collaborating environment. Our results can be used to augment the visual feedback along with pose information in collaborative touchless environments. For example, let us imagine a collaborative touchless environment that uses both hands and feet toward performing gestures. Multiple users may be color coded. Hands and feet may be distinguished using shape coding (or iconic images). The touchless cursors can appear as outlines while users are being tracked, but are not engaged. On successful gesture recognition, a touchless cursor may simply be filled with a certain level of transparency, or an iconic image of the pose can be transparently overlaid on the cursor.

Third, persistent visual feedback can benefit touchless operations that are affected by users' fast and large movements. When users erroneously gestured out of the display range, *Stoppers* significantly increased their efficiency in returning within the display range (experiment 6). However, trail—persistent visual feedback that echoed users' path of movement during drag-and-drop operations decreased users' efficiency (experiment 5). Users reported them as distracting and redundant. While stoppers provided users with *semantic feedback* (a meaningful representation of the system's knowhow about the user), trail provided *echo feedback* (an echo of minimally processed sensor data; p. 83, Wigdor and Wixon, 2011). Although further research is required to make a more general claim, semantic feedback seems to be more effective than echo feedback in large-display touchless interactions. Our findings suggest that persistent visual feedback in large-display touchless interactions should be: (1) visually unobtrusive, (2) salient, and (3) communicate only relevant information for the ongoing interaction. Based on these guidelines, we redesigned trail from a cubic Bezier curve to a simple straight path connecting the initial selection position during a drag-and-drop operation and the current position of the user's hand.

Additionally, we discovered a caveat about touchless gesture primitives that parametrize orthogonal movements. Our video recordings and logged data of users' de-selection errors showed that users always tend to follow the shortest path toward the center of their torso, rather than orthogonal movements (Figure 9). While performing de-select gestures, users frequently moved vertically downwards (or vertically upwards) while intending to move only orthogonal to the large display. This observation well aligns with the minimum energy cost model of human movement planning (Alexander, 1997); it states that while reaching an object, among infinitely many paths, we choose the one path that minimizes our metabolic energy cost. This phenomenon is most relevant for *large-display* touchless interactions, where to interact with display objects users stretch their hands beyond the space directly in front of their torso—up, down, left or right.

Overall, our findings suggest that given the large size of the display, and the lack of haptic feedback in touchless interactions, effective visual feedback plays a key role in improving the touchless user experience with large display interfaces. When proprioception is the only feedback for an interaction modality, visual cues can somewhat compensate the lack of haptic feedback. This work provides the first step toward building a visual feedback language for touchless interactions.

Finally, to crystallize in a coherent view the lessons learned across our six experiments, we propose a visual feedback routine for a simple interaction scenario: moving a folder using a drag-and-drop operation (Figure 10). We envision the large-display touchless system in three interaction states: idle, active, and engaged. In *idle* state, though users are being tracked by the motion sensor, they cannot interact with the system; for example the user may be out of the display range, or clutching. In *active* state, users are interacting with the system (e.g., pointing), but *not* performing any action, such as selecting, dragging, or resizing. In *engaged* state, users either make a gesture to initiate an operation, or continue an ongoing operation; the system in this state would register a gesture, allow the user to continue a gesture, or recognize gesture termination. In our visualization instance, we provide *stoppers* to represent when users are out of the display range (Figure 10.a); a circular, unfilled touchless cursor to show users' position on the display (Figure 10.b); a partially filled (50%) touchless cursor to indicate that selection has been registered (Figure 10.c); and a trail to provide semantic context of the ongoing drag-and-drop operation (Figure 10.d). When users complete the drag-and-drop operation, the touchless cursor would change back to its default state, and indicate that de-selection has been registered. This simple *idle-active-engaged* model provides a preliminary framework to conceptualize interactions and their corresponding visual feedback routine in a touchless system.



(a) The user is out of the display range.

(b) The user is being tracked, and is within the display range.

(c) ❶ The user makes a *selection* gesture. ❷ The system registers the selection gesture. ❸ The user begins a *drag-and-drop* operation.

(d) The user continues the drag-and-drop operation.

Figure 10. Demonstrating visual feedback for the three interaction states—idle, active, and engaged—during a drag-and-drop operation: (a) Stoppers represent when users are out of the display range; (b) a circular, unfilled touchless cursor shows users' position on the display; (c) a partially filled (50%) touchless cursor indicates that selection has been registered; and (d) a trail provides semantic context of the ongoing drag-and-drop operation.

11.3. Limitations

The capability of our motion tracking sensor limits our findings. It operated with a maximum refresh rate of 30 fps: Users perceived a lag of about 33 ms between their movements and screen update. In our experimental setup, participants sat in a comfortable chair. This may have affected their ability to make certain gestures; but neither did we observe any ergonomic constraints, nor was reported by the participants. Moreover, our participants were right-handed. Although we do not think that this would affect our findings on visual feedback, we cannot claim a generalization of our findings across left-handed users.

We investigated visual feedback using only *select* and *de-select* gestures. Our performance measures may be biased by the gesture primitives we used in the experiment, and further research is necessary to tailor visual feedback to any particular interaction vocabulary. Our experimental system received a mean SUS score of 66 that suggests an average usability; but we did not record any subjective ratings for intuitiveness. Informally, users did not report any significant physical strain after the experiment. Based on current research, future studies should record user fatigue using objective measurements, such as consumed endurance (Hincapié-Ramos, Guo, Moghadasian, & Irani, 2014). Users' difficulty in performing the de-select gesture (Figure 9) was obvious during the practice trials; but that may not have significantly affected the experimental trials (in experiment 5) because participants only performed select and deselect gesture at their chest-level (when seated).

Our experiment used a simple point-and-select task, and a black solid background. Most real world tasks are complicated, and the display background is populated with other artifacts. Future research investigating visual feedback in large-display touchless interactions should use the display density of the background as an experimental factor. More complex tasks, such as matching, sorting or grouping of display objects may be used.

Though we provide some guidelines on how to design visual feedback for multiple users interacting simultaneously, future experiments—controlled or in-the-wild—are required to identify their role in collaborative touchless environments. Moreover, we did not investigate the aspect of clutching in touchless interactions. It is important to investigate how visual feedback can intuitively allow users to reposition their body parts without affecting the screen output.

11.4. External Validity

Our results are generalizable for large-display touchless interactions. Specifically, our findings about different types of visual feedback (experiment 1) and observations about de-select gestures (Figure 9) may not apply in gaming scenarios where users interact with standard television screens, such as 50" HDTVs, from a 7-9 feet distance. This is because in such scenarios the operating region of user's motor space (also known as user's control space) is much smaller compared with while interacting with larger displays. (Shrinking the motor space in large-display interactions—using a very high control display gain—would lead to quantization errors.) Although users were seated in our experiments, we expect our findings to stay valid in a standing posture. Visibility depends on the distance from the display. Our experiments were conducted at a fixed distance from the large display. Though distance from the display may affect the task efficiency of the users (since display objects get smaller), it is unlikely to affect our general findings on visual feedback. Finally, our design guidelines are agnostic of the control-display gain of the system, or how the control space is mapped to the display space. For our study, we used an off-the-shelf sensor inside a room with normal levels of fluorescent lighting. Outdoor lighting may affect the tracking noise, the screen glare, and the perception of color coding.

12. Conclusions

Touchless interactions lack haptic feedback, but effectively designed visual feedback can guide users to control their movements and still perform operations efficiently. Because large displays are often densely populated with artifacts, visual feedback in large-display touchless interactions should be easily perceivable. Motor science research suggests that visual feedback can improve motor control and learning; studies on visual perception present attributes that can be used to facilitate users' attention in visual search. Inspired by the potential of visual feedback in related fields, we systematically investigated types of feedback, alternative forms of touchless cursors, approaches to visualize target selection, and persistent visual feedback during drag-and-drop operation and out-of-range event.

Our findings suggest that continuous visual feedback is significantly effective than partial feedback; users' efficiency did not increase with their cursors increasing beyond the size of the display objects (200%); and users preferred slightly transparent (50%) cursors over completely opaque ones. We also found that semantic feedback located at the border of the display (Figures 1, C1 and C2) informing users when they were out of the display range helped users to efficiently return back; but echo feedback showing the path of users' movement made users inefficient during drag-and-drop operations. We additionally observed users making a wide range of hand postures during touchless selection. We also found that orthogonal movements as interaction primitives are limited: users obviously take the shortest path toward their torso, thus misfiring touchless gestures.

This work does not contradict the works on imaginary interfaces that show users can reliably perform spatial interaction using bare-hand movements without any visual feedback (Gustafson, Bierwirth, & Baudisch, 2010), or eyes-free distal pointing (Cockburn, Quinn, Gutwin, Ramos, & Looser, 2011). Instead, our work puts forth the importance of visual feedback in effectively controlling touchless interactions with large displays—where the display space is entirely decoupled from the motor space. The overarching contribution of our work is to confirm the key role of visual feedback in touchless interactions; and providing some early pointers on how the design of visual feedback can somewhat compensate the lack of haptic feedback. Future research on visual feedback need to mine specific requirements in different interaction scenarios, such as swiping-to-type on a keyboard, crossing-to-select a menu, or making finger poses to trigger commands. These requirements related to motor control, motor learning, and visual attention can then guide the design of a visual feedback language for those interaction scenarios. Another direction of research that we are investigating is—given our dependency on visual perception for triggering motor responses in touchless interactions—what other phenomena that affect visual perception (e.g., Gestalt principles) also affects touchless user experience.

References

Alexander, R. M. (1997). A minimum energy cost hypothesis for human arm trajectoires. *Biological cybernetics*, *76(2)*, 97-105.

Bailly, G., Walter, R., Müller, J., Ning, T., & Lecolinet, E. (2011). Comparing free hand menu techniques for distant displays using linear, marking and finger-count menus. In Proceedings of the INTERACT Conference, 248-262, Springer.

Baudisch, P., Cutrell, E., & Robertson, G. (2003). High-density cursor: a visualization technique that helps users keep track of fast-moving mouse cursors. In Proceedings of INTERACT, 236-243, Springer.

Beaudouin-Lafon, M., Huot, S., Nancel, M., Mackay, W., Pietriga, E., Primet, R., ... Klokmose, C. (2012). Multisurface interaction in the WILD room. *Computer*, *45(4)*, 48-56.

Bragdon, A., DeLine, R., Hinckley, K., & Morris, M. R. (2011). Code space: touch+ air gesture hybrid interactions for supporting developer meetings. In Proceedings of Interactive Tabletops and Surfaces, 212-221, ACM.

Carter, R. C. (1982). Visual search with color. *Journal of Experimental Psychology: Human Perception and Performance, 8(1),* 127.

Chattopadhyay, D., & Bolchini, D. (2014). Touchless circular menus: toward an intuitive UI for touchless interactions with large displays. In Proceedings of the International Working Conference on Advanced Visual Interfaces, 33-40, ACM.

Chattopadhyay, D., Pan, W. & Bolchini, D. (2013). A 'Stopper' Metaphor for Persistent Visual Feedback in Touchless Interactions with Wall-Sized Displays. . In Proceedings of the International Symposium on Pervasive Displays, Mountain View, USA.

Czerwinski, M., Smith, G., Regan, T., Meyers, B., Robertson, G., & Starkweather, G. (2003). Toward characterizing the productivity benefits of very large displays. In Proceedings of the INTERACT Conference, 3, 9 – 16, IOS Press.

Cockburn, A., Quinn, P., Gutwin, C., Ramos, G., & Looser, J. (2011). Air pointing: Design and evaluation of spatial target acquisition with and without visual feedback. *International Journal of Human-Computer Studies, 69(6)*, 401-414.

Dostal, J., Hinrichs, U., Kristensson, P. O., & Quigley, A. (2014). SpiderEyes: designing attention-and proximity-aware collaborative interfaces for wall-sized displays. In Proceedings of Intelligent User Interfaces, 143-152, ACM.

D'Zmura, M. (1991). Color in visual search. *Vision research*, *31*(6), 951-966.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology, 47(6),* 381.

Gupta, S., Morris, D., Patel, S. N., & Tan, D. (2013). Airwave: Non-contact haptic feedback using air vortex rings. In Proceedings of the ACM international joint conference on Pervasive and ubiquitous computing, 419-428, ACM.

Gustafson, S., Bierwirth, D., & Baudisch, P. (2010). Imaginary interfaces: spatial interaction with empty hands and without visual feedback. In Proceedings of UIST, 3-12, ACM.

Harrison, B. L., Kurtenbach, G., & Vicente, K. J. (1995). An experimental evaluation of transparent user interface tools and information content. In Proceedings of UIST, 81-90, ACM.

Hespanhol, L., Tomitsch, M., Grace, K., Collins, A., & Kay, J. (2012). Investigating intuitiveness and effectiveness of gestures for free spatial interaction with large displays. In Proceedings of the International Symposium on Pervasive Displays, 6, ACM.

Hincapié-Ramos, J. D., Guo, X., Moghadasian, P., & Irani, P. (2014). Consumed Endurance: A metric to quantify arm fatigue of mid-air interactions. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 1063-1072, ACM.

Huegel, J. C., Celik, O., Israr, A., & O'Malley, M. K. (2009). Expertise-based performance measures in a virtual training environment. *Presence: Teleoperators and Virtual Environments*, *18(6)*, 449-467.

Jagodic, R., Renambot, L., Johnson, A., Leigh, J., & Deshpande, S. (2011). Enabling multi-user interaction in large high-resolution distributed environments. *Future Generation Computer Systems, 27(7)*, 914-923.

Jakobsen, M. R., & HornbÆk, K. (2014). Up close and personal: Collaborative work on a high-resolution multitouch wall display. ACM *Transactions on Computer-Human Interaction (TOCHI), 21(2)*, 11.

Kajastila, R., & Lokki, T. (2013). Eyes-free interaction with free-hand gestures and auditory menus. *International Journal of Human-Computer Studies*, *71*(5), 627-640.

Liu, C., Chapuis, O., Beaudouin-Lafon, M., Lecolinet, E., & Mackay, W. E. (2014). Effects of display size and navigation type on a classification task. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 4147-4156, ACM.

Markussen, A., Jakobsen, M. R., & Hornbæk, K. (2014). Vulture: a mid-air word-gesture keyboard. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 1073-1082, ACM.

Microsoft Corporation. (2013). Human Interface Guidelines (HIG) version 1.8. [PDF Document]. Retrieved from http://go.microsoft.com/fwlink/?LinkID=247735

Morris, M. R. (2012). Web on the wall: insights from a multimodal interaction elicitation study. In Proceedings of Interactive Tabletops and Surfaces, 95-104, ACM.

Nancel, M., Chapuis, O., Pietriga, E., Yang, X. D., Irani, P. P., & Beaudouin-Lafon, M. (2013). High-precision pointing on large wall displays using small handheld devices. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 831-840, ACM.

Nancel, M., Wagner, J., Pietriga, E., Chapuis, O., & Mackay, W. (2011). Mid-air pan-and-zoom on wall-sized displays. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 177-186, ACM.

Ni, T., Schmidt, G. S., Staadt, O. G., Livingston, M. A., Ball, R., & May, R. (2006). A survey of large high-resolution display technologies, techniques, and applications. In Proceedings of the Virtual Reality Conference, 223-236, IEEE.

Norman, D. A. (2010). Natural user interfaces are not natural. *Interactions*, *17*(3), 6-10.

Notebaert, W., Houtman, F., Opstal, F. V., Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. *Cognition, 111(2)*, 275-279.

O'Hara, K., Gonzalez, G., Sellen, A., Penney, G., Varnavas, A., Mentis, H., ... & Carrell, T. (2014). Touchless interaction in surgery. *Communications of the ACM*, *57(1)*, 70-77.

Peirce, Charles Sanders (1931-58): *Collected Writings* (8 Vols.). Charles Hartshorne, Paul Weiss & Arthur W Burks (Ed.). Cambridge, MA: Harvard University Press.

Rosa, G. M., & Elizondo, M. L. (2014). Use of a gesture user interface as a touchless image navigation system in dental surgery: Case series report. *Imaging science in dentistry, 44(2)*, 155-160

Rovelo Ruiz, G. A., Vanacken, D., Luyten, K., Abad, F., & Camahort, E. (2014). Multi-viewer gesture-based interaction for omni-directional video. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 4077-4086, ACM.

Saunders, J. A., & Knill, D. C. (2004). Visual feedback control of hand movements. *The Journal of neuroscience, 24(13)*, 3223-3234.

Scheidt, R. A., Conditt, M. A., Secco, E. L., & Mussa-Ivaldi, F. A. (2005). Interaction of visual and proprioceptive feedback during adaptation of human reaching movements. *Journal of Neurophysiology, 93(6)*, 3200-3213.

Sülzenbrück, S. (2012). The impact of visual feedback type on the mastery of visuo-motor transformations. *Zeitschrift für Psychologie, 220(1),* 3.

Smith, S. L., & Thomas, D. W. (1964). Color versus shape coding in information displays. *Journal of Applied Psychology, 48(3)*, 137.

Sodhi, R., Poupyrev, I., Glisson, M., & Israr, A. (2013). AIREAL: interactive tactile experiences in free air. *ACM Transactions on Graphics (TOG)*, *32*(4), 134.

Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. *Psychonomic bulletin & review*, *20*(1), 21-53.

Tan, D. S., Gergle, D., Scupelli, P., & Pausch, R. (2006). Physically large displays improve performance on spatial tasks. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *13(1)*, 71-99.

Valkanova, N., Walter, R., Vande Moere, A., & Müller, J. (2014). Myposition: Sparking civic discourse by a public interactive poll visualization. In Proceedings of Computer Supported Cooperative Work & Social Computing, 1323-1332, ACM.

Verwey, W. B., & Heuer, H. (2007). Nonlinear visuomotor transformations: locus and modularity. *The Quarterly Journal of Experimental Psychology, 60(12),* 1629-1659.

Vogel, D., & Balakrishnan, R. (2005). Distant freehand pointing and clicking on very large, high resolution displays. In Proceedings of UIST, 33-42, ACM.

Vogt, K., Bradel, L., Andrews, C., North, C., Endert, A., & Hutchings, D. (2011). Co-located collaborative sensemaking on a large high-resolution display with multiple input devices. In Proceedings of the INTERACT Conference, 589-604, Springer.

Walter, R., Bailly, G., & Müller, J. (2013). Strikeapose: revealing mid-air gestures on public displays. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 841-850, ACM.

Wigdor, D., Williams, S., Cronin, M., Levy, R., White, K., Mazeev, M., & Benko, H. (2009). Ripples: utilizing per-contact visualizations to improve user interaction with touch displays. In Proceedings of UIST, 3-12, ACM.

Wigdor, D., & Wixon, D. (2011). *Brave NUI world: designing natural user interfaces for touch and gesture.* Burlington, MA: Morgan Kauffman.

Wolfe, J. M. (1998). Visual search. *Attention*, *1*, 13-73.

Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience, 5(6),* 495-501.

Wolfe, J. M., Birnkrant, R. S., Kunar, M. A., & Horowitz, T. S. (2005). Visual search for transparency and opacity: attentional guidance by cue combination? *Journal of vision, 5(3),* 9.

Wu, M., Shen, C., Ryall, K., Forlines, C., & Balakrishnan, R. (2006). Gesture registration, relaxation, and reuse for multi-point direct-touch surfaces. In IEEE International Workshop on Horizontal Interactive Human-Computer Systems (TableTop), 183-190, IEEE.

Zelaznik, H. N., Hawkins, B., & Kisselburgh, L. (1983). Rapid visual feedback processing in single-aiming movements. *Journal of motor behavior, 15(3),* 217-236.

Appendix A: Training

During the training session in the first round of the study (experiments 1 - 5), participants practiced select and de-select gestures by solving a picture puzzle (Figure A1). They rearranged a puzzle using drag-and-drop operations. Each participant completed three picture puzzles, and on average took 10 – 15 minutes to complete all three of them.

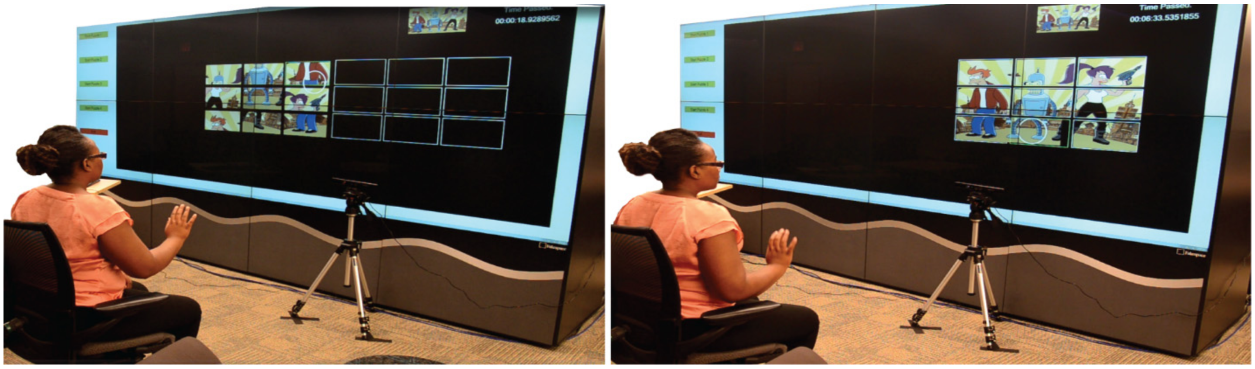


Figure A1. During the training session in the first round of the study, participants practiced select and de-select gestures by solving a picture puzzle.

Appendix B: Color Conversion from Munsell Notation to RGB

Five Munsell colors (Fig.1, p. 139, Smith and Thomas, 1964)—red, green, blue, yellow and white was used in experiment 2. Munsell notation was converted to RGB hex values using an R script. An example of the conversion code for color green (2.5G 5/8) is given below:

```
library(aqp)
library(colorspace)
rgbVal <- expand.grid(hue='2.5G', value=5,chroma=8)
rgbVal.rgb <- with(rgbVal, munsell2rgb(hue, value, chroma,return_triplets=TRUE))
newRgb = rgb(rgbVal.rgb$r, rgbVal.rgb$g, rgbVal.rgb$b)
```

After conversion, each color corresponded to a hex color code: green (2.5G 5/8) to #238C57; blue (5BG 4/5) to #156D69; white (5Y 8/4) to #D9CA93; red (5R 4/9) to #A34143; and yellow (10YR 6/10) to #C68A13.

Appendix C: Stoppers—Semantic Feedback for Out-of-Range Gestures

Figure C1. A user points in mid-air to a target folder on a large display (left); Stoppers provide visual feedback as the user's gesture goes out of the display range (center) and guide her back within the display range (right).

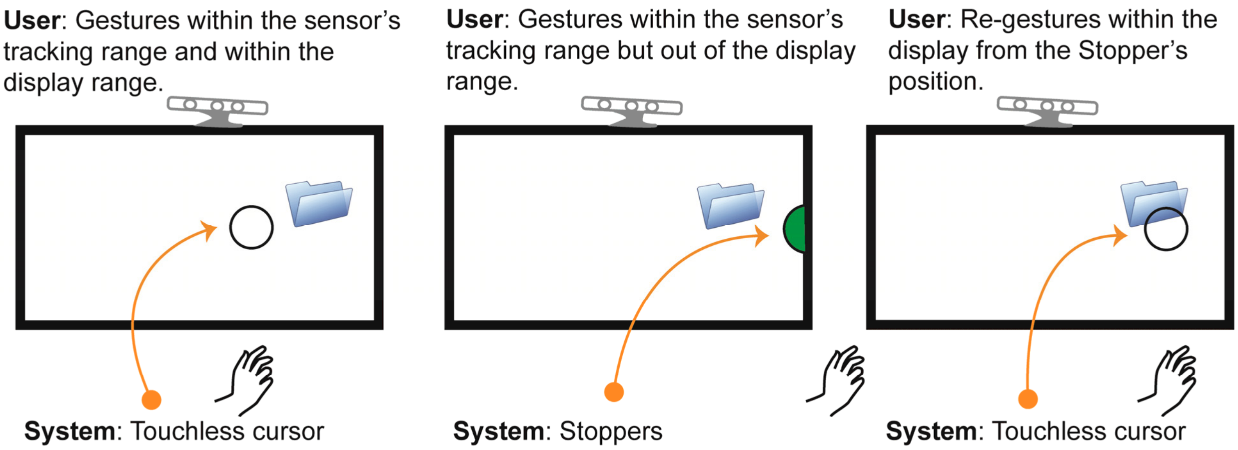


Figure C2. By introducing persistent visual feedback as users move out of the display range (center), Stoppers decrease users' disorientation and facilitate the recovery of touchless gestures within the display range (right).

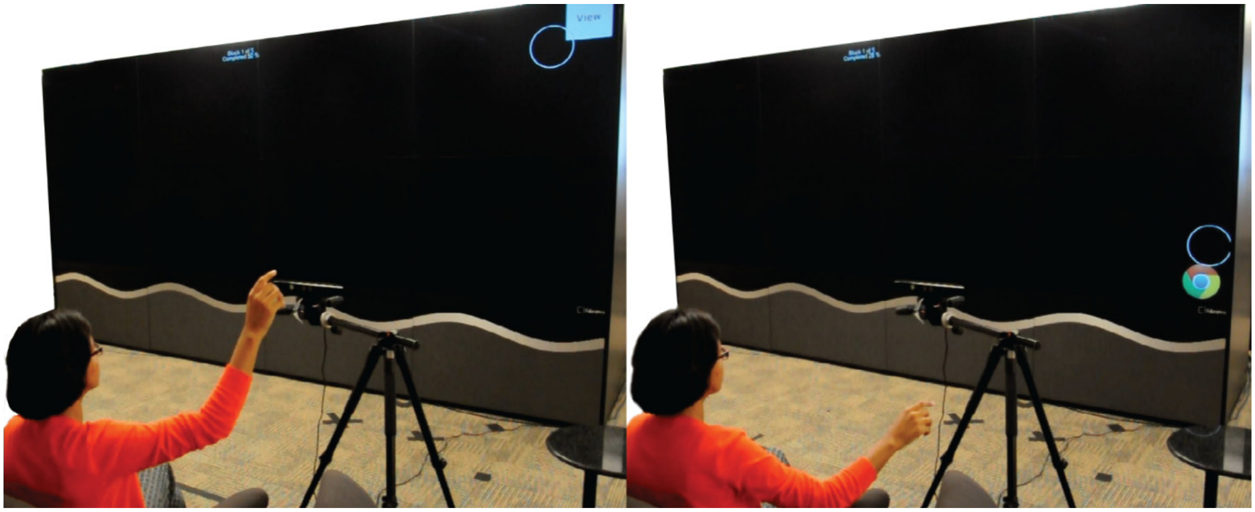


Figure C3. In the second round, participants performed a pointing task with targets (256 pixels x 256 pixels) randomly appearing at the top, left or right border of the large display.