

Analysis and comparison of target assistance techniques for relative ray-cast pointing

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Abstract

Pointing at displays from a distance is becoming a common method of interacting with computer applications and entertainment systems, using devices such as the Wii Remote, the PlayStation Move controller, or the Microsoft Kinect. These systems often implement relative forms of ray-cast pointing, in which the user simply points a hand-held input device towards targets on the screen. Ray-casting interaction is easy for novices to learn and understand, but this technique often suffers from accuracy problems: for example, hand jitter, arm fatigue, calibration drift, or lack of skill can all reduce people's ability to acquire and select on-screen targets. In this paper, we analyse and evaluate the idea of target assistance as a way to address the accuracy problems of ray-cast pointing. Although several assistance schemes have been proposed for mouse-based pointing, these ideas have not been tested in distant-pointing settings, and there is little knowledge available to guide design in this increasingly common interaction scenario. To establish this basic design knowledge, we carried out four studies of relative ray-casting using three different target assistance techniques—two motor-space techniques (sticky targets and a novel form of target gravity), and one acquisition-feedback technique that combined visual, tactile, and auditory feedback. Our first three studies tested each assistance technique separately, to explore how different parameters for each method affected performance and perceptibility. Our fourth study carried out a direct comparison of the best versions of each technique, and also examined the effects of distractor objects placed in the path to the target. Our studies found that the two motor-space techniques were extremely effective in improving selection accuracy without being highly obvious to users, and that the new gravity-based technique (which attracts the cursor even when it is not over the target) performed best of all. There was no observed effect on performance when the combined acquisition-feedback technique was used. Our studies are the first to comprehensively explore the optimization, performance, and perceptibility of target assistance techniques for relative ray-casting—our results provide designers with clear guidelines about what methods to use, how to configure the techniques, and what effects can be expected from their use.

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1. Introduction

Distant pointing involves pointer-based interaction with a visual interface that is out of arm's reach—for example, a family sitting on a living-room couch, controlling a game system on the television across the room. Pointing from a distance is becoming common in both work and domestic environments, and is used for a variety of applications such as playing games, giving presentations, or working on large-scale datasets. In these settings, traditional pointing devices such as mice do not work well, and direct-pointing hardware like the Nintendo Wii Remote, the Playstation Move controller, or the Microsoft Kinect are becoming

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popular (e.g., see Fig. 1). Pointing with these devices is simple—the user aims the device or their hand at the target that they wish to select, and an on-screen cursor provides feedback about the focus point of the targeting action. This kind of interaction is called relative ray-cast pointing: it is based on the idea of absolute ray-casting (e.g., laser pointers), but the use of a cursor means that there can be divergence between the actual direction of the device and the focus point. Although relative ray-cast pointing is simple and natural, the approach also presents problems: researchers have reported difficulties with fatigue (Oh and Stuerzlinger, 2002) and poor accuracy (Myers et al., 2002; Kopper et al., 2010) that can make relative ray-casting a tiresome and inefficient selection method, particularly with smaller targets. In addition, the relative nature of the technique means that clutching can be required when the on-screen cursor diverges from the actual direction that the user is pointing (Vogel and Balakrishnan, 2005).

In this paper, we investigate ways of addressing the accuracy and performance problems of relative ray-cast pointing; in particular, we are interested in target-assistance techniques that help users select targets. Several kinds of target-assistance techniques exist for mouse-based desktop environments, and these techniques can improve both accuracy and movement time. Researchers have considered several approaches including acquisition feedback (Akamatsu and MacKenzie, 1996; Akamatsu et al., 1995; Cockburn and Brewster, 2005; Cockburn and Firth, 2003; Fraser and Gutwin, 2000; Oakley et al., 2000), cursor warping methods (Ahlström et al., 2001; Hurst et al., 2007; Mandryk and Gutwin, 2008), expansions of the target in both visual space (Blanch et al., 2004; Grossman and Balakrishnan, 2005; McGuffin and Balakrishnan, 2002) and motor space (Blanch et al., 2004; Grossman and Balakrishnan, 2005; Worden et al., 1997), and reduction of distance to the target (Ahlström et al., 2001; Asano et al., 2005; Baudisch et al., 2003). Further, target assistance techniques have been widely used in video games

in order to address the lack of precision when aiming with a thumb-stick on a gamepad (Nelson, 2009). However, despite the large amount of research in these settings, very little work examines target assistance for distant-pointing scenarios. Some researchers have studied limited aspects of the problem, such as: the value of haptic feedback (Krol et al., 2009); assists for pointing in conjunction with speech (Tse et al., 2007); or, improvements for pointing on a tabletop (Parker et al., 2005). Previous work has not tested or compared a wide range of techniques, has not considered the perceptibility of the techniques, and has not examined settings in which people interact with a single large display, which we see as the most common usage scenario.

To provide a comprehensive investigation of the potential for target assistance in distant pointing, and to establish concrete guidelines for designers of systems that use distant pointing, we carried out several studies that tested and compared three representative target-assistance techniques. We focus on pointing devices that use relative ray-casting, and so we are able to explore motor-space assistance techniques that make corrections to cursor position. Relative ray-casting differs slightly from absolute ray-casting, where targeting is always determined by a direct line extending from a device (e.g., a laser pointer). Relative ray-casting has fewer constraints than absolute ray-casting, because cursor position is calculated—using technologies such as infrared cameras (e.g., the Wiimote and PSMove), accelerometers (e.g., the iPhone), depth cameras (e.g., the Microsoft Kinect), or gyroscopes (e.g., the Logitech MX Air Mouse). This means that there can be a difference between the pointing direction and the position of the cursor (called cursor divergence).

We tested three kinds of assistance technique: sticky targets, a motor-space technique that manipulates the pointing device's control-to-display ratio in order to increase the effective width of targets; target gravity, a motor-space technique that uses simulated gravity to increase effective target size and also decrease the effective distance to a target; and sensory acquisition feedback, a non-motor technique that provides visual, tactile and auditory signals when the cursor is over the target. The choice of these techniques is based on the observation that many of the causes of the accuracy problem in distant pointing (e.g., hand jitter, parallax between the eye and the device, button jitter, and the angular motion of the cursor) (Kopper et al., 2010) are ones that affect the acquisition stage of targeting, rather than the ballistic phase—that is, while it is not difficult to get the cursor near to the target with a ballistic motion, it is difficult to precisely place the cursor onto the target and hold it there while making a selection. The techniques we tested, therefore, all assist in the acquisition phase, rather than simply reducing the distance to the target.

In our investigation we first conducted three studies that tested the techniques individually, in order to determine each approach's effectiveness and perceptibility, and in



Fig. 1. Distant pointing in a casual computing environment.

order to find the optimal parameters for each technique. We then used the best versions of each technique in a larger comparison study testing both time and error rate. This study also introduced conditions with distractor targets that had to be crossed during the targeting motion (see Fig. 8); this is an important real-world factor for motor-space techniques, since the intermediate targets can cause problems by exerting drag on the cursor and by increasing the amount of cursor divergence. To explore these conditions more fully, we also tested a ‘speed-coupled’ variant of the sticky target technique that reduces drag effects when crossing distractors at high cursor speeds.

Our studies produced several new results that help designers understand the performance capabilities of the individual target-assistance techniques, the differences between the techniques’ underlying approaches, and the effects of real-world issues such as distractor targets and cursor divergence. The experiments show that motor-space assistance provides substantial improvements in distance-pointing settings: both sticky targets and target gravity provided significant improvements, reducing targeting time by almost one third and reducing errors by more than two thirds. In the comparison study, the target gravity technique performed best of all, with significantly faster performance than sticky targets. None of the sensory acquisition-feedback techniques performed better than no assistance, suggesting that the main problem in distant pointing is one of motor control (i.e., getting the cursor to the target), not one of feedback (i.e., perceiving that the cursor is on the target). Participants also preferred the motor-space techniques, and ranked the gravity technique highest.

In addition to the strong performance results for both motor techniques, our fourth study showed that the presence of distractor targets did not substantially affect performance. As a result, the ‘speed coupled’ variant of sticky targets was not better than the standard techniques. Finally, we observed that the issue of cursor divergence (separation between the on-screen cursor and the actual pointing direction), which can result from motor-space manipulations, did not seem to be perceived by users. These results suggest that motor-space assistance can be simply implemented and feasibly deployed in many different usage scenarios.

Our research makes five main contributions. First, we show that motor-space target assistance substantially improves targeting for relative ray-casting, and that this assistance is not highly perceptible to users. Second, we provide a novel implementation of target gravity that outperforms all other techniques, and was preferred by participants. Third, we provide concrete details for designers about how to configure both the sticky targets technique and the target gravity technique in order to obtain maximum efficiency, considering both effectiveness and perceptibility. Fourth, we provide evidence that motor-space techniques are not strongly affected by en-route distractors—a result that substantially improves

prospects for real-world deployment of these ideas. Fifth, we reinforce earlier studies showing that in typical usage situations, sensory acquisition feedback is unlikely to give performance improvements for distant pointing.

2. Background and related work

Targeting has been widely studied in HCI, and the underlying principles of aimed movement are well understood. In particular, Fitts’s (1954) Law states that targeting difficulty is determined by the index of difficulty (ID), which is calculated based on the size of the target and its distance from the starting location (MacKenzie, 1992). Kopper et al. (2010) found that the ID could be modelled more accurately in distant pointing scenarios by using the angular width of a target and the angular amplitude of the movement to the target. Selecting a target involves three phases: a ballistic motion, a corrective phase, and a final acquisition phase where the pointer is moved into the target and the selection action is performed (Meyer et al., 1988). The following sections review related literature for distant pointing and targeting assistance.

2.1. Distant pointing and ray-casting

Distant pointing techniques let people use natural pointing motions to interact with a distant display. The term ray-casting is used to indicate the basic idea of these techniques—that a control point on the display is projected as if it were a ray emanating from the user’s finger or handheld device.

Distant pointing provides a natural interaction solution in many computing environments where traditional pointing devices, such as a mouse, do not work well (e.g., domestic settings, presentation rooms, or multi-display environments). In these environments users may be relatively far from the displays, and there is often no surface that can be used for a mouse. Researchers have proposed multiple technologies for supporting these different types of input environments, including 3D input devices such as flying mice and hand-held isometric input (MacKenzie and Jusoh, 2001; Zhai, 1998), secondary displays that use world-in-miniature methods (Myers et al., 2002), hand tracking and glove technology (Sturman and Zeltzer, 1994; Tse et al., 2007; Vogel and Balakrishnan, 2005), absolute ray-casting using devices similar to laser pointers (Myers et al., 2002; Oh and Stuerzlinger, 2002; Olsen and Nielsen, 2001; Parker et al., 2005), and relative ray-casting using devices such as the Wiimote or the PlayStation Move (Campbell et al., 2008; Krol et al., 2009; McArthur et al., 2009; Natapov et al., 2009; Vogel and Balakrishnan, 2005).

2.1.1. Absolute ray-casting

Absolute ray-casting techniques are exemplified by laser-based pointing techniques that have been proposed and tested in prior work (Myers et al., 2002; Oh and Stuerzlinger, 2002; Olsen and Nielsen, 2001; Parker et al., 2005); other devices

such as 3D trackers have also been used for absolute ray-casting (Vogel and Balakrishnan, 2005; Jota et al., 2010). Researchers have looked at various issues in the use of these techniques, including the problem of reduced accuracy due to hand jitter (Olsen and Nielsen, 2001), and fatigue induced by need to hold the arm extended during pointing actions (Oh and Stuerzlinger, 2002).

Recent work by Jota et al. (2010) examined different pointing variants for absolute ray-casting, and considered both the way in which pointing gestures are made (i.e., using a finger or a handheld device), and the amount of parallax that exists in the technique. Parallax describes the apparent differences of an object's position when viewed from different locations, and in Jota et al.'s work it was used to describe the distance between the eye and the pointing device, leading to differences in the ability to correctly perceive pointing direction. The pointing variants were found to perform differently between task types (a pointing task versus a tracing task), indicating that people's perception of pointing direction depends on device and posture characteristics. It was also found that for pointing at very large screens, the angular formulation of Fitts's Law (Kondraske, 1994) provided better modeling than the traditional linear formulation (MacKenzie, 1992).

2.1.2. Relative ray-casting

Relative ray-casting techniques are similar to absolute methods, but relax the exact correspondence between the control point on the screen and the actual pointing direction of the user's arm or device (Vogel and Balakrishnan, 2005). This is a necessity with devices that determine position using accelerometers or external-to-display infrared light sources (such as that used in the Wiimote), since these technologies do not provide absolute sensing of the user's actual pointing direction. In relative techniques, there is a cursor on the screen that determines the selection location, but the position of the cursor is controlled by relative left-right-up-down movements of the device in the user's hand. In most situations, relative ray-casting can feel and work the same as the absolute technique; however, in some cases relative ray-casting can be affected by cursor drift, in which the on-screen cursor differs from the user's absolute pointing direction. Accumulated drift is called cursor divergence, and is investigated in more detail in the studies described below. To minimize cursor divergence some systems provide an onscreen calibration task, which allows a user to express their intended direction of pointing toward several onscreen targets. The system captures the direction of pointing during the calibration task, and calculates an offset between the raw pointing direction captured by the system and the user's intended pointing direction towards a defined target. Because such a system uses relative ray-casting, the system is able to use the calibration to mimic absolute pointing from a particular user's point of view.

Vogel and Balakrishnan (2005) compared different cursor-control schemes (absolute ray-casting, relative ray-casting, and a hybrid that combined relative and absolute) in combination with different hand positions for pointing and clicking targets on wall displays. They found that there were few differences between the techniques except in tasks in which the relative ray-casting method required clutching (i.e., disengaging the cursor while repositioning the hand to a more comfortable position). In these situations, the direction of pointing had become so different from that of the onscreen cursor (i.e., cursor divergence) that users needed to re-set their absolute pointing direction. Clutching is common with mouse-based pointing (e.g., when a user reaches the edge of the pointing surface), but has not been widely considered for distant pointing. Vogel and Balakrishnan (2005) implemented a clutching mechanism to allow users to self-correct cursor divergence.

2.2. Pointing studies with relative ray-cast devices

Our studies below use the Nintendo Wiimote as a representative device for relative ray-casting, so here we review work that has studied or used this device. We believe, however, that the underlying similarity of the Wiimote to other devices in terms of relative ray-casting means that our results will generalize to other devices such as the PlayStation Move controller, the Logitech MX Air Mouse, and the Microsoft Kinect.

The availability and low cost of devices like the Wiimote has allowed a variety of research involving distant pointing and relative ray-casting tasks (although prior work has not evaluated target assistance in-depth). Several researchers have compared the Wiimote to other devices: for example, Natapov et al. (2009) compared the performance of different video game controllers including the Wiimote, and found that the Wiimote had a throughput 31.5% lower than a standard mouse; McArthur et al. (2009) tested performance using different Wiimote attachments (e.g., a gun attachment) and different device buttons, but found only small differences between configurations.

Others have looked more specifically at pointing with the Wiimote. Campbell et al. (2008) investigated the differences between using the Wiimote as a zero-order device (i.e., controlling cursor position, as in ray-cast pointing) and as a first-order device (i.e., controlling cursor velocity, as with an isometric joystick), and found that using ray-cast pointing improved target selection times by a factor of 2.5. Finally, Krol et al. (2009) used the Wiimote in an initial study of sensory-acquisition feedback, which we describe in more detail below (Section 2.4).

Some research has also looked at the use of the Microsoft Kinect and other technology to enable distant pointing; e.g., (Reilly, 2011; Vogel and Balakrishnan, 2005). However, this previous work has not evaluated how target assistance could improve pointing performance using now common devices and displays, nor has a

comparison between techniques been performed, when using the Kinect or other devices.

2.3. Target assistance

The goal of target-assistance techniques is to improve the user's ability to select on-screen targets quickly and effectively, and it has been studied in a number of computing scenarios: desktop pointing using a mouse (e.g., Chapuis et al., 2009; Grossman and Balakrishnan, 2005), pointing in virtual environments (e.g., Elmqvist and Fekete, 2008; Frees et al., 2007), and in distant pointing (e.g., Bateman et al., 2011; Gallo and Minutolo, 2012).

Target assistance has been directed at all of three phases of pointing (ballistic motion, correction, and final acquisition) and techniques can be organized into four groups: manipulation of amplitude, manipulation of width, manipulation of both amplitude and width, and provision of sensory feedback during the acquisition phase. Here we briefly review each category; further details on target assistance in general, and on specific previous techniques, can be found in recent review of Balakrishnan (2004).

2.3.1. Amplitude manipulation

One class of techniques reduces targeting time by reducing the distance between the pointer and the target (i.e., the amplitude). Some techniques work by moving targets closer to the cursor: for example, the Drag-and-pop (Baudisch et al., 2003) and Vacuum (Bezerianos and Balakrishnan, 2005) techniques create proxies for likely target objects based on the initial movement of a drag action. Both of these techniques were shown to significantly improve targeting time on large touchscreen displays, where long-distance stylus translations require a considerable amount of time (note that the pointing method was direct touch, which differs substantially from the angular pointing of ray-casting techniques).

Other techniques warp the cursor closer to the target by predicting the endpoint of the targeting movement (Asano et al., 2005). For example, the Delphian Desktop uses initial trajectory and velocity information to determine a likely final location for the targeting action, and moves the cursor directly to that location with an animated transition. The technique was shown to be effective at distances of more than 800 pixels; however, accurate prediction of the final position of a moving cursor remains a difficult problem (Balakrishnan, 2004). In addition, cursor-warping strategies are less applicable to relative ray-casting techniques, since they (by definition) cause cursor divergence, sometimes substantially. This occurs because the cursor jumps towards the target, causing it to be out of line with the current pointing direction.

2.3.2. Width manipulation

A second type of target assistance increases either the visual-space width or the motor-space width of the target (we note here that 'width' implies the size of the target in

the direction of approach, not just the horizontal size). Visual expansion makes the target appear bigger (e.g., through the use of a fisheye lens, as in the Macintosh OS X Dock), which can assist users in seeing visual details of the target and in determining whether their pointer is on the target (McGuffin and Balakrishnan, 2002). However, visual-space expansion can also trick users into thinking that the target is larger in motor space than it really is, leading to overshooting errors (Gutwin, 2002). Even when the target size is increased in both visual and motor space, problems such as occlusion of neighbouring targets still exist (McGuffin and Balakrishnan, 2002).

Motor-space expansions increase the effective selection area of a target, rather than its visual size—that is, they increase the amount of movement in the real world (e.g., of the user's hand or mouse) needed to span a target. There are two main approaches: global techniques that increase the motor size of the target regardless of the cursor's location; and local techniques that operate only when the cursor is within the target's boundaries.

Global width-manipulation techniques use a variety of methods to increase the target's effective size. Some methods change the activation region of the cursor—for example, 'area cursors' allow users to select a target whenever the target overlaps a square or circular area around the cursor; this increases the size of any target by the width of the cursor's active region (Kabbash and Buxton, 1995). A recent approach called DynaSpot improves the precision of area cursors by increasing the size of the active region at higher movement speeds, and reducing it to a single point at low speeds, allowing more precise selection (Chapuis et al., 2009). Other techniques use the empty space around existing targets to increase their effective size. For example, the Bubble Cursor (Grossman and Balakrishnan, 2005) selects the closest target, regardless of the actual location of the cursor (i.e., targets fill their Voronoi region). This approach can dramatically increase target size, particularly for sparse target sets, but prevents selection of the empty space between targets (e.g., for 'rubber-band' multiple selection).

Local width manipulation occurs only when the cursor is on top of the target. The main strategy in the local approach (sometimes called 'sticky targets') changes the control-to-display ratio (i.e., CD gain) of the input device when the cursor is over a selectable target (Blanch et al., 2004). This means that the user must move the mouse farther to achieve the same cursor movement; the result is that the motor space of the target is increased (Fig. 2). The change in CD gain determines the degree of 'stickiness'; for example, an increase in CD ratio from 1:1 to 2:1 when the cursor is on the target results in an effective doubling of the width of the target. Researchers have found that sticky targets can improve aiming time in both 1D (Blanch et al., 2004; Cockburn and Brewster, 2005; Cockburn and Firth, 2003; Mandryk and Gutwin, 2008) and 2D (Worden et al., 1997), particularly for small targets (Cockburn and Firth, 2003). Previous work has also shown that users' perception

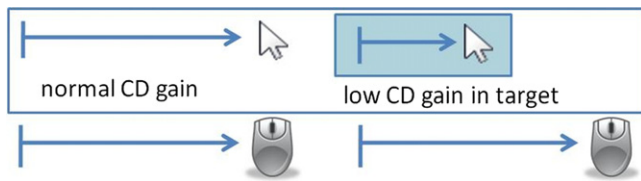


Fig. 2. Sticky targets. When the cursor is on the target (the shaded rectangle), more mouse movement is required to cross the target.

of the changing CD ratio is not as strong as the effect itself—at low to moderate levels of the effect, users rarely notice it at all, and at higher levels, they underestimate its effects (Mandryk and Gutwin, 2008). Research has also investigated scaling the CD ratio dynamically during a pointing task. In this work, CD ratio is set higher during rapid movements (the ballistic phase) to get the cursor as close to the target as possible while minimizing the required movement, and is set lower during slower movements (the corrective phase) to facilitate final acquisition (Rodgers et al., 2006). The use of CD ratio adaptation has also been investigated in distant pointing scenarios (Gallo and Minutolo, 2012).

Finally, we note that changing CD ratios with a relative ray-casting technique can also cause the cursor to drift from the user's actual pointing direction, although the effect is not as severe as with cursor-warping methods.

2.3.3. Manipulating both amplitude and width

A third class of techniques simultaneously changes both the size of a target and its distance; these techniques often use an 'attraction' metaphor in which the cursor is 'pulled towards' the targets. Some techniques use the idea of C:D manipulation described above, but act throughout the targeting motion rather than just over the target (e.g., Cockburn and Firth, 2003; Hurst et al., 2007; Worden et al., 1997). Studies have shown improved targeting times with these techniques, particularly for older adults (Worden et al., 1997) and very small targets (Cockburn and Firth, 2003).

The 'force fields' technique (Ahlström et al., 2001) exemplifies the approach. In this technique, pre-defined activation areas around a target pull the cursor towards the target; when the cursor is inside the force field, the cursor is subtly adjusted such that movements towards the target are slightly increased, and movements away are slightly decreased. Our target gravity technique (described below) is based on the force-fields approach. A similar technique uses the metaphor of 'magnetic dust' that is left around windows and widgets as they are used. The magnetic dust accumulates over time, meaning that frequently-used interface elements become more attractive to the cursor and thus easier to select (Hurst et al., 2007). One main potential drawback of these techniques is that of distractor targets—that is, if the user passes over or near a target on the way to their intended destination, the attraction forces of the en-route targets may disrupt the

user's targeting motion. We consider this issue further in the studies described below.

2.3.4. Acquisition-phase sensory feedback

In the acquisition phase of targeting, the user needs to know whether their cursor is correctly positioned over the target before they can carry out a selection action such as clicking a button on the pointing device. Most interfaces already provide basic visual feedback to support acquisition (i.e., the visible representation of the pointer over the target object), but the visual display may not be enough in some cases, particularly when targets are small or hard to see (Cockburn and Brewster, 2005; Cockburn and Firth, 2003). Researchers have investigated several types of additional sensory feedback for the acquisition phase, including extra visual highlighting on the target or the cursor, or other modalities including sound, tactile, or vibration feedback, e.g., (Akamatsu and MacKenzie, 1996; Cockburn and Brewster, 2005; Fraser and Gutwin, 2000; Oakley et al., 2000).

Auditory and tactile acquisition feedback has been used in assistive technology for users with reduced visual acuity, e.g., (Fraser and Gutwin, 2000), and force-feedback mice have been used to provide haptic feedback when the cursor is over the target (Oakley et al., 2000). In ordinary pointing situations, however, acquisition feedback appears to have only minor effects on targeting performance: a comparison of four types of feedback (visual, auditory, tactile, and a combination) did not find a significant improvement in targeting time or error rates with a mouse, but did find an increased preference for the additional feedback (Akamatsu and MacKenzie, 1996). Recent work has found some exceptions to this general result, however: one study focused on very small targets and showed that both audio and tactile feedback can reduce targeting time with a mouse by about 4% each (Cockburn and Brewster, 2005); and a study by Krol et al. (2009) found that selections with haptic and auditory feedback were faster than with visual feedback.

2.4. Targeting support for remote pointing

Research into remote pointing has primarily focused on correcting problems with specific devices, e.g., hand-jitter when using laser pointers (Oh and Stuerzlinger, 2002; Olsen and Nielsen, 2001), and on developing new interaction techniques that improve overall usability and expressiveness (e.g., Myers et al., 2002; Oh and Stuerzlinger, 2002; Olsen and Nielsen, 2001). However, a few projects have recognized the potential of target assistance for distant pointing. First, a small study by Krol et al. (2009) tested sensory acquisition feedback using a relative ray-casting device called the uWand, and showed that haptic and auditory information reduced targeting time compared with visual feedback. However, both the haptic and auditory conditions had higher error rates, and none of the participants preferred the haptic feedback. Second,

the bubble cursor technique was used in conjunction with speech input to create the Speech-Filtered Bubble Ray (Tse et al., 2007), which was used for large-screen displays and which added the ability to filter tightly clustered distractors using speech. The Speech-Filtered Bubble Ray outperformed both an unfiltered bubble ray and simple ray-casting. Third, work on the TractorBeam technique for distant pointing on tabletop displays investigated several methods for increasing the target width or reducing target distance (e.g., by snapping to the target when inside a threshold). While no one variant outperformed the others, participants preferred the distance-minimizing snap-to-target technique (Parker et al., 2005).

Recent work has explored the use of target assistance for balancing competition in a two-player pointing-based game (Bateman et al., 2011). One of the players was given target assistance in shooting onscreen objects, which increased their score. A study found that providing targeting assistance to the less-skilled player led to significantly closer game scores overall. In addition, as games became closer assisted players reported having more fun, and non-assisted players did not report any reduction in fun. Importantly, none of the players noticed that assistance had been given. This work provides evidence for the applicability and effectiveness of target assistance in entertainment scenarios; however, the techniques used and their perceptibility were not evaluated systematically.

While these techniques have shown promise in small-scale studies or domain-specific settings, it is important to note that they often change the target-selection process when compared to the traditional point-and-click interactions used with the mouse. In particular, users must learn new ways of understanding pointing and selecting (e.g., that they can click anywhere near the target with the bubble cursor, instead of needing to be inside the target),

which may cause difficulties for casual users. As a result, we chose techniques for our comparison study (described in the following section) that behaved as similarly as possible to standard pointing.

3. Techniques chosen for the comparison study

The goal of our investigation was to determine whether target-assistance techniques can reduce target selection time and error rate for relative ray-casting, and how the different techniques compare to one another. Our studies compare three representative techniques that have been considered in previous work: a sticky targets technique that changes effective target width when the cursor is on the target (Blanch et al., 2004; Cockburn and Brewster, 2005; Cockburn and Firth, 2003; Mandryk and Gutwin, 2008; Worden et al., 1997); a target gravity technique that attracts the cursor towards the target, inspired by Ahlström et al. (2001) and similar to Elmqvist and Fekete (2008); and feedback techniques that provide sensory indication when the cursor is over the target (Akamatsu and MacKenzie, 1996; Cockburn and Firth, 2003; Fraser and Gutwin, 2000; Oakley et al., 2000).

These techniques were selected in particular because we believed they would offer a good mix of low perceptibility (Mandryk and Gutwin, 2008) and potential for improving target acquisition. Further, because these techniques do not fundamentally change the on-screen appearance of targets or the cursor (e.g., they do not use visual expansion) and do not change the way that targets are selected (e.g., they do not use space outside the targets) they may be more widely applicable in real-world situations. All of the techniques were implemented in a custom study system (described below in Section 4.2) and were tested in the setting shown in Fig. 3 (which replicates display location

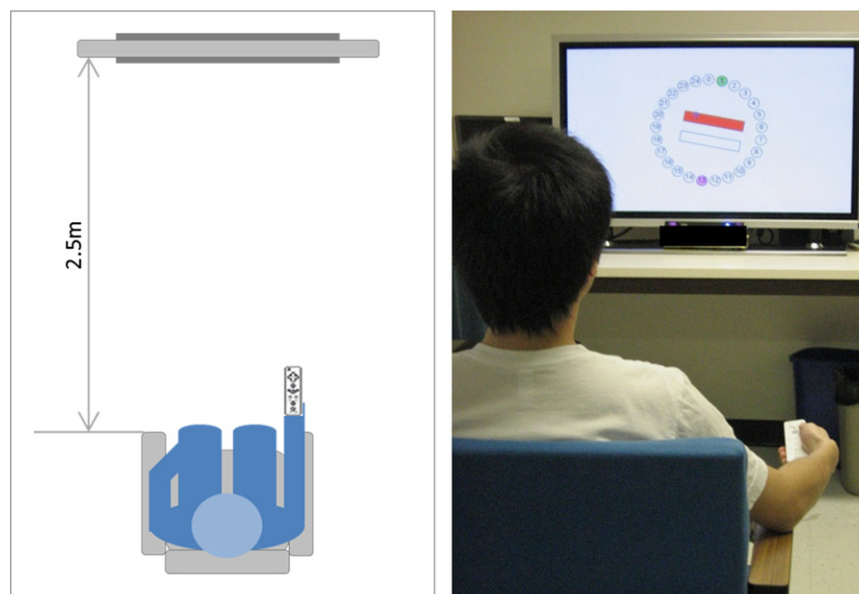


Fig. 3. Setting for evaluation of the target-assistance techniques.

and distances that are common in use of the Nintendo Wii game system).

3.1. The sticky targets technique

The sticky targets technique was built as a custom module that intercepted movement events from the system cursor, manipulated the resulting cursor locations, and displayed a replacement cursor in the study application (the system cursor was hidden). Target stickiness was applied when the cursor was over a target, by changing the CD ratio of the input signal. Stickiness levels were calculated as $1 - \text{CD gain}$: the higher the level, the stickier the target. For example, a level of 0.4 meant that while on the target, a mouse movement would result in a 40% reduction in the normal cursor movement on screen.

We used a sweep-test technique to avoid the problem of missing targets due to low sampling rates (Cockburn and Firth, 2003): for every movement event from the device, we calculated whether the cursor had crossed a target since the last location, and adjusted the cursor position accordingly.

3.2. The target gravity technique

Our implementation of target gravity is similar to the ‘force field’ technique (Ahlström et al., 2001); but instead of restricting a target’s attraction to a limited range around the target, we calculate the gravity effect for all targets at all times, regardless of the position of the cursor. Because target gravity is inversely proportional to the square of the distance between the cursor and the target, the influence of a target decreases rapidly at greater distances.

Our gravity effect is calculated as follows. For n targets, let p_1, p_2, \dots, p_n be the positions of the targets with radii r_1, r_2, \dots, r_n . Let p_0 represent the true position of the cursor (i.e., without any gravity effect applied), and let p_w be the warped position. Let G be the ‘gravitational constant’ (i.e., a weight multiplier that determines the strength of the attractive effect). Then, for each target $i=1..n$, compute the target’s level of attraction (w_i) with Eq. (1). Finally, the warped position (p_w) of the cursor is calculated using Eq. (2).

$$w_i = \frac{Gr_i^2}{|p_0 - p_i|^2 + 1}, \quad \text{with } w_0 = 1 \quad (1)$$

$$p_w = \frac{\sum_{i=0}^n w_i p_i}{\sum_{i=0}^n w_i} \quad (2)$$

The warped position is a weighted average of the true cursor position and the positions of each target. The weight for the cursor position is fixed at 1.0, and the weight for each target is inversely proportional to the square of the distance between the cursor and that target. The weights for each target are proportional to the area of the target, and are multiplied by the gravitational constant G . Manipulating G in the study changed the strength of the

gravity effect. We note that our formula is similar to an approach from previous work, but applied to a different context; the original research concerned selection of objects with a mouse in a 3D virtual environment (Elmqvist and Fekete, 2008).

3.3. Sensory acquisition feedback

Previous research has shown at least limited benefit in providing both tactile and auditory feedback; we considered these two modalities as well as basic visual feedback. In our studies, the feedback was given continuously when the cursor was over the target.

- Tactile feedback was provided with the Wiimote vibration motor; tactile feedback started when the cursor entered the bounds of the target, and ended when the cursor left the target. Although Krol et al. (2009) found a 70 ms delay in the start of the vibration motor (using the uWand device), our pilot testing with the Wiimote showed vibration to be approximately coincident with target entry, so we assume a negligible latency.
- Auditory feedback was provided by playing a continuous 130 Hz sine-wave tone through external speakers placed beside the display; as used by previous study of Cockburn and Brewster (2005).
- Visual feedback was provided by changing the target’s colour to red whenever the cursor was within the target’s boundaries.

4. Studies of target assistance for relative ray-casting

We carried out four studies to investigate performance and perceptibility of the target-assistance techniques described above. The first three studies investigated each technique separately (allowing us to explore a wider range of values and task difficulties); the fourth study compared the best versions of each technique. In selecting the best versions from the first three studies, we chose two versions that provided a large performance improvement with only a small degree of perceptibility. These two qualities are important because real-world applicability requires that techniques offer substantial advantages in facilitating pointing, but without distracting the user or interfering with existing interactions.

4.1. Study apparatus and task

All studies used a custom experiment system built in C that took input from a Wiimote input device, using the Wii Device Library (code.google.com/p/wiidevicelibrary). The system ran on a Windows 7 Core 2 Duo machine and displayed output on a Dell 107 cm plasma television with a resolution of 1280×768 pixels. The testing system was able to achieve a sampling rate from the Wii Remote of at least 90 samples per second. Participants sat in an office chair with armrests, 2.5 m from the screen (see experiment setup in Fig. 3).

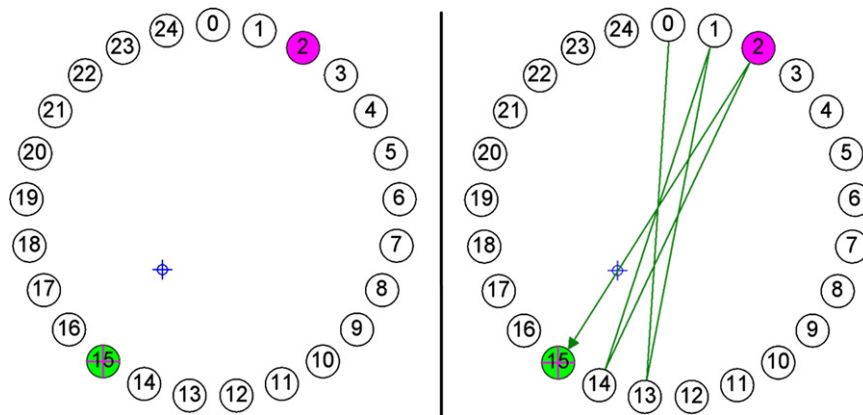


Fig. 4. Examples of the study system and the ISO pointing task. The right image shows the targeting sequence for first 5 trials (beginning at 0 ending at 15). The initial target of each trial is coloured purple, and the end target is green with a purple cross. When the end target is selected, it becomes the starting target (i.e., it changes to purple) for the next trial. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The targeting task was the two-dimensional pointing task specified in standard 9241 of ISO (1998). This task shows a ring of circular targets and asks participants to select each target one at a time; the next target is always directly across the ring (see Fig. 4). The next target to be selected is coloured green and marked with a purple cross. Participants selected the target by moving the cursor onto the target area and clicking the ‘B’ button on the bottom of the Wiimote device.

5. Study 1: Sticky targets

The first study investigated the effectiveness and perceptibility of the sticky-targets technique, and also determined which level of the effect provided the best mix of these two factors, for later use in the comparison study.

5.1. Methods

5.1.1. Participants

Nine volunteers (six females) aged 19–30 years were recruited from a local university. All were right-handed and all were experienced users of computers (> 7 h per week). All participants were familiar with the Wiimote device, and seven of the participants were regular users of the device (at least once per week).

5.1.2. Experimental conditions, design, and procedure

Study 1 used a $10 \times 3 \times 3$ repeated-measures design, with three factors:

- stickiness (ten levels from 0.0 to 0.9);
- target width (2 cm, 2.8 cm, 3.6 cm);
- movement amplitude (30 cm, 35 cm, and 40 cm).

The study was organized into 10 effect blocks (representing each level of stickiness). Target widths and

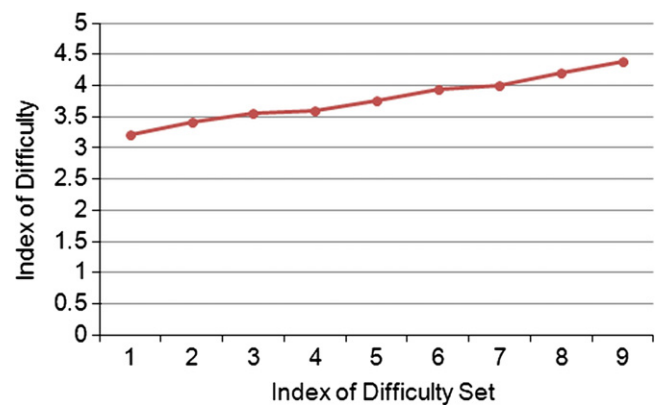


Fig. 5. Indices of difficulty of the targeting tasks used in studies 1–3.

movement amplitudes were chosen to provide a range of indices of difficulty, as shown in Fig. 5. These widths were selected based on providing a range of target widths that approximated the size of buttons in systems such as the Wii or Playstation, and that we had determined through informal piloting to be large enough to be consistently acquired by all participants. The amplitudes were selected such that the largest amplitude allowed all targets to fit within the bounds of the display, and the smallest amplitude allowed all targets to be displayed without overlapping one another. This produced a range of IDs (3.2–4.3) that is consistent with previous work in Fitts’s law studies (Soukoreff and MacKenzie, 2004) and distant pointing (Oh and Stuerzlinger, 2002). The IDs (Fig. 5) were calculated using the Shannon formulation of Fitts’s law (MacKenzie, 1992). The model of distal pointing proposed by Kopper et al. (2010) calculates IDs based on the angular width of the target and the angular amplitude, which would result in higher IDs than those provided in Fig. 5.

Users worked in a block completing one set of trials (25 trials or one trip around the circle, see Fig. 4) for each

unique combination of amplitude and width. This equated to 10 blocks \times 9 index-of-difficulty sets = 90 conditions, and 90 conditions \times 25 trials = 2250 trials/participant. Blocks were ordered using a Latin square design.

At the beginning of the experiment, the participant completed a short background questionnaire regarding their general computer use and experience with different pointing devices; they were then introduced to the sticky targets technique. Before each effect block, the participant completed a set of practice trials to introduce them to the new effect level. They then completed the nine sets of trials for each index of difficulty in the effect block. In all conditions, standard visual feedback was provided by changing the target's background colour to red when the cursor entered the target boundary. After each effect block the participant completed a survey asking about the overall perceptibility of the effect. The study took approximately 1 h to complete.

5.1.3. Data collection and analysis

Movement time and error rate for each targeting trial were collected through computer logs, and user perceptions of the effect were recorded in the surveys. Movement time (MT) was calculated as the time from selection of one target to selection of the next target. Errors were counted whenever a user clicked outside of the target prior to acquiring it, thus it was possible for a single trial to have multiple errors. The error rate was then calculated by dividing the total number of errors counted for one 25-trial block and dividing by 25, to get a per trial error rate (ER). Outlier trials (when MT was more than 3 standard deviations above the mean for the block) were removed (230 trials; 1.0% of the total number). Mean MT and ER were used in subsequent analyses.

Quantitative data were analysed using repeated-measures multivariate analysis of variance (RM-MANOVA) with $\alpha=0.05$, and the Bonferroni adjustment was used for all pairwise comparisons. When the sphericity assumption was violated, the Huynh–Feldt method for adjusting the degrees of freedom was used. Survey data were analysed using the appropriate non-parametric technique.

5.2. Study 1 results: Effects of stickiness on movement time and error rate

We conducted a $10 \times 3 \times 3$ RM-MANOVA on MT and error rate with stickiness, width, and amplitude as factors. There were significant main effects of stickiness on both dependent measures (MT: $F_{9,72}=11.31$, $p \approx .000$. ER: $F_{9,72}=5.83$, $p \approx .000$). As shown in Fig. 6, increasing stickiness to 0.6 or above reduced targeting time by about three-tenths of a second per trial. Fig. 3 also shows that the effect on errors was more dramatic: increasing stickiness to 0.6 or above reduced the error rate from nearly 0.40 errors per trial to 0.16. Although the sticky targets technique is clearly effective, higher levels of stickiness reached a performance plateau for both MT and ER, suggesting there is a point at which having increasingly stickier targets does not improve performance.

We note that the error rate was considerably higher than in many targeting experiments (i.e., almost 0.4 errors/trial when no assistance was given). This is a characteristic of distant pointing with a device like the Wiimote—it is more difficult to keep the cursor on the target than in a mouse-based environment, because of hand and arm jitter and button jitter (i.e., the device moves when the button is pressed). This characteristic makes it all the more important to provide target assistance that can reduce errors, as discussed further below.

There was no interaction between movement amplitude and stickiness for either measure (MT: $F_{18,144}=1.6$, $p=.067$; ER: $F_{18,144}=0.8$, $p=.746$). There were, however, significant interactions between target width and stickiness (MT: $F_{18,144}=3.6$, $p \approx .000$; ER: $F_{18,144}=2.8$, $p \approx .000$), see Fig. 7. Pairwise comparisons showed that stickiness had more of an effect on both time and errors when targets were small.

5.3. User perception of stickiness

After each block of trials, we asked participants rate the stickiness of the target on a scale from 0 to 6 (higher is more sticky—see Fig. 8). There was a significant correlation between actual and perceived stickiness (Spearman's $\rho=.513$, $p \approx .000$). It is important to note that even when no assistance was given (sticky level = 0) participants

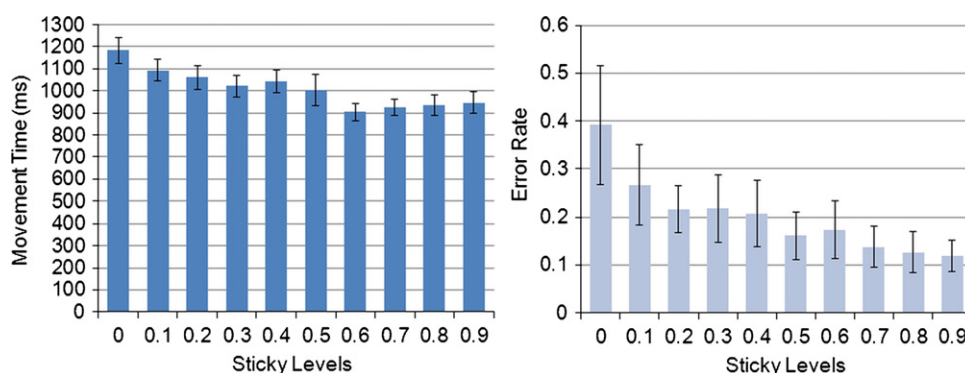


Fig. 6. Mean MT (left) and ER (right) \pm SEM, by level of stickiness. (the level number indicates the degree of reduction in on-screen cursor movement; e.g., level 0.6 implies that mouse movement is multiplied by 0.6).

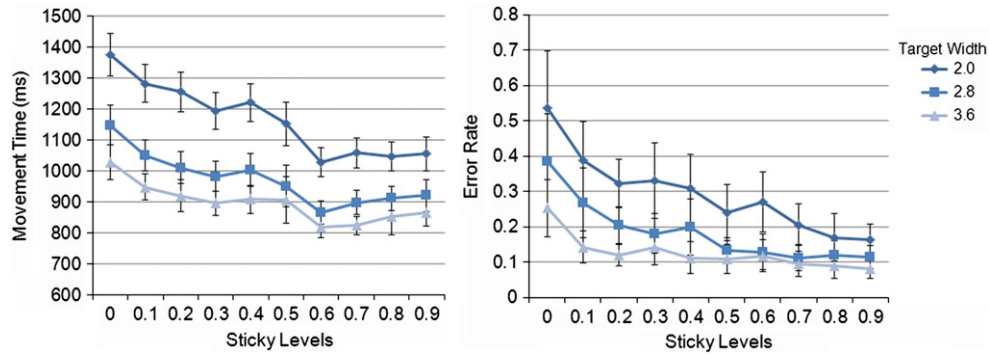


Fig. 7. Interaction effects of sticky level and target width on MT \pm SEM (left) and ER \pm SEM (right).

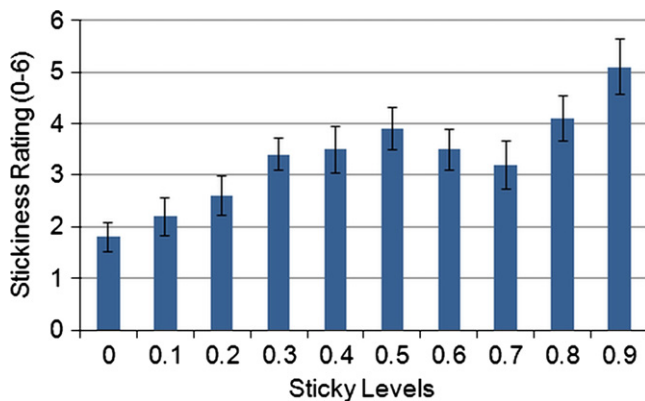


Fig. 8. Mean user ratings of perceived stickiness \pm SEM.

still perceived an effect; likely due to a combination of jitter that is inherent in the device and an existing expectation for an effect to be present. However, as the effect increased to moderate levels, participants ratings of stickiness did not increase substantially. In particular, there does not seem to be much of a difference in the mid-range of stickiness and participants' perceptions of how sticky the effect was. This indicates that it is difficult for people to detect differences in the strength of the technique, despite the fact as targets became stickier performance was benefitted.

We did not test for differences in all levels of perceived stickiness, but did use this data to assist us in choosing levels of stickiness for study 4. For our comparison in study 4, we wanted levels of stickiness that combined improved targeting and low perceptibility. We selected two levels: a low-perceptibility level (the highest level that was not perceptibly different than no stickiness as determined by Wilcoxon signed ranks tests), and a high-assist level (the highest level before performance reached a plateau, as shown in Fig. 6). These criteria indicated stickiness of 0.2 for the lower level and 0.6 for the higher.

6. Study 2: Target gravity

Study two duplicated the sticky targets study, but with target gravity as the assistance technique. Methods and analyses were identical to study one, with exceptions as

noted below. The target gravity technique works by both decreasing target amplitude and increasing target width (in contrast to sticky targets, which only manipulates target width). In addition, our version of target gravity addresses some of the shortfalls we saw in similar techniques (described below).

6.1. Methods

Nine volunteers (seven females) aged 20–29, who did not participate in study 1, were recruited from a local university. All were experienced computer users (> 7 h per week), all were familiar with the Wiimote device, and four participants were regular users of the device (at least once per week).

Study 2 used the same $10 \times 3 \times 3$ design as study 1, but with ten levels of target gravity (i.e., the 'gravitational constant' G as described in Section 3.2): 0.0, 0.01, 0.03, 0.08, 0.22, 0.63, 1.76, 5.0, 14.1, and 39.8. These values were chosen by selecting equally-spaced values (on a log10 scale) between 0 and 39.8; the upper value was identified during pilot testing as the maximum value that still allowed users to complete their tasks. The other factors were the same as in study 1 (target widths were 2 cm, 2.8 cm, and 3.6 cm; movement amplitudes were 30 cm, 35 cm, and 40 cm). All other methods, including the task, experimental setup, and procedure were identical to those of study 1.

6.2. Study 2 results: Effects of gravity on movement time and error rate

A $10 \times 3 \times 3$ RM-MANOVA on time and error data (347 outliers were removed, 1.7% of the total) showed main effects of gravity level on both dependent measures (MT: $F_{9,72}=25.8$, $p \approx .000$. ER: $F_{0,72}=9.3$, $p \approx .000$). Fig. 9 shows that increasing target gravity reduced MT and ER; in addition, these reductions continued at higher levels of gravity (i.e., there is no plateau as was seen with sticky targets).

There was no interaction between movement amplitude and gravity for either measure (MT: $F_{18,144}=0.5$, $p=.972$; ER: $F_{18,144}=0.5$, $p=.971$). There was a significant interaction between target width and gravity for MT,

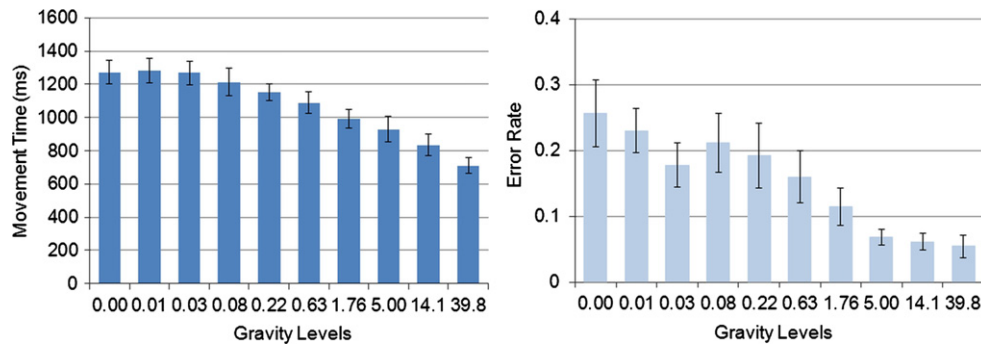


Fig. 9. Mean MT (left) and ER (right) \pm SEM, by level of gravity.

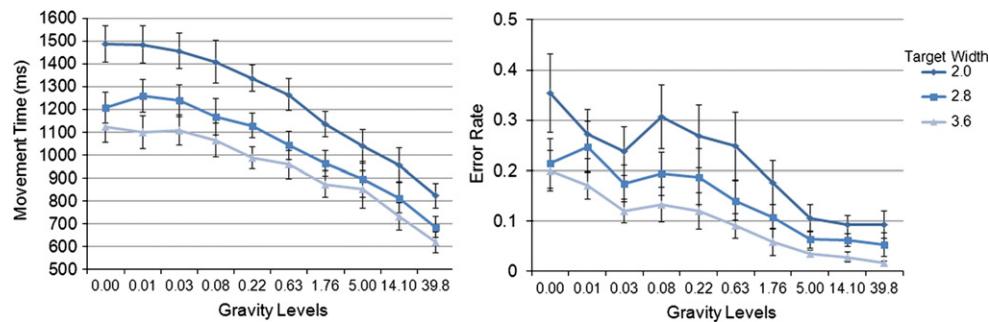


Fig. 10. Interaction effects of target width and gravity level, on MT (left) and ER (right) \pm SEM.

but not for ER (MT: $F_{18,144}=5.1$, $p \approx .000$; ER: $F_{18,144}=1.4$, $p=.120$), see Fig. 10. The effect of width on MT was reduced for high gravity levels.

6.3. User perception of gravity

We recorded participant perceptions of the level of gravity after each block (see Fig. 11). There was a significant correlation between actual and perceived gravity levels (Spearman's $\rho=.464$, $p \approx .000$). However, as observed in the sticky targets study, participants perceived the effect even when there was none present. Further, Wilcoxon signed ranks test showed that users did not perceive a difference between no gravity and gravity until the two highest levels. This means that even though the gravity technique provided benefit at lower levels, participants did not rate it as being particularly perceptible. Overall, participants did not rate the perceptibility of the techniques in accordance with the real benefits they received in terms of reduced errors and time.

We did not test for differences in all levels of perceived gravity, but did use this data to assist us in choosing levels of gravity for study 4. For later comparison in study 4, we again chose two levels of the assistance technique: a low-perceptibility level and a high-assist level. For the low-perceptibility level, we chose gravity of 0.03 to correspond with the choice for stickiness from study 1. For the high-assist level, we chose a gravity of 5.0 (high assistance without a significantly-different level of perception from no gravity).

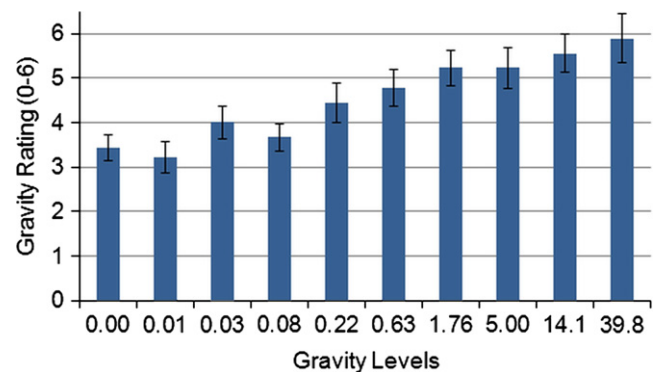


Fig. 11. Mean user ratings of perceived gravity \pm SEM.

7. Study 3: Acquisition feedback

The third study tested the effects of acquisition feedback on targeting. As described above in Section 3.3, the types of feedback included tactile (the Wiimote vibration motor), visual (red highlight on the target), and auditory (a 130-Hz tone). The study looked at all combinations of these three types (three conditions with one type, three with two types, one with all three, and one with no feedback at all). The study was again similar to study 1, with exceptions as outlined below.

7.1. Methods

Eight volunteers (3 female), aged 20–29 years, who had not been in the other studies, were recruited from a local

university. All participants were experienced computer users (>7 h per week) and all were familiar with the Wiimote device (at least once per week). Study 3 used an $8 \times 3 \times 3$ repeated-measures design, but with sensory feedback as the main factor (eight levels for the different combinations of visual, auditory, and tactile feedback as described above). The other factors were again the same (target widths 2 cm, 2.8 cm, and 3.6 cm; amplitudes 30 cm, 35 cm, and 40 cm), and all other methods were identical to those of study 1.

7.2. Study 3 results: Effects of feedback on performance

An $8 \times 3 \times 3$ RM-MANOVA on time and error data (231 outliers removed, 1.6% of the total) showed no significant main effects of feedback on either measure (MT: $F_{2,6,18.7}=1.0$, $p=.412$. ER: $F_{3,1,21.4}=1.4$, $p=.275$). As shown in Fig. 12, none of the different feedback combinations led to a clear improvement in time or errors.

There was no interaction between movement amplitude and feedback type for either measure (MT: $F_{14,98}=0.7$, $p=.740$. ER: $F_{14,98}=1.1$, $p=.348$), or between width and feedback type (MT: $F_{14,98}=1.2$, $p=.262$. ER: $F_{14,98}=0.5$, $p=.928$).

Even though these results showed no clear advantage of providing sensory feedback, we selected a version of the technique for comparison in study 4. Because there was no one feedback technique that outperformed others, we chose the combination of all feedback types; previous work has shown that while the sensory techniques do not have an additive benefit, they also do not interact negatively (Akamatsu and MacKenzie, 1996).

8. Summary of the three initial studies

There are three main results from the initial studies:

- Both gravity and target stickiness had a significant effect on both targeting time and error rate; as stickiness or gravity level increased, both time and errors decreased (Figs. 6 and 9).
- Perception of gravity and stickiness lagged behind benefit: that is, the effects of gravity and stickiness

could provide benefits without being perceived significantly differently by participants than when no effect was used.

- Gravity and stickiness were perceived inconsistently: Although, in general, effects were more perceived as they increased, participants rated the level of the techniques inconsistently between levels. This means that it is difficult for people accurately detect the strength of the techniques, likely because they are quite subtle.
- No significant effect was observed for any of the sensory feedback techniques on either completion time or error rate (Fig. 12).

9. Study 4: Comparison study

In order to directly compare the different techniques, we carried out a fourth study that included several target-assistance techniques from the initial experiments. In the fourth study, we looked at performance in standard targeting tasks (i.e., the task used in the earlier studies), but also investigated the effects of intermediate distractor targets, which could hinder the effectiveness of targeting assists by introducing cursor divergence (see Fig. 13). The intermediate targets conditions also led us to test a speed-coupled variant of sticky targets (described below in Section 9.1.4).

9.1. Methods

9.1.1. Participants

We recruited 16 volunteers (8 females), aged 18–34 years, who did not participate in any of the previous studies. All were experienced users of computers (>7 h per week), and all were familiar with the Wiimote (seven participants used it more than once per week).

9.1.2. Experimental conditions: Target-assistance Techniques

As described above, we used the results from the preliminary studies to select five techniques for the comparison study. These five, along with two forms of the speed-coupled technique and a control condition, made eight techniques in total:

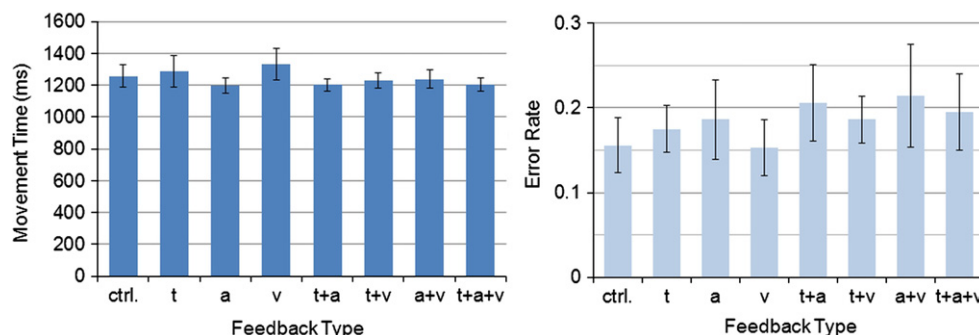


Fig. 12. Mean MT (left) and ER (right) \pm SEM, by feedback type (ctrl=no feedback, t=tactile, a=auditory, v=visual).

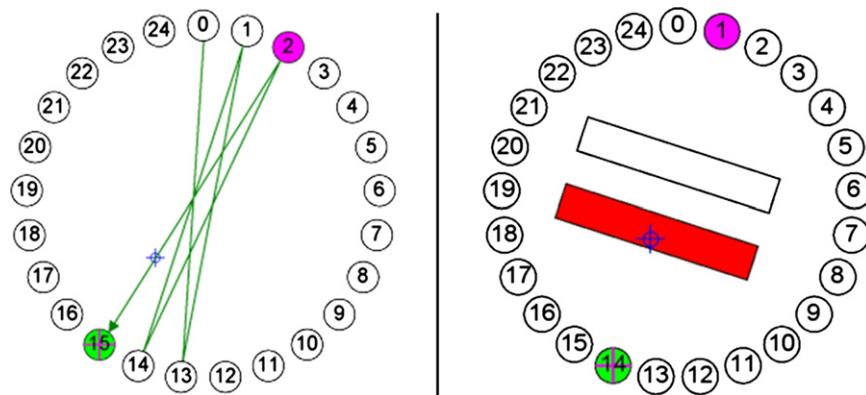


Fig. 13. Examples of the study system. On the left, the system with no distractors (as used in the earlier studies); green lines indicate the first five trials. The right side shows the system with two intermediate distractors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- Sticky targets ‘low’: stickiness of 0.2;
- Sticky targets ‘high’: stickiness of 0.6;
- Target gravity ‘low’: gravity of 0.03;
- Target gravity ‘high’: gravity of 5.0;
- Sensory acquisition feedback: combination of tactile+auditory+visual;
- Speed-coupled sticky targets ‘low’: stickiness of 0.2 with reduction at high cursor velocity;
- Speed-coupled sticky targets ‘high’: stickiness of 0.6 with reduction at high cursor velocity;
- Control: visual feedback only (targets turn red when the cursor enters).

were centered in the circle, and were always perpendicular to the direction of motion.

9.1.4. Study design, procedure, and data analyses

The study used an $8 \times 3 \times 3$ repeated-measures design, with three factors:

- assistance technique: control, sticky-low, sticky-high, gravity-low, gravity-high, low speed-coupled sticky (low sc sticky), high speed-coupled sticky (high sc sticky), sensory-feedback (tactile+auditory+visual);
- target width: 2 cm, 2.8 cm, 3.6 cm;
- number of intermediate distractors: 0, 1, or 2.

The speed-coupled sticky targeting technique reduces stickiness at higher cursor speeds, similar to previous approaches for improving sticky targets (Rodgers et al., 2006) and also to the DynaPoint (Chapuis et al., 2009) and PRISM (Frees et al., 2007) techniques. We implemented this technique to explore a method of counteracting the cursor divergence problem (which is intensified by moving through distractor targets). When the cursor movement is above a preset threshold, then targets have no sticky effect; when speed is below the threshold the effect is scaled linearly, so that it approaches full stickiness at slower movements. We selected a movement threshold of approximately 500 cm/s based on results from pilot tests.

9.1.3. Intermediate distractor targets

We used intermediate distractors to model the real-world situation of having to move the cursor through additional objects en route to the desired target. This factor is important in identifying potential problems for target assistance in realistic use. We incorporated zero, one, or two intermediate distractor targets into the targeting tasks, implemented as 20 cm bars inside the circle of targets (see Fig. 4). The bars were the same width as the targets for the condition being tested, and also employed the current targeting assist (i.e., they were sticky, or exerted gravity, or provided sensory feedback). The bars

We did not vary movement amplitude in this study, as it showed no interaction in our initial experiments; amplitude was therefore fixed at 30 cm. Visual acquisition feedback (i.e., a simple target highlight) was provided in all conditions.

The study was organized into 8 effect blocks (representing each assistance technique). Users worked in a block completing one set of trials (25 trials, one trip around the circle) for each unique combination of target width and number of distractors. With 8 effect blocks, 3 target widths, 3 distractor combinations, and 25 trials per condition, there was a total of 1800 trials per participant. Order of effect blocks was balanced using a reverse Latin square. The study procedure was similar to that described above, with introductions to the different techniques and practice trials given at the start of each effect block. The study took approximately 45 min to complete.

Data analyses involved the dependent variables movement time and error rate; these were collected for each targeting trial and were recorded by the study software. As in the previous studies, movement time (MT) was calculated as the time from selection of one target to selection of the next target; errors were counted whenever a user clicked outside of the target prior to acquiring it. Outlier trials (when MT was more than 3 standard deviations above the mean) were removed (250 trials were removed,

comprising 1.0% of total trials). Mean MT and the sum of errors for the 25 trials in each set were used in subsequent analyses.

Quantitative data were analysed using repeated-measures multivariate analysis of variance (RM-MANOVA) with $\alpha=0.05$; the Bonferroni adjustment was used for all pairwise comparisons. When the sphericity assumption was violated, the Huynh–Feldt method for adjusting the degrees of freedom was used.

After each condition, we also asked participants to rate each technique for ease of use, perceived accuracy, and overall impression. Survey data were analysed using the appropriate non-parametric technique.

9.2. Study 4 results

We carried out an $8 \times 3 \times 3$ RM-MANOVA on MT and ER. See Table 1 for a summary of the statistical tests, and Fig. 14 for a visual summary of MT and ER. Note that the 3-way interaction (not reported) was not significant for either time or errors. In the following paragraphs, we interpret these results in terms of the effects of feedback type and target width, the effects of intermediate distractors, and user preferences. We also report observations about participant experiences with cursor divergence.

9.2.1. Main effects of assistance technique, target width, and distractors

Assistance Technique—RM-MANOVA showed a significant main effect of assistance technique on both MT ($F_{5.5,82.4}=21.3$, $p \approx 0.00$) and ER ($F_{1.6, 23.3}=7.7$,

$p=0.005$). Pairwise comparisons for assistance technique on MT showed that the gravity-high technique was faster than all other assistance types. The sticky-high technique was faster than all lower types except for speed-coupled-high. Finally, speed-coupled-high sticky was comparable to speed-coupled-low sticky, but faster than gravity-low, sticky-low, sensory-feedback, and control. Pairwise comparisons for assistance technique on error rate showed that the high levels of the motor-control assists (gravity-high, sticky-high, and speed-coupled-high) resulted in fewer errors than speed-coupled-low, sensory-feedback, and control. Movement time and error rate results are shown in Fig. 14.

The data show that adding a speed-coupling effect to the sticky techniques did not improve performance, and may in fact have slightly diminished the usefulness of the assistance technique, even when there were distractor targets. This could be because the addition of speed coupling actually reduces the sticky effect too much during the final acquisition phase of targeting; we discuss this possibility further below.

Target width—There was, as expected, a significant main effect of target width on both MT ($F_{1.2, 17.6}=148.5$, $p \approx 0.00$) and ER ($F_{1.1, 15.8}=21.4$, $p \approx 0.00$). Pairwise comparisons showed that all levels of target widths were significantly different for both MT and ER. These data are shown in Fig. 15.

Number of distractors—There was a significant main effect of the number of distractor targets on movement time ($F_{2.0, 30.0}=5.7$, $p=0.008$), but not on error rate ($F_{2.0, 30.0}=0.1$, $p=0.927$). Pairwise comparisons for number of distractors on MT show only that aiming with no distractors was faster than aiming with two. These data are shown in Fig. 16.

Table 1
Results of RM-MANOVA on MT and ER.

	MT			ER		
	Df	F	p	df	F	p
Assistance technique	5.5, 82.4	21.3	.000	1.6, 23.3	7.7	.005
Target width	1.2, 17.6	148.5	.000	1.1, 15.8	21.4	.000
Number of distractors	2.0, 30.0	5.7	.008	2.0, 30.0	0.1	.927
Width \times feedback	11.0, 164.8	8.2	.000	2.5, 37.4	3.3	.037
Width \times distractors	4.0, 60.0	0.6	.698	4.0, 60.0	0.8	.548
Distractors \times feedback	9.6, 143.5	2.8	.003	1.4, 20.8	1.3	.279

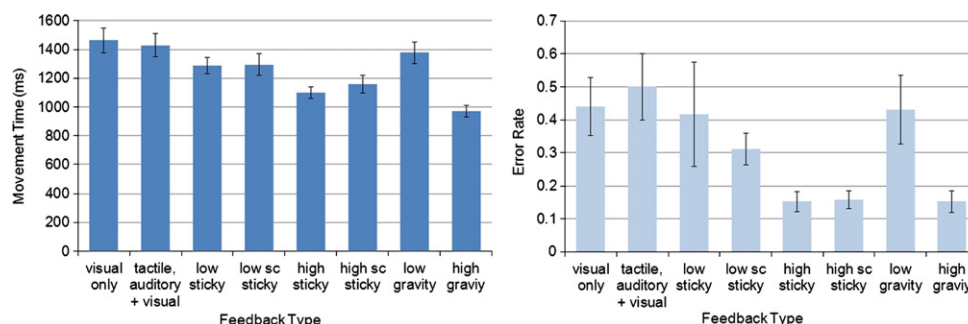


Fig. 14. MT and ER per trial (\pm SEM), by feedback type.

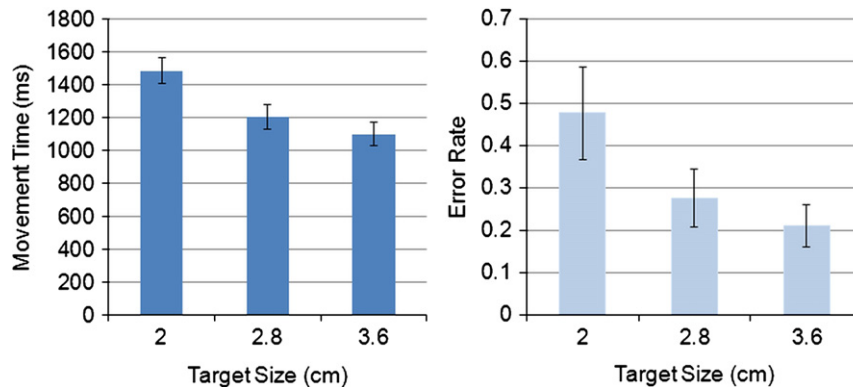
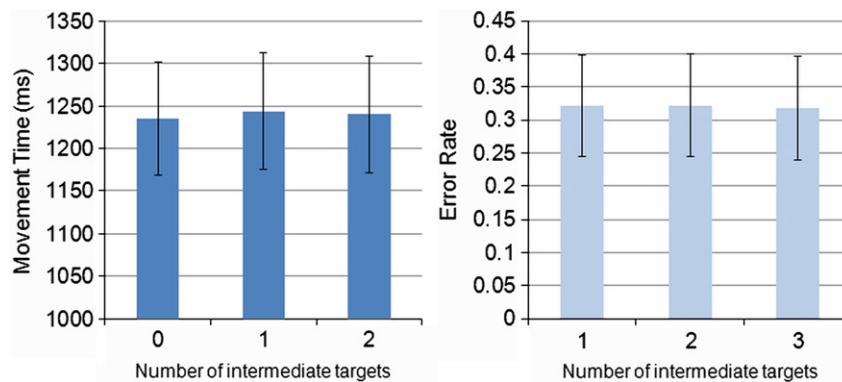
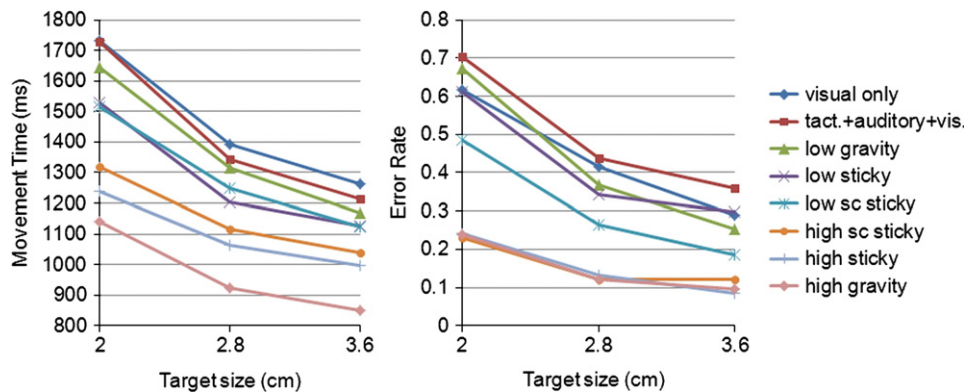
Fig. 15. MT by target size (left) and ER by target size (right) \pm SEM.Fig. 16. MT by target size (left) and ER by target size (right), \pm SEM.

Fig. 17. MT (left) and ER (right) by target size and technique.

The width-by-technique interaction on MT indicates that the differences between assistance techniques vary by target width. Two of these variations are evident in the summary shown in Fig. 17. First, the advantage of the gravity-high technique is greater at larger target widths. This is not surprising given that in our formulation of the technique, target gravity is directly proportional to the target width; as the target gets smaller the strength of the effect is reduced compared to the other assists. Second, the advantage of speed-coupled-high sticky is greater for small targets, and there is less difference between this technique and the lower-performing techniques at the medium and large target sizes.

The width-by-technique interaction on error rate (Fig. 17) showed that for some techniques (e.g., all of the 'high' techniques) the error rate did not change between the medium and large target widths. One reason for this result is that at high levels of motor manipulation, the width of the medium and large targets in motor space would likely be larger than what the participants needed to aim accurately.

The distractors-by-technique interaction on MT suggests that different techniques were affected differently by the en route distractors; this is expected, since some techniques (e.g., control and sensory-feedback) were not slowed down at all when passing over the distractors (see Fig. 18).

In addition, Fig. 18 shows that the ‘high’ versions of the assistance techniques were more affected by the presence of distractors (also as expected). However, despite the fact that the distractors did significantly increase movement time for high levels of motor manipulation, this did not seem to bother participants and they were still significantly faster than the other techniques. Therefore, although distractors do affect the techniques, they do not negate their benefits.

9.2.3. User preferences

After participants used each assist technique, we asked them to rate that technique for ease of use, perceived accuracy, and overall preference, on a scale of 0–6 (higher is better). As Fig. 19 shows, users thought that the high levels of stickiness and gravity were easiest to use, were the most accurate, and were most preferred overall. In addition, participants thought that the control and sensory-feedback techniques were the least easy to use, and were least preferred.

9.2.4. Observations on cursor divergence

The two motor-space approaches that we tested (sticky targets and target gravity) both adjust the position of the cursor in order to achieve their motor-space effects. However, this meant that the actual position of the cursor in relation to the pointing direction of the device was constantly changing. Although each single adjustment is too small to be noticed, it is possible that an accumulation

of these adjustments could lead to noticeable cursor divergence. We considered two issues with cursor divergence: whether it would become a noticeable problem for users, and whether it would cause problems for completing the pointing tasks.

The overall degree of divergence was small in the vast majority of cases in the study, and no participant indicated that cursor divergence was a problem for them (in fact, one participant stated that they did not notice the motor control techniques at all). One reason for this success is that participants seemed entirely comfortable using their arm for relative ray-cast pointing (i.e., they were focused on the cursor on the screen, not on the direction of their arm), and cursor divergence does not compromise the relative up–down–right–left motions that are needed to control the cursor. A second reason is that the accumulation of cursor divergence was approximately balanced by the nature of our study task (i.e., moving to the next target in a ring was in approximately the opposite direction of the previous motion, balancing any divergence from the previous trial).

Second, our main investigation of cursor divergence involved single-direction pointing tasks, and for these targeting motions, there were a very few cases where divergence prevented the completion of the task. Four participants experienced a device limitation that arose from accumulated cursor divergence: these participants each had difficulty in a single trial of the sticky-high condition with two distractor objects, in which accumulated cursor divergence prevented them from being able to reach the target. In these cases, the cursor had diverged from the actual pointing direction such that the infra-red camera on the Wiimote could no longer see the IR light source positioned at the display. This is similar to the situation of reaching the edge of a table with a mouse (however, clutching was not implemented for our techniques). As discussed below, these experiences indicate that although problematic divergence may occur only rarely, it is necessary to provide a mechanism for resetting the actual pointing direction to the cursor location. Fortunately, as Vogel and Balakrishnan (2005) have shown, clutching mechanisms for relative ray-casting are simple to implement and easily understandable to users.

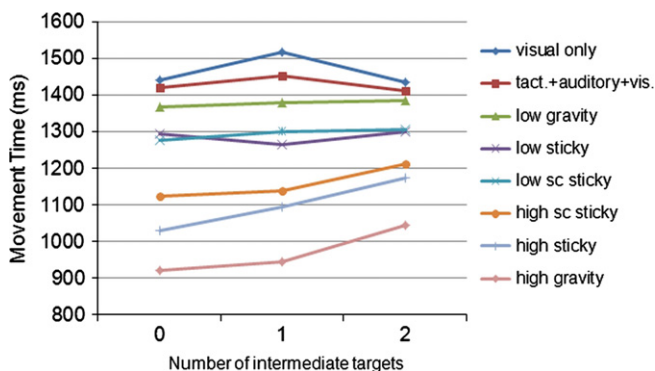


Fig. 18. MT by technique and number of intermediate targets.

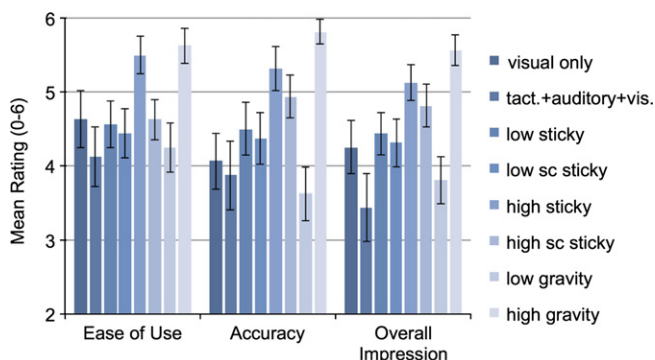


Fig. 19. Mean user ratings \pm SEM; 0–6 scale (higher is better).

10. Discussion

There are seven main results from our four studies:

1. Motor-space target-assistance techniques (sticky targets and target gravity) improve relative ray-casting performance, reducing targeting time by almost one-third and reducing the error rate by more than two-thirds. (Studies 1, 2, and 4).
2. Target gravity was the fastest of all techniques (Study 4).
3. Both sticky targets and target gravity can be operated at fairly high levels (i.e., levels that provide a substantial performance benefit) without the effect being obvious to users. (Studies 1 and 2).

4. Sensory acquisition feedback did not improve performance (Studies 3 and 4).
5. Participants preferred the ‘high effect’ versions of the motor space techniques, and liked the gravity-high technique most of all (Study 4).
6. Cursor divergence did not cause major problems for any participant, and was only a factor in four out of more than 28,000 trials.
7. Intermediate distractor targets did not cause major problems for any of the techniques; as a result, the speed-coupled variant of sticky targets did not outperform the standard version of the technique.

In the following sections, we discuss these results and their implications. We begin by reviewing each of the techniques and providing explanations for their performance and behaviour in the studies; we then outline how designers can apply our findings, consider the issue of cursor divergence in more detail, and discuss the generalizability of our results to other devices and other situations.

10.1. Review of techniques and explanation for performance

10.1.1. Sticky targets

Sticky targets provided significant and substantial reductions in time and errors compared to standard pointing and feedback techniques. The technique was effective even with small CD gain changes, and was not highly perceptible. Although sticky targets provided a smaller performance benefit than target gravity, stickiness has an important advantage—that the effect is limited to the target regions. This means that control actions outside the targets (such as drawing or steering) are not affected by the technique. However, in some scenarios a technique that draws the cursor to a target may be more desirable. In a recent study, sticky targets provided little benefit when used in the context of a video game with fast moving targets. Because acquiring the moving targets was difficult, players received less benefit from sticky targets (Bateman et al., 2011).

Performance with sticky targets was also not greatly hampered by intermediate distractors; the speed-coupled variant of the technique did not perform better than the standard ‘high-stickiness’ version, and participants did not have difficulty with divergence of the pointing device from the cursor. The performance of sticky targets techniques in the presence of intermediate targets has not been widely studied, and these results provide evidence that the approach can work in real-world interfaces.

10.1.2. Target gravity

Target gravity was significantly faster than any other technique, was one of the best in terms of errors, and was preferred by participants. Like sticky targets, participants did not perceive a strong effect, even when the gravity was high. The technique works well because it acts both during movement (drawing the cursor towards a target) as well as over the

target (by reducing cursor movement as the cursor moves away).

Our technique is based on force fields of Ahlström et al. (2001), but contains two noteworthy improvements. First, force fields allow influence from only one target at a time, and at a limited distance around a target. Target gravity allows all targets to attract the cursor at all times, making increasingly strong adjustments as the cursor nears a target. Second, target gravity provides a parameterization which governs how attractive a target should be. While this was not a factor in our experiments (all targets were treated equally), it would allow more important targets to exert more gravity. For this reason it could be valuable to couple target gravity with ‘semantic pointing’ widgets (Blanch et al., 2004), which would allow interface elements to occupy greater area in visual and motor space, and also increase the attractiveness they have over the cursor. Further, unlike magnetic dust techniques (Hurst et al., 2007), our approach does not require any user-specific interaction history before its use, but could easily be used to reflect usage frequencies (by adjusting target parameters based on user actions).

Our participants’ experience with small targets suggests that the algorithm used to define the gravity technique could be tuned to improve overall performance. Our implementation of gravity gives greater attractive force to larger targets (which is correct from a physics perspective), but in future work we will experiment with other formulations that may improve performance with small targets. For example, we could allocate equal initial ‘mass’ for all targets regardless of size (i.e., remove the size term from the equations and calculate gravity based only on distance), or even invert the relationship and provide smaller targets with greater attractive power.

When using target gravity, participants had no problems with cursor divergence, and no difficulties with the intermediate distractor targets. However, a potential limitation of target gravity in this area is the issue of orthogonal distractors. It is possible that targets orthogonal to the cursor’s path could cause problems for users, since these distractors will bend the motion of the cursor. We believe that at moderate levels of gravity, users will be unaware of the slightly altered path, because these will occur mostly in the ballistic phase of a movement. On the other hand, in scenarios where steering is needed, such as navigating a hierarchical menu, any movement outside of the desired trajectory may lead to undesirable effects. Further work is needed to investigate this effect.

10.1.3. Sensory acquisition feedback

We expected that the sensory acquisition feedback technique would perform somewhat better than the control condition, based on previous research results (Krol et al., 2009), but there was no improvement in terms of either time or errors. Previous literature shows mixed results for acquisition feedback in general, and in our study participants neither performed well with this techniques, nor did they prefer it. Several participants stated that they found tactile feedback frustrating, because the vibration made it more difficult to stay on the small targets;

also reported in earlier research (Akamatsu and MacKenzie, 1996). Other participants said that they found the tone used for auditory feedback annoying.

It is possible, however, that the main reason for the poor performance of sensory feedback is that our targets were not small enough for this feedback to make a major difference. Other studies have found that acquisition feedback is primarily useful when targets are so small that it is difficult to determine whether the cursor is correctly on the target—this was the case in the work of Cockburn and Brewster (2005), who found that auditory feedback did aided selection when targets were very small.

Regardless of these possibilities, it was clear that sensory feedback techniques were greatly outperformed by motor-space assistance. The reason for this advantage is that motor-control techniques can reduce the index of difficulty of the task in motor space, thereby ‘beating’ Fitts’s Law (Balakrishnan, 2004), while feedback techniques can only assist with final acquisition and do not alter the effective difficulty of the task.

10.1.4. Speed-coupled techniques

Our study showed that the speed-coupled versions of the sticky-targets technique did not perform better than the standard version. We see two main reasons for the performance of this technique. First, the proportion of a targeting motion that was affected by our distractor targets (even when there were three of them) was relatively small—as shown in Fig. 13, only about 20% of the motion path is covered by distractors. This meant that the standard techniques were not slowed a great deal; the effect likely shortens a ballistic targeting motion by a few pixels, which was not enough for participants to notice in our study.

Second, the variable degree of stickiness in the speed-coupled technique meant that the average attractive effect was usually lower than that of the fixed high-effect techniques. Therefore, the overall benefit provided by the adaptive technique was slightly reduced, leading to slightly higher movement times.

However, we do not suggest that speed-coupled techniques be abandoned. There may be usage situations with more distractors that cover a larger proportion of the targeting path; in these situations, the advantage of the speed-coupled technique may become more apparent. In addition, if the speed-coupled idea is applied to the target gravity technique, then the adaptivity could also help to reduce the problem of orthogonal distractors mentioned above.

10.2. Lessons for designers

There are several ideas and suggestions that we believe can be immediately taken up by designers of systems that use relative ray-casting as a pointing technique:

- The primary lesson from this research is that designers should consider using motor-space target assistance, as these techniques greatly facilitate targeting.

- Employing low levels of both target gravity and sticky targets are safe choices, because these provide significant performance gains but are nearly imperceptible and are unlikely to cause any cursor divergence problems.
- Designers should carefully match the relative strengths and limitations of the different target-assistance techniques to the characteristics of the task setting.
- Techniques that operate globally on the screen (such as target gravity) can provide value in situations where targets are small or sparsely placed, but these techniques must be used cautiously in situations with densely-packed targets, large targets orthogonal to the motion paths, or a requirement for precise steering with the cursor.
- In scenarios with many potential distractor targets, but where distractors are not often crossed during targeting, the sticky target technique should perform well. (We note that beyond these initial clear findings, more testing in different scenarios is required to more fully explore the techniques’ trade-offs).
- Care should be taken with the use of sensory acquisition feedback techniques other than visual feedback. Although we did not find a performance reduction, some users complained about tactile and auditory feedback. Sensory feedback may provide additional assistance with very small targets.
- Designers must consider the issue of cursor divergence when using any technique that implements cursor adjustment or warping, particularly with devices that have range limitations, such as the infrared camera on the Wiimote. Designers should provide methods for dealing with cursor divergence, such as those discussed below.
- The number, density, and location of on-screen objects may become an issue for any motor-space assistance technique. Although we found no problems with one and two intermediate targets, we did not study other configurations and designers must consider how interface layout will affect assisted targeting.
- Designers must be cautious when employing very high levels of motor-control manipulation, as these can create situations where the cursor becomes permanently stuck on a target, or may dramatically increase cursor divergence.

10.3. Issues of cursor divergence

An important secondary part of our investigation was to determine whether people would have difficulty in cases where the cursor’s position was no longer directly in line with the direction of the device. It was clear from our studies that participants had no problem coping with small amounts of divergence. Although small amounts of drift occurred in almost all trials with the distractor targets, no participant had difficulty with these trials, and no participant remarked on the issue. It was clear that people were

focused on the on-screen cursor, and were not attending to the position of the device (to the point that they seemed unaware of the divergence). In our own informal trials where we tried out several levels of divergence, it seemed easy to control the cursor even when it was clear that the device was pointing somewhere else (since the up–down–left–right movement scheme is unchanged, the divergence does not cause a major change in the control paradigm).

Although the perception of drift was not a problem, cursor divergence did on a few occasions cause participants to run out of movement room (i.e., their arm movements went out of range of the Wiimote's IR tracking system). This problem affected only a few trials, but will require attention from designers who intend to employ these targeting assistance techniques in real world systems. There are several possible methods for dealing with the cursor-divergence problem, as outlined below.

- Do nothing. With low levels of assistance, cursor divergence is unlikely to cause a substantial problem. In addition, there are many situations where users carry out only a limited number of tasks at a time, and it may be possible for the system to simply reset the cursor position between uses. The angular range of sensing hardware will also likely increase over time, further reducing the 'running out of room' problem that we observed.
- Clutching. Adding a clutching mechanism to the interaction technique would allow the user to realign the pointing direction with the cursor whenever necessary. This approach was tested by Vogel and Balakrishnan (2005), and their participants found the solution easy to use. With the Wiimote, one of the buttons on the device could easily be used to disengage the cursor and perform clutching. The drawback of a clutching mechanism is that it requires the user to be actively involved in the management of the movement technique; in addition, the additional time needed for clutching will reduce the overall performance of the target-assistance techniques (e.g., by adding clutching time to some trials).
- Calibrate. An alternate to clutching is a simple mechanism where the user points the device at a known location and then presses a button to bring the cursor into alignment. This mechanism may be simpler for users to understand, but still requires that users actively manage cursor position.
- Snap-back. An approach used in many video games is to simply return the cursor to the position it would have otherwise reached had it not passed through a sticky target (i.e., the cursor snaps back to its true position after the targeting motion). This approach avoids accumulation of cursor divergence, and need not be managed by users. However, the technique can also cause undesired effects: as a user leaves a target, the cursor may jump forward in the direction of travel (Nelson, 2009), which can be disorienting.
- Smooth-to-normal. To minimize the effects of cursor jumping in the snap-back approach, cursor divergence

could be smoothly reduced over a period of time—e.g., each cursor movement is adjusted until the divergence has been eliminated. This approach may hold the most promise, given the low perceptibility of cursor adjustment seen in our studies; however, this technique could cause problems when users carry out successive targeting motions in the same direction.

11. Generalizing the results to real-world applications

Our task was based on the ISO standard, which is not typical of most real-world applications that will employ distant pointing. Despite this fact, we believe our results provide initial baseline results that show targeting assistance will be both worthwhile and achievable in real applications (although designers will need to spend time selecting an appropriate technique for their application, tuning it to an optimal level, and testing for undesirable interactions).

As distant pointing and the use of relative ray-casting hardware becomes increasingly common, target assistance will become an appropriate choice for interacting with many different display types and interfaces. For example, the main Nintendo Wii 'Home' menu provides a series of pages comprised of 12 large buttons, and this organization is due at least in part to targeting difficulty. This approach to interface design could lead to applications with many pages of options and controls; but with assisted targeting, designers of such entertainment consoles could use shallower menu organizations with an increased number of options on each screen.

Further, there are several common scenarios where targeting assistance could provide an improved experience for the user. A well-known problem is that of 'sliding' off a desired target when depressing the device's button to make a selection (McArthur et al., 2009). This occurs because the muscles required to select the target also control direction, and when the muscles contract to press a button, they sometimes move the cursor out of the target's boundaries before the selection is made. Both sticky targets and target gravity would reduce this effect. Another scenario involves interacting with large high-resolution screens at a distance. In these situations, targeting can be difficult because small device movements cause large cursor movements on the distant screen. Target assistance would help users acquire targets in these longer-distance pointing scenarios.

Target assistance techniques are also highly applicable to video games. Techniques similar to sticky targets are already in use in popular games that require precise targeting with game controllers; e.g., the Halo series (Nelson, 2009). As an example, target assistance can lower the level of difficulty in selection, while maintaining a relatively high level of perceived difficulty. For instance, on-screen targets can move at high speeds, which may better convey an appropriate experience to players, but the targets may still be relatively easy to acquire. Similarly,

target assistance can be exploited for game balance between players of different skill levels, as has been shown in other work (Bateman et al., 2011).

12. Conclusions and plans for future work

Systems that use distant pointing are now common in many home and work environments, and relative ray-casting devices such as the Nintendo Wiimote are becoming standard controllers for interacting with computer interfaces. To address problems of accuracy with these devices, we investigated several target-assistance techniques that can be used with relative ray-casting. We carried out three studies to investigate the performance and perceptibility of several techniques, and compared the best versions of each technique in a fourth comparison study. Ours is the first thorough investigation of motor-space assistance techniques such as sticky targets and target gravity in this new domain, and the first to consider real-world issues such as distractor targets. Our studies showed that motor control techniques are highly effective in improving targeting for distant pointing with relative ray-casting, that these techniques are preferred by users, and that they are robust in situations with a small number of en route distractors. Our studies also revealed several design issues and principles for the use of these techniques.

In future work, we will investigate motor-space assistance techniques in realistic environments such as media players and video game interfaces, to confirm that our results generalize to other numbers and arrangements of targets. Second, we will explore other motor-space methods such as area cursors, bubble cursor, and object pointing (Guiard et al., 2004), in order to develop a comprehensive understanding of what techniques are appropriate in different application situations. Third, we will investigate different types of relative ray-casting devices (e.g., gyroscope-based devices such as the Logitech Air Mouse) to further explore issues with distant pointing and user perception of divergence.

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