The Effect of Edge Targets on Touch Performance

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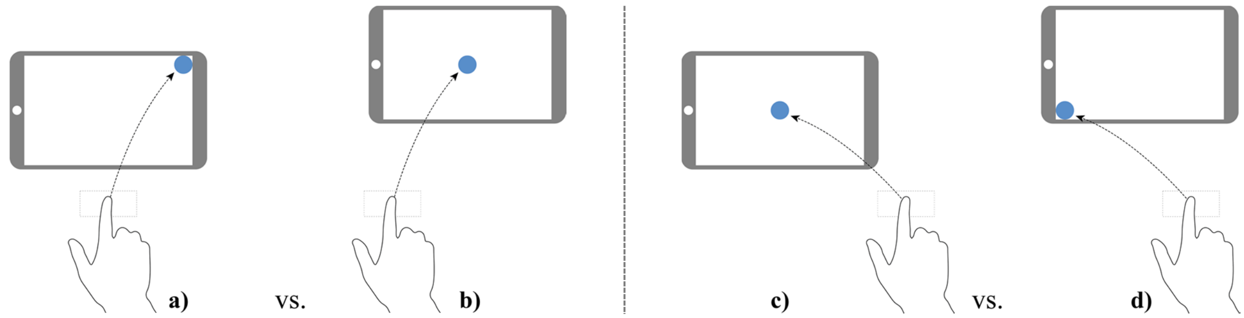

Figure 1. Edge-targets vs. Center targets on touch devices. Each pair shows a round target at a fixed distance from the user but at a different distance relative to the frame. In each pair, which target, if either, will have a faster reaction time?

ABSTRACT
Edge targets, such as buttons or menus along the edge of a screen, are known to afford fast acquisition performance in desktop mousing environments. As the popularity of touch-based devices continues to grow, understanding the affordances of edge targets on touchscreen is needed. This paper describes results from two controlled experiments that examine in detail the effect of edge targets on performance in touch devices. The results show that on touch devices, a target's proximity to the edge may have a significant negative effect on reaction time. We examine the effect in detail and explore mitigating factors. We discuss potential explanations for the effect and propose implications for the design of efficient interfaces for touch devices.

Author Keywords
Edge targets; target acquisition; human performance; touch

ACM Classification Keywords
H.5.2 [User Interface]: Input devices and strategies.

INTRODUCTION
Edge targets, such as buttons or menus along the edge of a screen, have long been used in desktop mousing environments to provide quick access to targets. Examples in commercial systems include menus along the top of the screen and the dock along the bottom of the screen in Mac OS, the taskbar and Start button along the bottom in the Windows operating system and buttons for closing and resizing windows at the top. However, with the growing shift to touch-based interaction, the advantage of edge targets must be revisited.

In mousing environments, the key attribute that makes edge targets advantageous is that the pointer stops when it reaches the edge of the screen. This allows the user to use a quick motion, without risk of over-shooting the target. In other words, since the pointer cannot advance beyond the edge of the screen (and thus the edge target), the effective size of edge targets can be considered as semi-infinite [3], along one or more dimensions (this attribute has been transferred and exploited also in the case of physical edges restricting the movement of a stylus [24]). Corner targets, for example, will have an infinite effective size along both horizontal and vertical dimensions, making them useful as quickly accessible targets (and the reason why they have been used as "hot spot" shortcuts in several operating systems).

Nowadays, finger touch is increasingly replacing traditional pointer interaction as the popularity of touch devices such as tablets and smartphones grows. The faceplate of most tablets and phones today is made of glass that spans to the edge of the bezel around the screen offering no physical break at the end of the screen (some touch devices even include bezel-less touchscreens).

This raises the question: Are edge targets on touch devices (that is, targets near the edge of the device screen) advantageous as they are in desktop environments? Are they harmful? Or does the proximity of a target to the edge of a touch device play no role in target acquisition performance?

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Consider for a moment the target pairs shown in Figure 1. In each pair, the distance between the finger's starting position and the target is identical (the target is in the same global position in 2D space). However, in each pair, the targets have a different position relative to their frame; the target in one is an edge target, and in the other it is not. We ask:

Which target (1a vs. 1b, 1c vs. 1d) yield faster reaction time?

One could expect that the edge will act as a perceptual aid for target acquisition, leading to faster reaction time for edge targets. Alternatively, if the edge doesn't aid in pointing, then hitting a target on the edge may be as difficult or easy as hitting any target not on the edge. Finally, there might be a "fear" of touching beyond the screen bounds, or even visual interference between frame and target, that may lead to slower acquisition time for edge targets.

This paper begins to answer these questions, reporting results from two experiments that investigate the effect of edge targets on performance in touch devices. The first experiment shows that on touch devices, unlike edge targets in traditional desktop mousing environments, proximity to the edge can have a significant *negative* effect on reaction time. The second study examines the effect of edge targets on small and large targets, and explores whether small changes in a target's distance from the edge can affect reaction time.

We believe that the findings presented in this paper are important for growing our understanding of human performance with touchscreen interaction, and should be considered in the design of efficient touch interfaces.

RELATED WORK

Edge targets have been discussed extensively in the context of pointing with devices such as a mouse or trackpad. In [1] and [2], Accot & Zhai broadened our understanding of human performance of pointing and crossing tasks, extending Fitts' law [10] to account for the difficulty resulting from target size and distance independently. They show that targets that provide larger amplitude tolerance will be faster to point at than targets with larger directional tolerance. This is the case with edge targets, such as menus along the very edge of a desktop screen (as in the Mac OS).

Appert et al. [3] investigated in detail mouse-based pointing, comparing regular pointing and edge pointing, and proposed an extension of Accot and Zhai's definition of index of difficulty (ID) to account for the case of edge targets. In their studies, edge targets, with their "semi-infinite" size, were acquired up to 44% faster than regular targets at the same distance in the central screen area.

The Use of Physical Edges

The benefit of edge targets in pointing tasks can be attributed to their large amplitude tolerance; that is, since the pointer does not pass through an edge target rather stops at the edge of the screen, a gross motion can be used to acquire the target. Several systems have adapted this concept to stylus-based pointing, leveraging elevated physical edges, to support accessible interfaces. For example, *Edge Keyboard* and *EdgeWrite* are text entry techniques designed for a handheld device with a raised bezel around the input area [24, 25]. The raised edge physically prevents the stylus from moving past the edge of the screen, allowing target selection with coarse movement. Froehlich et al. extend this concept as a pointing technique called *Barrier Pointing* [11]. Unlike this work, most current handheld devices such as smartphones and tablets do not offer a physical barrier at the edge of the screen.

From Pointers to Touch

With the growing availability and popularity of touch devices, an interest in understanding human performance on touch devices has increased (*c.f.* [7, 21]). Lee and Zhai [15] studied finger tapping performance on smartphones, showing that touch performance degraded faster than predicted by Fitts' law when targets became smaller. In [13], Holz and Baudisch show that much of the negative effect attributed to the "fat finger problem" can be explained by offsets of touch location from the intended point, affected by the angles between the finger and the touch surface. In order to provide a general model of performance on touch devices, Bi et al. [6] proposed FFitts Law, an extension of Fitts' law for finger touch input. With FFitts Law, Bi et al. propose that the index of difficulty is a combination of the absolute precision of the motor system and the relative precision stemming from a speed-accuracy tradeoff.

Prior work also showed that the intended application of the interactor can have a significant effect on posture and grasp planning. Olafsdottir et al. demonstrated that the orientation of finger placement on a touch object was significantly affected by the position and orientation of the target [17]. In the special case of text entry on touch devices, [5] and [12] showed a consistent touch offset between the visual position of keys and user's touch.

Perry and Hourcade evaluated one-handed thumb-based target acquisition on a small handheld device [19]. They found that reaction to targets on the edges of the screen was slower, but more accurate (potentially because their device's touchscreen was surrounded by a raised bezel). Unfortunately, determining whether edge targets were slower because of dexterity or for other reasons is not possible because in one-handed operation, edge targets are physically harder to hit (*c.f.* [18]). The work presented here sheds further light on their findings.

While modern touch devices often don't have any physical affordances at the edge of the screen, the perimeter of the device (not the screen itself) has been shown as useful for quick, coarse, actions. These include edge gestures, common in many operating systems designed for touch, including iOS, Android, and Windows 8.1. [20] describes a rich set of interaction techniques called *Bezel Swipe* that support multiple selection, cut, copy, paste and other operations.

Figure 2. Apparatus for Experiment 1. An 18" touch-surface displays targets at known positions. A moveable 0.5mm 3D-printed frame simulates the boundaries of a 7.9" tablet.

This paper builds on this prior work, focusing on extending our understanding of the effects of targets' proximity to the edge of a screen on performance, when physical guides are not present.

EXPERIMENT 1

The first experiment was designed to test whether the time to acquire a target will be significantly affected by the target's proximity to an edge, while maintaining complete control over the target's distance to the user. This was achieved by physically decoupling the position of the target relative to an edge from the position of the target relative to the user: We used a large, 18" touch surface for displaying targets at known positions relative to the user, and used an extremely thin (less than 0.5mm) frame to simulate the bezel of a small tablet (see Figure 2). A light grey background around the frame, and near-black background inside, gave the illusion of a bounded device. In this experiment, we 3D-printed a frame such that it imitates the face of an Apple iPad Mini, which has a 7.9" screen. The frame is thin enough such that touch is sensed through it.

This unique setup allows displaying the same absolute target (in relation to the user), while placing the physical frame at different positions relative to that target. As illustrated in Figure 1, this allows, for example, a target to be a center target in one trial, and a corner target in another, while maintaining the same distance from the user.

Hypotheses

Our main hypothesis for Experiment 1 is that the time to acquire the same absolute target (in size and distance in relation to the user), will be significantly affected by the target's proximity to an edge. Put formally:

H_1: *Proximity to device edge will significantly affect touch-target acquisition time.*

Still, if H_1 is supported, would acquisition time of edge targets on touch devices be faster or slower? As mentioned earlier, different assumptions would suggest that acquisition time be affected in opposite directions. We thus pose two, contradicting, sub-hypotheses for H_1, expecting at least one to be rejected.

First we can hypothesize that the edge of the screen will act as an aid for target acquisition, leading to faster acquisition time for edge targets.

H_{1a}: *Independent of distance, proximity to device edge will result in faster reaction time.*

Conversely, reluctance to hit outside a border, or visual interference between frame and target, may lead to slower acquisition time for edge targets.

H_{1b}: *Independent of distance, proximity to device edge will result in slower reaction time.*

Method

Figure 3 illustrates the experimental setup. The experiment consisted of 3 blocks of target-acquisition trials. For each block, the frame was placed in one of three fixed positions (marked A, B, and C). For each trial, a round target, with a fixed diameter of 11mm, was selected from an 8x6 grid. The target and frame positions were designed such that a target in row 4 column 4 (from here on (4,4)) would appear in the center of the frame in position A, and in the corner of the frame in positions B and C. Likewise, targets (2,2) and (2,6) would appear in the center of the frame (in positions B and C, respectively) and in the top corners of the frame when in position A. As seen in Figure 3, each frame position contained 13 target positions. The area of overlap between frame positions contained 9 targets. So as to keep the overall number of trials small, but still collect as much data for targets in the area that overlaps between blocks, a non-uniform distribution was used, giving preference to targets in the overlap area. Targets belonged to one of four tiers, as labeled in Figure 3. Each tier-4 target (those targets without any overlap) would appear six times per block, each tier-3 target nine times per block, tier-2 18 times per block, and each tier-1 target (highlighted in Figure 3) 30 times per block, resulting in a total of 504 trials. As a result, 66% of

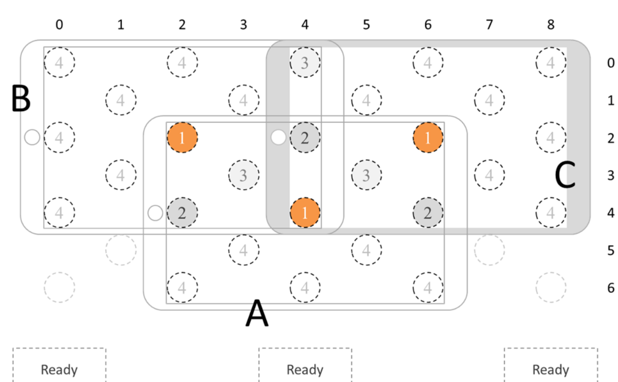

Figure 3. The experimental design: The frame was positioned in one of three locations (labeled A, B, C). Frame and target positions are such that a center target in one frame position is a corner target in another frame position. Targets within the overlap area are highlighted.

trials were of targets vital to the investigation. By including all possible target positions, however, participants still had to pay attention to the full area of the frame.

In order to have complete control over the point of origin for each target acquisition task, each trial started with the user pressing a button labeled "Ready" that appeared in one of three positions seen at the bottom of Figure 3 (In previous work (e.g. [6]), users were asked to start each trial with fingers rested comfortably off the screen.) Once pressed, the Ready button would disappear and a target (yellow on a near-black background) appeared. The time until the user tapped the screen and the location of the tap was measured. If the tap was outside the boundary of the target, time was recorded but the target's color was changed to red and the user would continue until successfully tapping within the target. This was done to encourage participants to be both fast and accurate. Upon successfully tapping the target, the target would disappear and a new Ready button would appear. Each target appeared an equal number of times with each Ready button.

Apparatus

The experiment was conducted on a Dell XPS 18 Portable All-In-One PC running Windows 8.1. The device was placed flat on a desk. Screen resolution was set to 1920 x 1080. The software for the experiment was written in C#. To avoid users accidentally touching the home button, the tablet was used upside-down, with the screen rotated 180 degrees.

Procedure

After completing a demographics form, each participant was given a short practice session. As part of the practice we asked the participant to miss one of the practice targets intentionally to highlight the need for accuracy. We also showed how tapping will work through the plastic frame so that they should not be worried about hitting it. Finally, we reminded participants that time is measured only between pressing a "Ready" button and hitting a target, so they can take a break if they need to when the Ready button is showing. Participants were instructed that after hitting a Ready button, they should acquire the target as quickly and accurately as possible.

Each participant then completed three blocks – one in each frame position. The order of blocks (ergo the position of the frame), and the order of trials within each block, was randomized. At the beginning of each block, the experimenter would move the frame to one of the three positions; invisible to participants, a thin layer of Play-Doh was used on the underside of the frame to create friction so that the frame wouldn't move during the block.

Measures

The following dependent and independent measures were determined for each trial:

- *Reaction Time*: The elapsed time (in milliseconds) between tapping the "Ready" button and tapping the screen again.
- *Touch-Point Offset*: Measured as the distance from the user's touch and the target's center.
- *Error*: A trial was marked an error if the distance from the user's touch to the target's center was greater than the target's radius.
- *Distance*: For each trial, we calculate the distance between the user's initial touch on the "Ready" button and the target's center. This measure is used in the analysis as a covariate to control for its known effect on performance. In keeping with Fitts' Law and related work, we apply a log2 transformation to this measure.
- *Ready-Button Position*: The starting position of each trial (Left, Center, and Right) was recorded and used as control.
- *Target Type*: Finally, this categorical measure describes the relationship between target and edge. Categories are: Corner, Horizontal Edge, Vertical Edge, Inner Target, and Center.

Participants

We recruited 12 participants (1 female), between the ages of 20 and 36 (M=27.6, SD=4.8), all were student interns in our lab and had experience using touch devices. 11 were right-handed and 7 wore glasses. Participants completed 504 trials each, taking 13:21 minutes, on average, to complete the experiment. This resulted in a total of 6,048 trials. However, one of the participants twice started the next block before the experimenter could move the frame to its new location, and so the first trials from these two blocks were discarded, leaving 6,046 trials. Upon completion, participants received a donut as a thank-you.

RESULTS (EXP 1)

In this section, we first describe the (lack of) effect of edges on error rate and touch point offset. We then describe a significant effect of edges on reaction time. Taking advantage of our experimental setup, we are able to examine how changing the position of the frame affected specific targets.

Removing outliers

In preparing the data for analysis, we first calculated T^2 Statistic for reaction time and distance from the target's center. We considered any trial with a T^2 greater than 2x the Upper Control Limit (UCL) as an outlier. This resulted in the exclusion of 86 trials (1.4% of the data), leaving 5,960 of the 6,046 trials for analysis.

Error Rate and Touch-Point Offset

Overall error rate was 6.2%. A Wilcoxon Signed Rank test showed no significant difference between error rates for edge targets (M=6%) and non-edge targets (M=6.4%; p=0.9).

We next looked at the effect of a target being an edge target on the Touch-Point Offset (the distance of touch from a target's center). We used a mixed model ANOVA with *Offset* as the dependent variable. Edge-Target (1 vs 0) as well as Trial Number, Reaction Time, and Distance were modeled as fixed effects, and Participant ID was modeled as a random effect. The analysis showed no significant effect for Edge-

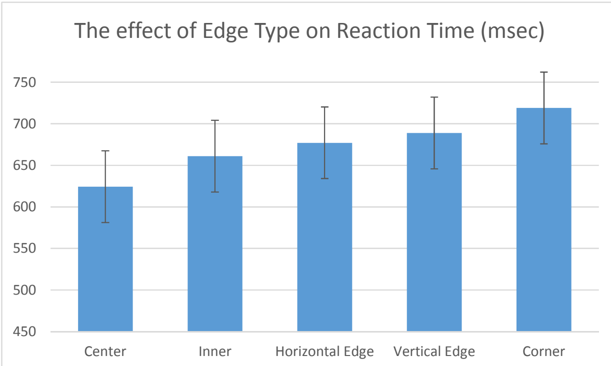

Figure 4. The significant effect of Target Type on Reaction Time, showing means and standard error. A Tukey-HSD pairwise comparison found a significant difference between each edge type.

Target on Offset (p=.56). Reaction Time had a significant effect (with faster reaction correlated with greater offset; F[1, 3887]=18.0; p<.001). Similarly, Distance had a significant effect (with longer distances correlated with greater offset; F[1, 3887]=18.0; p<.001).

Given no effect of edges on offset or error rate, in subsequent analyses we consider the first reaction time for all trials, including those coded as errors.

Reaction Time

Average reaction time in all trials was 651 milliseconds (*SD*=117). We first conducted a mixed-model ANOVA with *Reaction Time* as the dependent variable, and Trial Number, Distance, Touch-Point Offset, Ready-Button Position, Age, Handedness, and Corrected Vision (Yes/No) as fixed effects. Participant ID was modeled as a random effect.

As expected, Distance had a strong effect on reaction time (F[1,5943]=681.6; p<.001) with faster reaction to closer targets. Trial Number had a significant *negative* effect on reaction time, with reaction time getting faster over the course of the experiment (F[1,5943]=162.9; p<.001). Ready-Button position had a significant but small effect on reaction time (F[1,5943]=8.4; p<.001), with Tukey-HSD post-hoc comparison showing faster reaction time for trials beginning on the right (presumably because the vast majority of the participants were right-handed). Finally, Age showed a small significant effect (F[1,8]=6.1; p=.036) with higher age correlated with longer reaction time.

We were now ready to begin exploring hypothesis H_1.

Referring to Figure 3, we first compared reaction time to the trials of three targets: (2,2), (4,4), and (2,4). Each of these targets played the role of both Corner target and Center target, depending on the position of the frame. We created a second mixed-model ANOVA with *Reaction Time* as the dependent variable. In addition to the factors of our previous model, we also included *Target Type* (Center vs. Corner) and Target ID as fixed effects. Again, *Participant ID* was modeled as a random effect.

Our analysis found a large significant effect of Target Type on reaction time (F[1,2465]=1015.0; p<001), allowing us to **accept hypothesis H_1**. Our analysis shows that, independent of distance, reaction time to Corner targets was 14% *slower* than reaction to Center targets (M=723 msec vs. M=632 msec). This result allows us to accept hypothesis H_{1b} and reject H_{1a}, at least with regards to corner targets.

To further investigate H_{1b} and H_{1a}, and understand the relationship between target types (relative to the edge) on target acquisition performance, we repeated our model of the complete set of targets, including this time Target Type (Corner, Horizontal Edge, Vertical Edge, Inner Target, and Center) as a fixed effect, as well as the Frame Position (A, B, or C) for control.

The analysis showed a significant effect of Target Type on reaction time (F[4,5937]=313.6; p<.001). A post-hoc Tukey-HSD pairwise comparison, shown in Figure 4, revealed that the effect of proximity to the edge expands beyond corner targets. It shows a significant difference between each of the different target types, with corner targets resulting in the *slowest* reaction time, followed by targets along the vertical edge, targets along the horizontal edge, and finally inner then center targets. **This result allows us to fully accept hypothesis H_{1b} and reject H_{1a}.**

EXPERIMENT 2

The unique setup of Experiment 1, which allowed complete control over the absolute position of targets in 2D space in relation to the user, helped us uncover a significant negative effect of edge targets on performance, confirming hypotheses H_1 and H_{1b}, and rejecting hypothesis H_{1a}. However, several important questions remain: Would the effect persist when tested in a more natural setting on an actual handheld tablet? Would larger targets be susceptible to the same effect? And would varying the distance from the screen's edge, even slightly, mitigate the effect?

We designed Experiment 2 to try and answer these questions.

Hypotheses

In addition to re-testing hypothesis H_{1a}, Experiment 2 further tests several other hypotheses.

Since, according to models of target acquisition performance, larger targets are easier to acquire, we first hypothesize that increasing the size of targets will dampen the effect of the screen's edge.

H_2: *Large targets will not be affected by proximity to the edge.*

Furthermore, if the reason edge-targets are slower to acquire on touch devices is because they are harder to visually separate from the bezel, one would expect that introducing even a slight gap from the bezel should reduce or eliminate the effect. We thus hypothesize that:

H_3: *The effect of proximity to the edge can be significantly reduced with even a slight gap between target and edge.*

Figure 5. Apparatus for Experiment 2. An 8” tablet held in the user’s non-dominant hand showing a corner target.

Method

Experiment 2 was conducted on an 8” tablet (see Figure 5), where both targets and Ready buttons were drawn. Since tablets are frequently used in either portrait or landscape modes, we introduced Tablet Orientation (Landscape vs. Portrait) as a between-subject condition. As in Experiment 1, each target acquisition trial started with the participant hitting a Ready button, and finished when the participant successfully hit the target. Targets appeared along the top and bottom edges of the tablet (e.g., top-left, top-middle, and top-right).

To test hypothesis H_2, we used targets of two sizes: 11 mm in diameter (similar to Experiment 1) and 22 mm. To test hypothesis H_3, the distance of targets from the edge of the device was manipulated for each trial. We used 4 edge offset values: 0 mm, 1.5 mm, 4 mm or 11 mm (an edge offset of 0mm means that the target is right along the screen’s edge). Similar to Experiment 1, targets appeared as yellow circles.

Unlike in Experiment 1 where trials started at Ready buttons drawn outside the device’s boundaries, in Experiment 2 trials started inside the tablet’s bounds. Trials were performed in two blocks: In one block, the Ready button appears in one of two positions in the *bottom* part of the screen with targets at the top-left, top-middle, and top right. In the other block, the Ready button appears in one of two positions in the *top* part of the screen and targets were displayed at the bottom-left, bottom-center, and bottom-right. Figure 6 illustrates the positions of Ready buttons and targets in 4 trials. Figures 6a and 6b illustrate trials from the Landscape condition, with a small target and two edge gap values. Figures 6c and 6d illustrate trials from the Portrait condition with the large target size and two edge gap values. Using Figure 3 with frame position B as reference, possible positions for Ready buttons in Experiment 2 are (1,1), (1,3), (3,1), and (3,3). That is, the button’s center is one column and one row inwards from the edge of the screen. In order to maintain control over the distance from Ready button to the target in each trial, the Ready button was offset the same amount and direction as the upcoming target (as can be seen in Figure 6).

Apparatus

The experiment was conducted on an ASUS VivoTab Note 8 tablet running Windows 8.1. The resolution of the 8” screen is 1280 x 800. The software of Experiment 1, written in C#, was adapted for this experiment. To ensure that the screen would not accidentally rotate during the study, automatic screen rotation was disabled.

Procedure

After filling a short demographics questionnaire, participants were randomly assigned to one of the Tablet Orientation conditions and asked to hold the device in either Portrait or Landscape mode for the remainder of the experiment. They performed tasks in a “hold-and-tap” posture [5]: holding the tablet using the non-dominant hand and acquiring the targets with the index finger of the dominant hand (see Figure 5).

Similar to Experiment 1, participants started with a short practice block of 6 trials. Participants were instructed that after hitting a Ready button, they should acquire the target as quickly and accurately as possible. Here, again, the result of missing a target was explained.

The number of trials completed by each participant was 384: 2 blocks (Up-Down vs. Down-Up) x 3 target positions x 2 target sizes x 4 offsets from the edge (0mm, 1.5mm, 4mm, 1mm) x 2 Ready button positions x 4 repetitions.

The order of blocks and of trials within each block was randomized.

Measures

The following measures were recorded for each trial:

- *Reaction Time*: The elapsed time (in milliseconds) between tapping the “Ready” button and tapping the screen again.

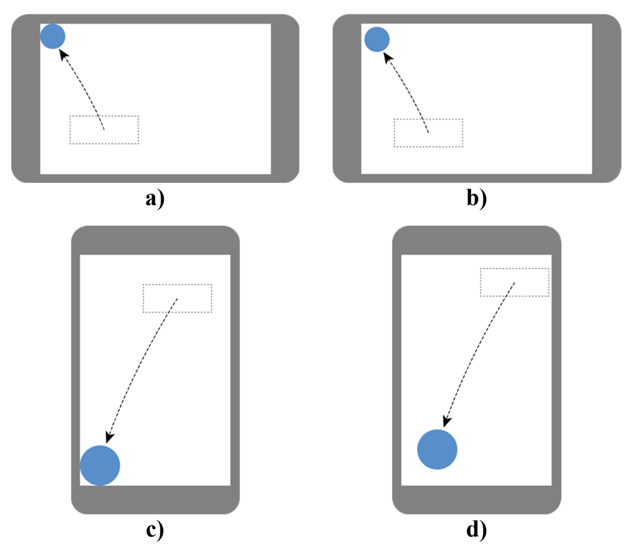

Figure 6. Examples of trials from Experiment 2 with Landscape and Portrait orientations. Trials vary by target size (11mm vs. 22mm) and the gap from the edge (0mm, 1.5mm, 4mm, or 11mm).

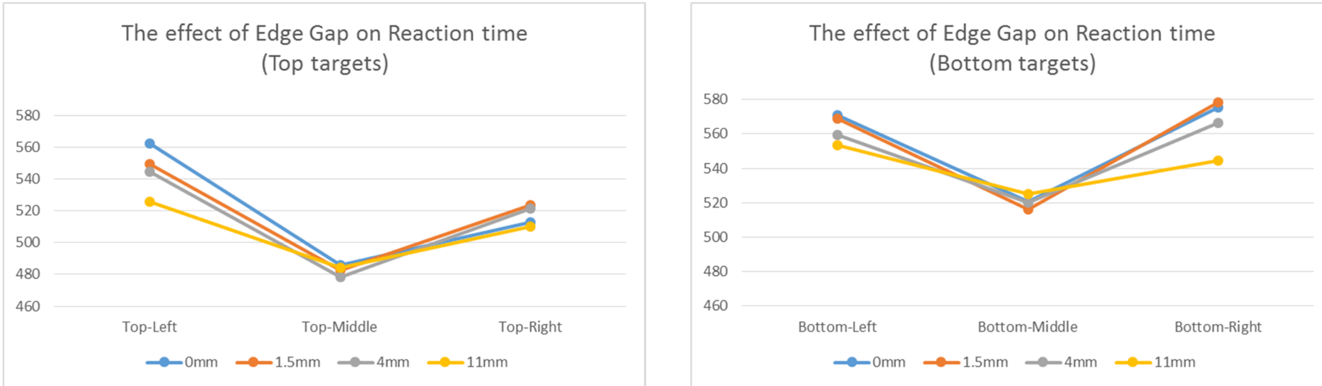

Figure 7. The effect of different gap sizes on reaction time, as a factor of the target's position on the screen. For readability, grouped by targets at the top and bottom of the screen.

- *Touch-Point Offset*: Measured as the distance from the user's touch and the target's center.
- *Error*: A trial was marked an error if the distance from the user's touch to the target's center was greater than the target's radius.
- *Distance*: For each trial, we calculate the distance (log2) between the user's initial touch on the "Ready" button and the target's center.
- *Target Position*: Targets were labeled Top-Left, Top-Middle, Top-Right, Bottom-Left, Bottom-Middle, or Bottom-Right.

Participants
We recruited 12 participants (5 women) at a local café. Participants' ages ranged from 15 to 42 (*M*=28.5, *SD*=8). All participants were right-handed and 3 wore glasses. Participants took 7:26 minutes, on average, to complete the study. Participants received a $10 gift card to the café where the study took place.

RESULTS (EXP 2)

Removing outliers
We collected a total of 4608 samples. As in Experiment 1, we excluded trials for which reaction time or offset from the target's center was greater than 2x the Upper Control Limit of the T^2 Statistic. This resulted in the exclusion of 65 trials (1.5% of the data) leaving 4,543 trials for analysis.

Error Rate and Touch-Point Offset
Overall error rate was 3%. A Wilcoxon Signed Rank test showed a significantly higher percent of error for the small target versus the larger targets (*M*=5.3% vs. *M*=0.7%; *p*=.001). However, the error rates for target at different distances from the edge of the screen were not different from one another.

We next tested whether a target's size and distance from the edge had an effect on the Touch-Point Offset (the distance of touch from a target's center). We used a mixed-model ANOVA with *Touch-Point Offset* as the dependent variable and Target Size (11mm vs. 22mm), Edge Gap (0,1.5,4, and 11), and the interaction between them as our main factors of interest. Trial Number, Reaction Time, and Distance were also modeled as fixed effects, and Participant ID was modeled as a random effect. The analysis showed no significant effect for Edge-Offset (p=.6), Target Size (p=.15) or the interaction (p=.36). Trial ID showed a small effect (F[1,4521]=4.0; *p*=.04) with touch accuracy dropping ever so slightly as the experiment progressed.

Given no effect of edges on touch-point offset or error rate, in subsequent analyses we consider the first reaction time for all trials, including those coded as errors.

Reaction Time
Average reaction time in all trials in Experiment 2 was 524 milliseconds (*SD*=117). To test the effect of the different factors on reaction time, we conducted a mixed-model ANOVA with *Reaction Time* as the dependent variable. Edge Gap, Device Orientation, Target Position, Target Size, and their 2-way interactions with Edge Gap were modeled as fixed effects. We also included Trial Number, Distance, Touch-Point Offset, Ready-Button Position, Age, and Corrected Vision (Yes/No) for control. Participant ID was modeled as a random effect.

Verifying Hypothesis H_{1b}
We started by testing whether the effect found in Experiment 1 holds in this setup. Our analysis found a significant main effect of Edge Gap on reaction time (F[3,4497]=13.1; *p*<.001), with significantly faster reaction time for targets farthest from the edge (Edge Gap = 11 mm). Recall that the distance between Ready Button and target remained the same, since both target and Ready button were shifted equally. **Accordingly, this result successfully reaffirms Hypothesis H_{1b}.**

While the difference in reaction time to targets at the very edge of the device and those 11mm away from the edge was smaller in comparison to the difference observed in Experiment 1 (only 3-7% slower), the presence of the effect is important, considering that non-edge targets in Experiment 1 were significantly farther from the edge than those present in Experiment 2.

Proximity to the Edge with Large Targets

In H_2, we hypothesized that the effect of proximity to the edge will be reduced for larger targets. Half of the trials presented larger targets, 22 mm in diameter. As to be expected, larger targets were acquired significantly faster than smaller targets (M=525 msec vs. M=550 msec; $F[1,4497]=48.3$; $p<.001$). Yet, even for the larger targets, the effect of Edge Gap remained significant ($F[3,2235]=7.7$; $p<.001$). A post-hoc Tukey-HSD pairwise comparison showed that when they were 0mm, 1.5mm or 4mm away from the edge, these large targets still had significantly *slower* reaction time than those 11mm away from the edge. While it is possible that the effect would disappear with even larger targets, the targets we used (22 mm) are already larger than a typical fingertip. **As a result, for the two sizes of targets we used, we *reject* hypothesis H_2.** Still, it is important to note that in our data, reaction time to a 22mm target with a 0mm gap was faster (M=524 msec) than to 11mm targets with an 11mm gap (M=538 msec).

The Effect of Gap Size in Detail

We next turn to examine whether introducing gaps of different sizes significantly changes reaction time to edge targets (to address H_3). While we already reported on the significantly faster reaction time of targets 11 mm away from the edge, we now examine whether introducing a 1.5 mm or a 4 mm gap would significantly affect reaction time.

In our study, moving targets 1.5 mm away from the edge did not produce a significant difference in reaction time ($F[1,2239]=.2$; $p=.7$). However, moving targets 4 mm away from the edge produced a small but significant difference in reaction time ($F[1,2234]=5.9$; $p=.02$). **We may thus only partially accept H_3.**

Looking again at all trials, our analysis shows a significant interaction between Edge Gap and Target Position on reaction time ($F[15,4497]=3.8$; $p<.001$). Figure 7 shows the effect of Edge Gap on reaction time for different target positions (for readability, we present reaction time to targets at the top and bottom of the screen separately). As is quickly evident from looking at Figure7, introducing gaps had an effect especially with targets at the Top-Left and Bottom-Right. On the other hand, non-corner targets (Top-Middle and Bottom-Middle) were faster, and different edge gaps had no effect on reaction time.

Proximity to the Edge and Device Orientation

Lastly, we examined whether the orientation of the device (Portrait or Landscape) would result in a different effect of edge targets on reaction time. However, Orientation did not show a significant effect on reaction time ($F[1,8]=.9$; $p=.4$), nor did the interaction between Orientation and Edge Gap ($F[3,4486]=.3$; $p=.8$). In fact, looking independently at the Portrait and Landscape conditions, both showed a significant effect of Edge Gap ($F[3,2246]=9.9$; $p<.001$ and $F[3,2223]=5.5$; $p<.001$, respectively).

H_1	Proximity to device edge will significantly affect touch-target acquisition time.	Accepted
H_{1a}	Independent of distance, proximity to device edge will result in faster reaction time.	Rejected
H_{1b}	Independent of distance, proximity to device edge will result in slower reaction time.	Accepted
H_2	Large targets will not be affected by proximity to the edge.	Rejected
H_3	The effect of proximity to the edge can be significantly reduced with even a slight gap between target and edge.	Accepted (partially)

Table 1. Summary of the hypotheses

DISCUSSION

In the two studies presented in this paper, we found a significant negative effect of a target's proximity to the edge of a tablet's screen on target acquisition performance. This slower reaction time to edge targets stands in stark contrast to the performance advantage that edge targets have in traditional desktop mousing environments. We also found that the negative effect persisted for larger targets, although, not surprisingly, the effect was lessened. Table 1 summarizes our hypotheses and whether our experiments allow us to accept or reject them.

Still, the effect found was not obvious and is, in some ways, surprising; while one may correctly argue that tablets' touchscreens don't offer physical affordances that could accelerate reaction to edge targets, we could then still expect that reaction to edge targets will be equally fast (or slow) as reaction to any target on the screen. In fact, for the most part, screen edges on current tablets are just barely distinguishable from the rest of the screen: the glass spans the screen and the bezel, and in many devices, the touch sensor itself extends into the bezel (albeit, with reduced accuracy). What could be the reason for the slower reaction time? While the experiments do not provide a definite answer, we will discuss several alternative explanations. Still, further investigations into these possible explanations is needed and is left for future work.

Visual Interference

A potential reasonable explanation for the slow reaction to edge targets may be that when a target is near the edge, the cognitive task of separating the edge and target into two distinct objects is more difficult. Extensive research exists in the field of cognitive psychology (for example, [4, 8, 14, 23]) that describes the cognitive processes involved in the perception of elements as objects (for a survey, see [22]).

Yet two points must be considered in relation to this potential explanation. First, our results show that reaction time to corner targets was consistently slower than reaction time to edge targets that are not edge targets (e.g., a target at the top-middle). Thus, if visual interference is indeed the culprit, it would mean that corner targets suffer from greater visual interference than an edge target (a reasonable expectation). However, in the second experiment, gaps of different values were added between target and edge. This allowed all targets except those with a 0mm gap to have some visual separation from the edge. Second, in the tablet used in Experiment 2, as with most tablets today, the visual difference between the edge of the screen and the bezel around it is subtle (see Figure 5): The screen is a very dark grey with backlight, but otherwise both are dark (when nothing is drawn on the screen) and covered by glass. Thus, the purely visual difference between edge targets and non-edge targets was minimal.

Global and Local Processing

Another potential and related cause for the slower reaction may be a two-level visual processing of a target's position. According to the theory proposed by [16], in a first stage, people will visually locate the large encompassing object and then, in a second stage, visually search for the smaller target within. Applying this theory to this case, the user would first visually locate the tablet, and then search within the tablet's bounds for the target.

This explanation properly accounts for the lack of statistical difference when targets were moved 1.5mm away from the edge (since the change to the second stage is minimal). However, if this explanation was sufficient, then no effect would be found in Experiment 2, since a user is already working within the boundaries of the tablet.

Preference for the center of the display

It is also possible that people "prefer" the inside area of a shape (in this case, a rectangular screen), and would be thus faster to react to targets in their preferred zone. However, in [9], Firestone and Scholl showed participants different shapes on a tablet (one shape at a time) and asked them to tap anywhere they wished. Their results show that in the aggregate, touches conformed to the medial-axis skeleton, and included many touches near corners.

Fear of going out of bounds

As mentioned above, the effect of edges persisted for large and small targets and even persisted when gaps were introduced around the targets. Since in the two experiments we fully control for distance and target size, we are allowed to assume that the cause for the effect is perceptual. Is it possible then that participants were, for some reason, reluctant to touch outside the edge of the screen? This, currently, seems like a most likely phenomenon behind the effect, but is insufficient to explain the cause of the phenomenon. To properly test this possibility, a setup would need to be created in which missing "outwards" is preferred to missing "inwards".

Implications for design

The findings presented in this paper may have immediate implications for the design of efficient interfaces for handheld touchscreens. Particularly, the findings highlight that edge targets, and in particular corner targets – often thought of as the prime position for quick interactions – may actually be slow in those touch devices. This is especially important with the growing popularity of interfaces that are used with touch and pointing devices interchangeably.

One recommendation that emerges from the results is that in order to mitigate the effect of proximity to the edge, when designing an interface for touch, edge targets should be made larger, particularly corner targets.

As mentioned above, the results of our second study hint that the reason for the slower reaction time is the visual appearance of the targets near the edge, and suggest that adding a gap as small as 4mm may partially improve reaction to corner targets (for our right-handed participants, these were the top-left and bottom-right corners).

For the design of underlying pointing acceleration and assistance techniques, it is interesting to note that edge targets did not result in significantly higher touch offset from the center of the target. This suggests that simply increasing the underlying effective area of a target, but not making it visually larger may not sufficiently improve reaction time. Still, an examination of the effect of edge targets with realistic interfaces is needed.

LIMITATIONS AND FUTURE WORK

One potential limitation of the findings is that in both experiments, only a single target was shown on the screen at any given time. Indeed, the case of a singleton target, common in abstract experiments of human performance, is quite rare in real-world interfaces. In future work, we plan to examine the effect of edge targets in the presence of competing targets. Whether edge targets suffer more or less from such distractors is an interesting question that would shed further light on the root cause of the effect described here, and allow for broader design recommendation.

Another limitation of this work is the focus on a single device category (8" tablets). While this represents a popular segment, investigating the effect of edge targets on performance on other form factors such as smartphones needs to be verified experimentally. One could expect that edge targets will have a smaller effect in smartphones, and potentially a greater effect in larger tablets geared at productivity applications. Testing the effect of edge targets with different size screens, more target sizes and additional edge gap values is necessary but left for future work.

Finally, the work presented here looked exclusively at tasks where a target's position was unknown in advance. Understanding the effect of edge-targets in cases where their position is fixed and known in advance is needed. In future work, we plan to investigate the effect of edge targets when the user plans, ahead of time, to hit them. This can be done, for example, by having participants tap targets (both edge and non-edge) in a pre-defined sequence.

CONCLUSIONS

Edge targets, such as buttons and menus organized along the edge of the screen, have long been used in desktop mousing environments to provide quick access to targets. This paper presented a surprising negative effect of edge targets on reaction time when using touch. The effect was found through two experiments: In the first experiment, we used a setup designed specifically to allow decoupling of the distance of targets from the user and the distance of targets from the frame around them. A second experiment confirmed the presence of the effect and explored potential mitigating solutions, including different sized targets, and the introduction of small gaps around the targets.

The findings presented in this paper grow our understanding of human performance with touchscreen interaction, and should be considered in the design of efficient interfaces for touch devices.

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