Adaptive Click-and-Cross: Adapting to Both Abilities and Task Improves Performance of Users With Impaired Dexterity

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ABSTRACT

Computer users with impaired dexterity often have difficulty accessing small, densely packed user interface elements. Past research in software-based solutions has mainly employed two approaches: modifying the interface and modifying the interaction with the cursor. Each approach, however, has limitations. Modifying the user interface by enlarging interactive elements makes access efficient for simple interfaces but increases the cost of navigation for complex ones by displacing items to screens that require tabs or scrolling to reach. Modifying the interaction with the cursor makes access possible to unmodified interfaces but may perform poorly on densely packed targets or require the user to perform multiple steps. We developed a new approach that combines the strengths of the existing approaches while minimizing their shortcomings, introducing only minimal distortion to the original interface while making access to frequently used parts of the user interface efficient and access to all other parts possible. We instantiated this concept as Adaptive Click-and-Cross, a novel interaction technique. Our user study demonstrates that, for sufficiently complex interfaces, Adaptive Click-and-Cross slightly improves the performance of users with impaired dexterity compared to only modifying the interface or only modifying the cursor.

Keywords: Accessibility; area cursors; adaptive user interface

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION

Computer users with impaired dexterity often have difficulty with mainstream user interfaces, especially when these user interfaces contain small, densely-packed interactive elements.

In the past few decades, a variety of software-based techniques have emerged to assist such users. These approaches fall broadly into two categories: those that modify the user interface itself (e.g., ability-based user interfaces generated with SUPPLE [8]) and those that modify the user's interaction with the mouse pointer (e.g., area cursor [15], bubble cursor [11], enhanced area cursors such as Click-and-Cross [3]).

Approaches that modify the interaction in order to adapt the user's abilities to the existing user interface make access possible without requiring substantial modifications to existing interfaces. However, these techniques may lack generality (e.g., area cursors and the bubble cursor enhance interaction only when clickable elements are sparsely laid out), or they may reduce the efficiency of the interaction (e.g., the Click-and-Cross technique from Findlater et al. [3] replaces a single click with two operations: a click in the vicinity of the desired target followed by a crossing action to make a specific selection, Figure 1a).

In contrast, approaches that adapt the user interface to the user's abilities by modifying the user interface enable efficient access to each item, optimizing the interaction to each user's strengths [8, 21]. However, adapting user interfaces to the abilities of users with impaired dexterity involves an important trade off: such adaptations typically involve making clickable elements larger at the cost of increased navigational complexity. This requires more scrolling and tab switching when navigating between user interface elements. Existing approaches often enlarge all clickable elements — even those that users rarely access — because not enlarging them might render them inaccessible. The increased navigational complexity from such a broad approach is a source of inefficiency.

We set out to combine the strengths of the two approaches: making access possible and efficient while minimizing modifications of the original design. To do this, we build on a third adaptive approach: user interfaces that adapt themselves to the user's *task* (e.g., [2, 6, 9, 18]). Such interfaces have been demonstrated to improve users' performance by leveraging predictive models for each user's actions to ease access to the features that the user is most likely to access next (e.g., by copying them to a more easily accessible location, by making them larger or more visually salient).

Building on these three ideas of adaptation, we have developed Adaptive Click-and-Cross. As illustrated in Figure 1, with Adaptive Click-and-Cross, user interface elements that are predicted to be most frequently accessed by the user are enlarged and can be accessed efficiently with a single click (adapting the interface to the user, adapting the interface to the task). The remaining elements are left unmodified and can be accessed through the Click-and-Cross technique: the user can click anywhere in the vicinity of the desired target and subsequently refine the selection with a crossing interaction (adapting the user's abilities to the interface). This approach achieves three things: it enables *efficient* access to frequently accessed user interface elements, makes access to all other
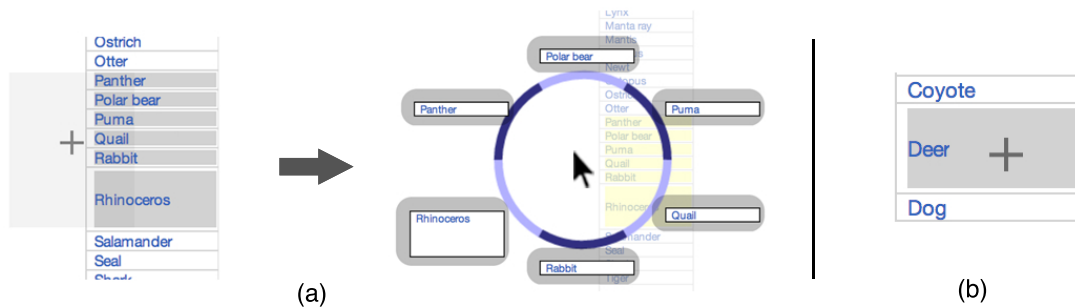
Figure 1: Adaptive Click-and-Cross. **(a)** When users click near or directly on small targets, Click-and-Cross is triggered: a circular overlay of the nearby targets appears. Users can then cross through the corresponding arc to select the item. **(b)** Users can directly click on a large target to select it.

elements *possible*, and minimizes the distortion of modifying the user interface.

The results of our study with 12 participants of impaired dexterity demonstrate that for a complex user interface (where enlarging all interface elements substantially increases the cost of navigation), Adaptive Click-and-Cross results in significantly shorter task completion times compared to either adapting the interface by enlarging all elements or Click-and-Cross alone. We observed no significant differences in error rates or subjective preference across the three techniques. However, participants subjectively perceived the interface with all elements enlarged as more efficient than either Click-and-Cross or Adaptive Click-and-Cross.

RELATED WORK

Many existing software solutions improve accessibility by modifying users' methods of interaction. Such solutions may adapt the behavior of a pointing cursor to the user (e.g., Steady Clicks [19], Angle Mouse [22]), or they may introduce entirely new interaction techniques (e.g., area cursor [15], bubble cursor [11], enhanced area cursors [3]).

Approaches that directly modify the user interface have also been investigated. These approaches advocate adapting the user interface to users' needs (e.g., EyeDraw [13] and Voice-Draw [12]). Although creating accessible designs that are well suited to a particular set of abilities can be time consuming, previous work has begun to demonstrate how such modifications could be automated [8].

However, for complex user interfaces, adapting the user interface to the abilities of users with impaired dexterity requires either reducing the available functionality to fit all elements on the screen [13, 12] or increasing navigational complexity by requiring more scrolling, switching between tab panes, etc. [8]. Recent work has examined the efficacy of on-demand expansion of targets (i.e., dynamically expanding the target after the user begins to move the cursor in its direction) [14]. This approach prevents targets from being enlarged unnecessarily, minimizing the potential increase in navigational complexity from enlarging targets. While the experimental results show that the approach improves performance, its effectiveness is likely to diminish in densely packed user interfaces.

Adaptive Click-and-Cross aims to minimize the costs of modifying the user interface by leveraging past results showing that most users only access a small subset of the available
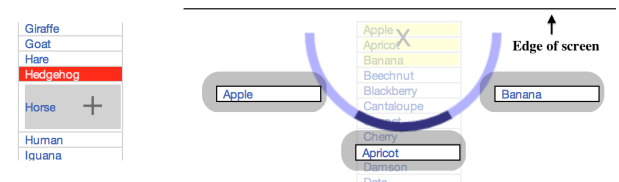
Figure 2: (a) In Adaptive Click-and-Cross, when target is bordered by an enlarged item, the target has a decreased amount of space for activating Click-and-Cross. **(b)** Near the edge of the screen, the Click-and-Cross cursor only displays a subset of the circle.

functionality, though each user accesses a *different* subset [10, 17]. This finding has been used to design user interfaces that enable efficient access to a subset of items that are predicted to be of most use to the user. For example, in split interfaces [5, 6, 18], the elements predicted to be most useful are duplicated to a convenient location to support more immediate access. In contrast, morphing menus [1, 20], which have been tested with able-bodied users, do not duplicate elements but instead enlarge predicted items to enable efficient access.

ADAPTIVE CLICK-AND-CROSS

The original Click-and-Cross technique [3] is illustrated in Figure 1a: when the user clicks near or directly on a user interface element, a circular overlay is displayed with several (up to six in our implementation) of the closest interface elements laid out along the circumference. Moving the mouse such that it crosses the circumference triggers a "click" on the corresponding element. If the first click was made by mistake, performing another click inside the circle cancels the interaction.

In Adaptive Click-and-Cross, a small number of the user interface elements — those predicted to be of immediate use to the user — are enlarged to enable efficient access with a direct click (Figure 1b). For the remaining elements, which may be too small for a user to access reliably, Adaptive Click-and-Cross employs the Click-and-Cross technique.

The appearance of the cursor changes depending on the position of the pointer (Figure 1). By default, the cursor is an *area cursor [15]:* a translucent, gray rectangle with a crosshair in the center. When placed directly over an enlarged item, the gray rectangle disappears, but the underlying item is highlighted in gray. When the cursor is not over an enlarged element, the cursor will resize in order to surround those targets that are projected to appear if Click-and-Cross is acti-

No.	Method	Age	Device	Gender	Condition
1	Remote	59	Mouse	M	Essential tremor
2	Remote	23	Touchpad	M	C-6 quadraplegic
3	Remote	49	Mouse	F	Spinal stenosis, ruptured cervical disks
4	Remote	62	Mouse	F	Multiple sclerosis
5	Remote	38	Mouse	F	Ankylosing spondylitis, fibromyalgia
6	Remote	42	Mouse	F	Duchene muscular dystrophy
7	Remote	65	Trackball	M	Spinal cord injury
8	Remote	38	Mouse	M	Spinal cord injury
9	Remote	43	Headmouse	M	Cerebral palsy
10	Remote	19	Mouse	F	Familiar essential tremor, Parkinson's
11	In-person	49	Trackball	F	Multiple sclerosis
12	In-person	59	Trackball	M	Multiple sclerosis

Table 1: Our participants.

vated. For useful visual feedback, these targets will also be highlighted in gray. Upon activation of the Click-and-Cross cursor, the gray rectangle disappears, revealing a traditional point cursor for making the crossing selection.

In situations where only a part of the circle can be rendered on the screen, such as when the initial click occurs near the edge of the screen (Figure 2b), the area cursor is appropriately resized to provide accurate visual feedback as to which items can be accessed.

When activated, the Click-and-Cross cursor also includes enlarged items in the overlay, meaning that enlarged items can be acquired either through Click-and-Cross or direct clicks.

EXPERIMENT

Participants. Twelve people (six male, aged 19–65) with dexterity impairments participated in the study. Table 1 provides additional details about each participant.

Two people participated in person and 10 remotely. Recent work has provided compelling evidence showing that performance evaluations of user interfaces can be performed reliably with remote participants [16], provided that a few basic safeguards (such as testing for instruction comprehension, selecting appropriate outlier removal criteria) are maintained. We have built on those insights to ensure reliability of the results collected from our remote participants.

Apparatus. The experiment was implemented as a web site written in HTML, CSS, and JavaScript. Remote participants completed the study using their own computers and devices. To ensure consistency between participants, remote participants were asked to reset the zoom levels on their browsers and make their browser windows as large as possible, and the visible portion of the scrolling menu interface (i.e., the number of items displayed at a given scroll position) was held constant at 475 pixels. A summary of the input devices used by the participants can be found in Table 1.

Tasks. Building on prior empirical research on adaptive user interfaces [1, 4, 5, 20], we chose menu selection as our experimental task. This task naturally supports manipulation of navigational complexity (i.e., by changing what fraction of the menu is visible in the application window, we could control how much scrolling was required on average to reach a menu item [5]).

We tested four designs in the study. Abbreviations for each design are used throughout the paper.

1. *Enlarged* (ENLG): traditional cursor pointing with all menu items enlarged (80×40 pixels);
2. *Click-and-Cross* (CNC): the Click-and-Cross cursor, menu items are the default size (80×10 pixels);
3. *Adaptive Click-and-Cross* (ACNC): a menu where some items are large and can be acquired directly through normal clicking, and some items are the default size and can be acquired using Click-and-Cross;
4. *Baseline* (BASE): traditional mouse pointing, menu items are the default size.

The order of the conditions was counterbalanced using a partial Latin square design. The tasks in each condition were isomorphic, but each condition used a different vocabulary (i.e., fruits, vegetables, animals, colors) and differed in the order of the sets of trials within each condition. In each design, the menu interface consisted of 60 items.

The targets that participants had to acquire during the experiment were distributed uniformly throughout the menu. In CNC and BASE conditions (where all items were the default size), this resulted in approximately 60% of the trials with targets on the first screen—those targets could be acquired without scrolling. In the ENLG condition, where all menu items were enlarged, fewer items were visible on the screen at once: in only 20% of the trials the desired targets could be reached without scrolling. In the ACNC condition, where only a small fraction of the items were enlarged while the rest were the default size, in 50% of the trials the desired targets could be accessed without scrolling.

In the ACNC condition, we simulated a system with a 70% accuracy in predicting what menu items the user would use. Similarly to others [2, 5, 6, 7], we did so by designing the experimental task such that 70% of the items that the participants were asked to select in that condition were enlarged, while the remaining 30% were not. This is a popular experimental paradigm that allows adaptive user interfaces to be evaluated under reasonable assumptions about accuracy of the predictive algorithm that might be used.

Procedure. Each participant first filled out a demographic survey containing questions about his or her computer usage and motor and/or visual impairments. Participants then proceeded to the main part of the experiment. For each participant, there were 4 conditions $\times$ 5 blocks $\times$ 10 trials $=$ 200 trials. At the beginning of each condition, each participant was presented with an instructional video describing the cursor behavior or the condition. The first block of each condition was a practice block, allowing the participant to become accustomed to the design. Performance on the practice blocks was not included in the analysis. Thus, the analysis for each participant were performed using 4 conditions $\times$ 4 blocks $\times$ 10 trials $=$ 160 trials. At the end of each condition, participants rated the condition on a 7-point Likert scale on how easy, tiring, or efficient they found the particular design to be. At the end of the study, each participant ranked the conditions in order of overall preference and perceived efficiency. The study took 40 to 80 minutes depending on individual abilities.

Design and Analysis. We used a within-subjects factorial design for our analysis with Design {ENLG, CNC, ACNC} as the main factor.

We did not necessarily expect to see benefits of any of the adaptations compared to the non-adaptive baseline: the results of a prior evaluation of CNC [3] suggest that the technique provides substantial performance benefits for very small targets (8 pixels or smaller) or for participants with severely impaired dexterity. In our experiment, we used larger targets (80×10 pixels) to ensure that minor visual impairments, which are common among elderly participants, would not preclude participation in our study. Additionally, most of our participants had moderate rather than severe dexterity impairments. For these reasons, we excluded the non-adaptive baseline from our analysis, but we do include those results for completeness.

The main measures in this experiment were *target acquisition time*, computed over error-free trials, and *error rate*, computed as the fraction of the trials that contained at least one error. Subjective measures for each condition also included *perceived efficiency*, *perceived fatigue*, *perceived ease of use*, *efficiency ranking*, and *overall preference ranking*.

The following (within-subjects) factors were also included in some of the follow-up analyses:

- On First Screen {Yes, No}: We recorded whether an item was *on the first screen* — the initial part of the menu presented to the participant — meaning that the participant did not have to scroll to acquire the target.

- On Edge {Yes, No}: For CNC and ACNC, we recorded whether an item was *on the edge* of the visible part of the application window at the time of acquisition. Because only part of the circular overlay is shown when there is not enough space for the circle, this could potentially impact acquisition time (Figure 2b).

- Bordered by Enlarged Item {Yes, No}: For ACNC specifically, we recorded whether the target item was *bordered by an enlarged item*. Because enlarged items could immediately be acquired by the user through a normal click, small items bordering an enlarged item had less space in which the area cursor could be triggered (Figure 2a).

In total, data were collected for 1440 acquisition trials. Trials with acquisition times outside of two interquartile ranges from the median were discarded as outliers ($42/1440 = 2.9\%$ of the trials). To account for the wide range of individual abilities, the outlier removal procedure was performed separately for each participant. This median-based approach was selected over the standard approach of discarding trials outside of ± 2 standard deviations, as it is more robust for remote experiments, where extreme outliers may heavily impact the mean and standard deviation [16]. After discarding outliers, timing data were log-transformed to account for the skewed distribution found in such data.

Analysis of acquisition time was performed using repeated measures analysis of variance. We used binomial logistic regression to examine the effect of condition on error rate, because a binary measure was used to capture whether an error occurred in each trial. The subjective results were analyzed using non-parametric Friedman tests. The findings for subjective data that were statistically significant were followed up with pairwise Wilcoxon tests with Bonferroni correction.
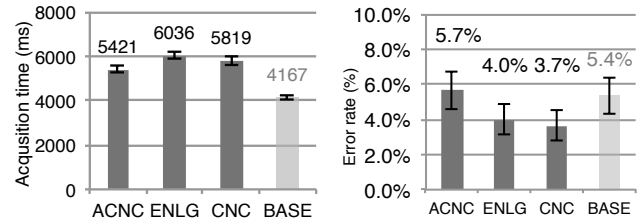
Figure 3: Mean acquisition times and error rates for each condition. Error bars represent ± 1 standard error of the mean (SEM). Baseline is included for completeness but was not included in the analysis (see Design and Analysis for further discussion)

For the analyses specific to the effect of *On Edge* and *Bordered by Enlarged Item* on performance with CNC and ACNC, paired t-tests were used. Trials with errors were included in those analyses. Because these analyses were designed to investigate whether the activation of a partial circle (On Edge) or the reduced space for activation (Bordered By Enlarged Item) affected acquisition time, we focused on the scenarios where the user was likely to make an error, either from failing to include a target near the edge or attempting to activate CNC but instead clicking an enlarged item.

RESULTS

As discussed in *Design and Analysis*, we include the baseline results for completeness but perform our analyses on the three adaptive designs: ENLG, CNC, ACNC.

Preliminaries. We first conducted an analysis to test for the presence of any prominent learning effects. We used Condition and Block Number as factors and acquisition time as the dependent variable. We observed no significant effect of block on acquisition time ($F_{3,9} = 1.322, p = 0.327$). There was also no significant interaction between condition and block number ($F_{6,6} = 0.164, p = 0.978$). These results indicate that, on average, participants' performance did not vary systematically from block to block after they had completed the practice trial for each condition. Thus, all blocks were used in the subsequent analyses.

Overall acquisition times. We observed a significant main effect of Design on acquisition time ($F_{2,10} = 1.15, p < 0.05$). ACNC had the lowest average acquisition time of the three adaptive designs: 5.4 s for ACNC, 5.8 s for CNC, and 6.0 s for ENLG. These results are illustrated in Figure 3.

There was a significant interaction effect between Design and On First Screen ($F_{2,21} = 0.67, p < 0.005$). ENLG was the slowest overall, but for trials where targets were on the first screen and required no scrolling to acquire, ENLG was the fastest with an average acquisition time of 2.6 s. ACNC (3.8 s) was still faster than CNC (4.6 s). In contrast, when users had to scroll in order to reach the target item, ACNC and ENLG had comparable acquisition times (6.6 s v 6.7 s). CNC was again slower than the other two designs (7.0 s). These results are illustrated in Figure 4.

This supports the notion that, given large menu items that require no navigation to acquire, very large menu items are easy for users with dexterity impairments to acquire. However, despite the large speed advantage of ENLG when items are on

the first screen, this advantage is offset in the overall acquisition times by the increased scrolling required in ENLG.

Errors. As illustrated in Figure 3, participants were slightly more likely to make an error with ACNC than with the other conditions, but the difference was not significant ($\chi^2(2) = 2.43, p = 0.30$).

Subjective Results. After each condition, participants rated the design they interacted with on a 7-point Likert scale for how easy, efficient, or physically tiring they felt the condition to be. There was no significant effect of condition on any of these perceived traits, though the perception of efficiency was marginally significant (easy: $\chi^2_{(2,n=12)} = 3.74, p = 0.15$, efficient: $\chi^2_{(2,n=12)} = 5.87, p = 0.053$, tiring: $\chi^2_{(2,n=12)} = 2.72, p = 0.26$) with participants perceiving the ENLG condition as being more efficient than the other two.

At the end of the study, participants ranked the designs in order of overall preference and perceived efficiency. There was a significant main effect of condition on subjective efficiency rankings ($\chi^2_{(2,N=12)} = 8.17, p < 0.05$). Pairwise comparisons showed that participants perceived ENLG to be more efficient than either CNC or ACNC, but there was no significant difference in efficiency rankings between CNC and ACNC. There was no significant effect of condition on the overall preference rankings ($\chi^2_{(2,N=12)} = 4.67, p = 0.097$).

The perceived efficiency of ENLG agreed with many of the comments from participants, who cited the enlarged elements in both ACNC and ENLG as favorable. One participant stated, "I liked the combined method the most, but with the large boxes ... I found the larger boxes easier to focus on and scroll over." Regarding the ENLG design, one participant said, "[The] target was larger, but [...] lots and lots of scrolling [was] needed."

Additional Analyses

We performed two additional analyses to investigate how design choices specific to CNC and ACNC impacted participants' performance.

Performance for targets located near the edge of the screen. In both CNC and ACNC, if a user clicks on a user interface element located at the edge of the screen, only a fraction of the circular overlay can be shown on the screen (Figure 2b). We conducted an additional analysis over trials from the CNC and ACNC condition with On Edge as the within subjects factor. In ACNC condition, only those trials where the CNC technique was used to acquire the target were included in this analysis. Because we expected both CNC and ACNC to be affected in the same way by targets on the edge of the screen, these trials were analyzed together.

We observed a marginally significant main effect of On Edge on acquisition time ($t_{23} = 1.58, p = 0.06$) in the CNC and ACNC conditions. Acquisition times for items near the edge were slightly shorter (6.4 s vs 5.8 s) (Figure 5).

Performance for targets that are bordered by enlarged items. In ACNC, some small menu items were bordered by enlarged items. These items had a decreased amount of space in which the CNC cursor could be activated (Figure 2a).
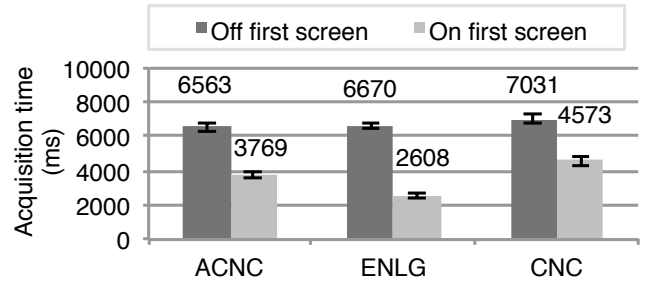
Figure 4: Mean acquisition times for each condition, grouped by whether or not the item was on the first screen presented to the user. Error bars represent ±1 SEM.
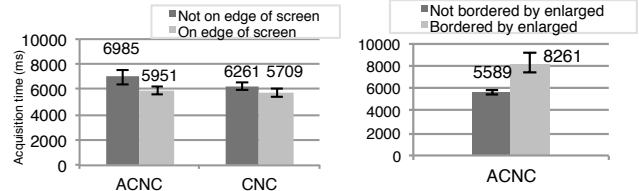
Figure 5: Mean acquisition times for ACNC and CNC, grouped by whether the target was (left) near the edge of the screen at the time of acquisition (for trials where the CNC technique was triggered) (right) bordered by an enlarged item. Error bars represent ±1 SEM.

We observed a significant main effect of whether an item was bordered by an enlarged item on acquisition time ($t_{11} = 6.33, p < 0.0001$). In examining trials where the target item was small (i.e., not predicted to be useful) but bordered by an enlarged target on either the top or bottom, acquisition times were substantially longer than for targets that were bordered only by regularly sized neighbors (8.3 s vs 5.6 s) (Figure 5).

DISCUSSION

This study explored one point in the design space of interaction techniques that combine multiple adaptations: our Adaptive Click-and-Cross technique, which combines adaptation to user's motor abilities with adaptation to a user's task, was designed to explore this concept in the context of improving the performance of users with dexterity impairments.

In our study, Adaptive Click-and-Cross was shown to result in significantly faster performance than either Enlarged or Click-and-Cross. There were no significant differences in accuracy across the three conditions. There were also no significant differences in subjective preferences across the three designs, though participants perceived the Enlarged design to be subjectively more efficient than either Adaptive Click-and-Cross or Click-and-Cross. However, participants' comments during interviews indicated that they were aware of the trade-off of enlarging all interactive elements: they commented on the ease of clicking on enlarged targets, but they also noted the increased effort required to scroll to the desired target.

Our study also allowed us to explore several practical considerations relevant to any real deployments of either Click-and-Cross or Adaptive Click-and-Cross. First, we investigated the performance of Click-and-Cross and Adaptive Click-and-Cross when used to access items near the edge of the window, where there is not enough space to display the full overlay for the subsequent crossing interaction. Our results show that performance on such targets is actually marginally faster than

for targets placed in the middle of the screen where the entire circular overlay can be displayed.

Second, for Adaptive Click-and-Cross, our results show that acquisition time was negatively affected for non-enlarged targets that were bordered by an enlarged item. Because the enlarged item can be acquired through a direct click, the presence of the enlarged item reduces the available space for activating the Click-and-Cross interaction to acquire the neighboring non-enlarged item. This suggests a second design consideration for Adaptive Click-and-Cross: enlarging a larger number of items both increases the amount of scrolling required to navigate the interface *and* makes some of the non-enlarged items harder to access than they would have been with the Click-and-Cross technique alone. An important implication of this is that two enlarged items should be carefully placed such that there is enough space to acquire the non-enlarged items in between.

One limitation of our study was that most of the participants we recruited had only moderate levels of impairment. For that reason, we were not able to demonstrate the benefit of Adaptive Click-and-Cross over non-adaptive interfaces. However, we were able to meaningfully demonstrate that Adaptive Click-and-Cross improves participants' performance in comparison to two existing approaches: adapting the size of elements to users' motor abilities and Click-and-Cross, both of which had been previously shown to benefit users with severely impaired dexterity [3, 8].

While this study evaluated a single technique, Adaptive Click-and-Cross, varying further parameters can provide insight into the factors that affect such techniques, such as the choice of enhanced area cursor, different target sizes, predictive accuracy, and the severity of user impairments.

CONCLUSION

This work was spurred in part by the observation that the word "adaptive" is used to describe a multitude of different approaches in the context of interactive systems. We hypothesized that these approaches can be synergistically combined, and we explored this synergy through Adaptive Click-and-Cross, an interaction technique designed to improve the performance of users with severe dexterity impairments. Adaptive Click-and-Cross relies on knowledge of a user's task to combine two adaptive approaches: adapting frequently used interface elements to a user's motor abilities while using an adaptive accessibility technique (Click-and-Cross) to enable access to those elements that are unlikely to be used.

Our results demonstrate that Adaptive Click-and-Cross slightly improved efficiency without sacrificing accuracy compared to two previously studied adaptive approaches: enlarging all user interface elements, and Click-and-Cross. Our work explored one point in a large design space, but the results suggest that hybrid adaptive approaches are a promising area of inquiry.

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