Effects of Interior Bezels of Tiled-Monitor Large Displays on Visual Search, Tunnel Steering, and Target Selection

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ABSTRACT

Tiled-monitor large displays are widely used in various application domains. However, how their interior bezels affect user performance and behavior has not been fully understood. We conducted three controlled experiments to investigate effects of tiled-monitor interior bezels on visual search, straight-tunnel steering, and target selection tasks. The conclusions of our paper are: 1) interior bezels do not affect visual search time nor error rate; however, splitting objects across bezels is detrimental to search accuracy, 2) interior bezels are detrimental to straight-tunnel steering, but not to target selection. In addition, we discuss how interior bezels affect user behaviors, and suggest guidelines for effectively using tiled-monitor large displays and designing user interfaces suited to them.

Author Keywords

Tiled-monitor large display, interior bezels, visual search, tunnel steering, target selection.

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms

Experimentation, Human Factors

INTRODUCTION

The research literature shows that a large high-resolution display is beneficial in many application domains. The large visualization surface facilitates collaboration among multiple persons [6], improves 3D navigation performance by providing a wider field of view [15, 16, 17], and prompts physical navigation thus improving performance in navigation tasks [3, 4]. However, although display technologies have been advancing rapidly, producing a seamless large high-resolution display is still difficult and expensive.

With currently available technologies, there are two common approaches to construct a large display – tiling multiple projectors or normal monitors. Carefully calibrating and tiling multiple projectors can create a large display surface with either no seams at all or at most very thin seams. However, this approach requires relatively large physical space for deploying projectors and excessive effort for calibrating them. An alternative is tiling multiple monitors. A tiled-monitor large display occupies less physical space and eases the calibration process. In addition, it is usually less expensive than tiled-projector ones, which require both projectors and back-projected surfaces. With these advantages, tiled-monitor displays are now widely used for many purposes in conference rooms, public places, data visualization centers [10], or even personal offices [2, 13] (Figure 1).
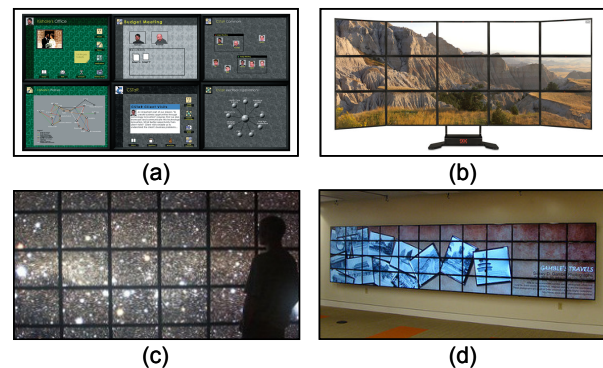

Figure 1. Tiled-monitor large displays in personal offices (a and b), data visualization center (c), and public place (d).

As indicated by previous studies [2, 12], a critical flaw of tiled-monitor large displays results from interior bezels, part of the physical bezel surrounding each component monitor. These interior bezels cause visual discontinuities of displayed images as well as cursor trajectory. On the other hand, since these bezels are relatively small compared to the display surface (e.g., a common 24″ LCD – 51 cm wide and 32 cm high – monitor frame is 2 cm wide, which is only 4% of the monitor width), it might be possible that users can successfully compensate for the difficulties caused by interior bezels in realistic tasks.

In this paper, we systematically investigate effects of tiled-monitor display (interior) bezels. Three experiments are deliberately designed to better understand bezel effects on user performances and behaviors in visual search, straight tunnel steering, and target selection tasks, respectively.

RELATED WORK

Research from three fields is relevant to our work. First, we survey work investigating the effects of interior bezels on tiled-monitor large displays. Next, we briefly summarize research studying the effects of bezels in normal multi-monitor environments, where their component displays that might have different sizes and resolutions are used without carefully tiling them with minimum offsets. Finally, we survey new interaction techniques addressing challenges imposed by bezels.

Bezel Effects on Tiled-Monitor Large Displays

The literature reveals that interior bezels can affect large display usage. Ball and North [2] studied user behavior on a large display consisting of nine 17″ monitors tiled together. Their work shows that the plastic borders surrounding a monitor can be both advantageous and disadvantageous: these bezels distort images and documents confusing users; on the other hand, users leverage bezels to segregate applications between monitors. Interestingly, users who intensively use such a tiled-monitor display gradually become more comfortable with images and text crossing bezels. Similarly, Robertson et al. [12] also reported that bezels present both opportunities and problems to users. One benefit is that interior bezels help users differentiate between different activities. However, bezels cause a visual discontinuity when images or text span across one or more bezels. It makes reading text and perceiving image patterns difficult. In addition, when the cursor moves across a bezel, its path often appears deflected because there is no virtual space corresponding to the physical space that the bezel occupies. Ball and North [2], and Robertson et al.'s work [12] reveal the potential effects of interior bezels on desktop work in qualitative studies. However, due to the difficulty of precise control over independent variables during their studies, they have not systematically assessed the effects of interior bezels on user performance or behaviors.

Bezel Effects in Normal Multi-Monitor Environments

Grudin's work [9] reported that the users deliberately separated work space with the bezels between multiple monitors and seldom spanned an image or text across bezels. Tan et al. [14] conducted a study examining effects of visual separation and physical discontinuities when distributing information across multiple displays. Their results showed that physical discontinuities introduced by bezels as well as by differences in depth do not affect performance on notification detection and text comparison tasks. However, displays in normal multi-monitor condition usually have different sizes and resolutions, as opposed to tiled-monitor condition in which displays with equal sizes and resolutions are carefully tiled. In addition, as displays in normal multi-monitor environment are all somewhat casually placed on a desk, there are some vertical, horizontal or depth offsets due to the placement. Hence, prior research on bezel effects on multi-monitor environment can serve as only a very rough guide to tiled-monitor large display usage.

Interaction Techniques Addressing Bezel Challenges

Mackinlay and Heer [11] proposed an approach to mitigate multi-monitor seams by treating each individual monitor as a view port into a large space. Based on this method, several seam-aware visualization applications were developed which could alleviate the visual discontinuities caused by interior bezels. Mouse ether [5] was designed to eliminate mouse warping effects caused by differences in screen resolution, vertical and horizontal offsets. As the cursor crosses a bezel, Mouse ether moves the cursor so that it follows the perceived trajectory as if it was in the first monitor. A user study showed that Mouse ether improved participants' performance on a target acquisition task across two screens running at different resolutions. To address the picture distortion problems across physical bezels, OneSpace [12] adjusted the computer's geometric model to reflect the actual physical distance between monitors. It let users view distortion-free image but hides part of images located behind bezels. Snapping and bumping techniques [12] were developed to avoid placing a window across bezels: snapping moves a window on the bezel or the edge of a screen; bumping moves windows to nearby empty space.

To integrate new interaction techniques with tiled-monitor display user interfaces, it will be crucial to firstly understand how much bezels affect user perception and interaction ability. Our study is not only to validate the necessity of new techniques, but also to guide how to effectively incorporate them into tiled-monitor UIs.

EXPERIMENT SETUP

In this section, we explain the common details of our three controlled experiments.

Tiling Configurations

One independent variable in all the three experiments is the degree of tiling, which relates to how many interior horizontal and vertical bezels exist on a tiled-monitor large display. In order to keep display size and performance parameters (e.g., brightness, contrast, etc.) constant, thus separating bezel effects from other factors, we use one projected display, on which virtual bezels are rendered to simulate tiled-monitor displays. We use three different degrees of tiling (1, 2, 3) to generate three tiling configurations as follows:

- **[1×1]**: There is no bezel on the display surface. This condition serves as baseline in the three experiments (Figure 2a).

- **[2×2]**: The display surface is equally subdivided into four areas by one horizontal and one vertical black bezel. This condition is to simulate a tiled-monitor large display consisting of four 40″ monitors (Figure 2b).

- **[3×3]**: The display surface is equally subdivided into nine areas by two horizontal and two vertical black bezels. This condition is to simulate a tiled-monitor large display consisting of nine 26″ monitors (Figure 2c).
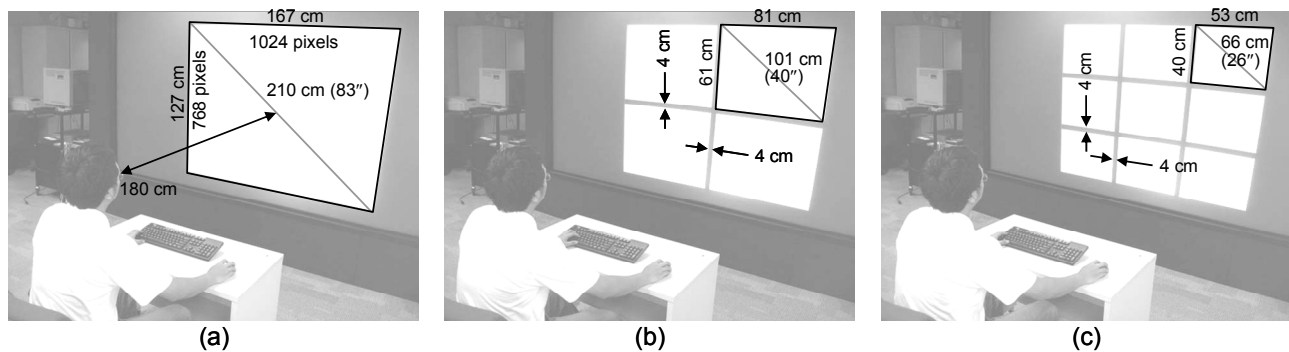
Figure 2. The three tiled-monitor large display configurations used in our experiments: (a) [1×1], (b) [2×2], and (c) [3×3].

For all the three conditions, a single projector with a resolution of 1024×768 pixels (NEC WT610) creates a 167 cm wide ×127 cm high display area. Each interior bezel is 4 cm wide and generated by the computer to simulate plastic bezels of physical tiled-monitor displays, which deflect cursor paths and separate images that are across the monitors. Current plastic frames on LCDs are usually 2 cm wide; hence, 4 cm reflects the width of bezels when multiple LCDs are tiled together. Note that replacing the default plastic frames with thinner frames might reduce the width of bezels. 4-cm width is a conservative estimation; it can be considered an upper bound for bezel width on tiled-monitor displays.

Participants

We recruited twelve participants (seven males and five females) between ages of 18 and 45. All of them are daily computer users and have normal or corrected-to-normal vision. They sat 1.8 m from the display, which is a preferred sitting distance determined by a pilot study, so that they could comfortably view the entire display with slight head rotation, and easily recognize displayed objects. Participants performed the three experiments in turn, with the presentation order of the experiments counter-balanced across the participants.

VISUAL SEARCH EXPERIMENT

The objective of this experiment is to investigate how interior bezels on tiled-monitor large displays affect users' visual searching performance and behavior.

Visual search is a commonly performed task on a large display. A larger display can visualize a greater amount of information simultaneously, thus improving visual search performance over a small-sized display [19]. On a tiled-monitor large display, however, its interior bezels might distract users. In addition, they may separate objects which are located across interior bezels apart (symbol split), thus impeding users from recognizing them. Given these two factors, we hypothesize that interior bezels are detrimental to user' visual search performances as follows:

H.1 The presence of interior bezels is detrimental to visual search performance.

H.2 Splitting data across interior bezels is detrimental to visual search performance.

Visual Search: Task

The experiment task is a traditional attentional image-searching task [18], in which participants are asked to identify whether a target object exists or not within a number of distracters. Our images use a light gray background, on which the two letters "VI" appear multiple times. In 50% of the images, one "IV" is present (Figure 3a). Participants are asked to search for an IV among VI's as quickly and as accurately as possible. They indicate the presence or absence of the target object using two keys on the keyboard. A beep sound is played if users make a mistake. To prevent participants from "racing through" our trials without regard for accuracy, the testing program freezes for five seconds whenever an error occurs. To specifically investigate symbol split effects, in 50% of the images, at least one VI or IV is located across interior bezels in both the [2×2] and [3×3] conditions (Figure 3b).
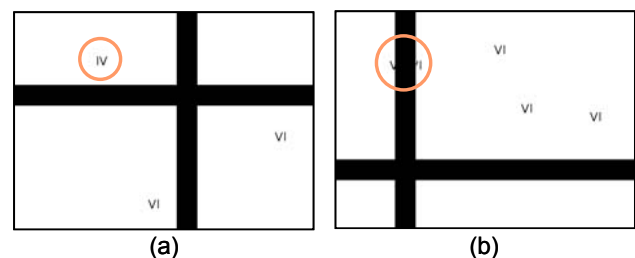

Figure 3. Visual search: (a) task – to identify if an IV exists among VI's in a given image, (b) the symbol-split condition – symbols might be displayed apart across an interior bezel(s).

Visual Search: Design

We used a within-subject, full-factorial repeated measures design with search time and error rate as our dependent measures. The search time is defined as the time lapse between when a stimulus image is initially presented on the display and when the "Present" or "Absent" key on the keyboard is pressed. The error rate is the percentage of erroneous trials.

The independent variables include the degree of tiling (1, 2, or 3), number of distracters (15 or 30 VI's), target presence (absence or presence of IV), and symbol-split status (split or non-split).

The presentation order of degree of tiling was fully counterbalanced with 6 combinations across the 12 participants. For each degree of tiling condition, participants searched the same set of 48 images that were presented in a random order. These 48 images consisted of 6 repetitions of 8 conditions, which represented the fully crossed combination of 2 number of distracter, 2 target presence, and 2 symbol-split status conditions. On each of the 48 images, the location of a symbol was randomly generated by the computer. Especially in the symbol-split condition, symbol locations were randomized with a constraint that in both the [2×2] and [3×3] degree of tiling conditions, at least one symbol is located across an interior bezel(s). In the final tested set of 48 images, the mean (SD: Standard Deviation) of the number of symbols across interior bezels was 1.4 (0.4) in the [2×2] × split condition and 1.6 (0.64) in the [3×3] × split condition.

The size of symbols was constant in the whole experiment. It was determined via a pilot study to ensure that users could easily recognize them.

In short, our design was:

> 12 participants ×
> 3 degree of tiling (1, 2, 3) ×
> 2 number of distractor VI's (15, 30) ×
> 2 target presence (present, absent) ×
> 2 symbol-split status (non-split, split) ×
> 6 repetitions =
>
> 1728 total trials.

Visual Search: Results

Search Time
The means (SD) of search time for the [1×1], [2×2], and [3×3] conditions were 6125 (3322), 6356 (3301), and 6284 (3394) ms, respectively. An ANOVA showed no significant main effect for the degree of tiling on the search time (F(2, 22)=0.89, p=0.42). The means (SD) of search time for the non-split and split conditions were 6260 (3264) and 6249 (3413) ms, respectively. No significant main effect for symbol-split status on the search time (F(1,11)=0.125, p=0.73) was observed either.

As expected from previous visual search studies, an ANOVA showed a main effect for the number of distracter VI's on the search time (F(1,11)=54.2, p<0.001), with 30 distracters resulting in longer search time than 15 distracters. The mean (SD) search times were 4970 (2440) and 7540 (3612) ms, with 15 distracters and 30 distracters, respectively.

The target-absent trials took a longer time than the target-present trials (F(1,11)=62.3, p<0.001): the mean (SD) search time for the target absent trials was 7392 (3513), and 5117 (3126) for the target present trials. This is typical in visual search experiments [7].

Error Rate
A repeated-measures ANOVA analysis showed no significant main effect for the degree of tiling on the error rate (F(2,22)=1.35, p=0.28), with the mean (SD) error rates of 5.324% (1.51), 8.33% (3.61), and 8.56% (6.11) for the [1×1], [2×2], and [3×3] conditions, respectively.

An ANOVA showed a significant main effect for symbol-split status on the error rate (F(1,11)=6.45, p<0.05). The mean (SD) error rates for the non-split and split conditions were 5.864% (3.00) and 8.796% (3.33) respectively, indicating that symbol split results in more searching errors (Figure 4).
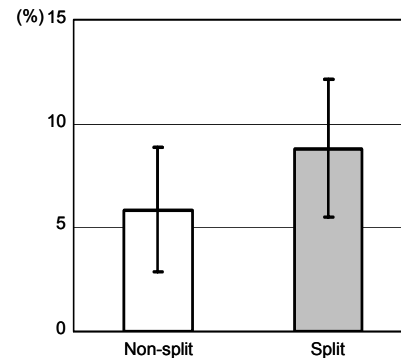

Figure 4. Mean (SD) error rate by symbol-split status.

Not surprisingly, the number of distracters had a significant main effect on the error rate (F(1,11)=15.6, p<0.05). The mean (SD) error rates for 15 distracters and 30 distracters were 4.63% (1.97) and 10.03% (4.26) respectively, indicating that more distracters cause a higher error rate. Target presence also had a main effect on the error rate (F(1,11)=27.5, p<0.05), with the mean (SD) of 1.39% (0.612) for the target-absence condition and 13.27% (5.7) for the target-present condition; participants often missed targets when they were present, whereas false positives were extremely rare.

Subjective Opinions
At the end of the experiment, a short questionnaire was administered to gather subjective opinions.

• "Did interior bezels hinder or improve search process?" Three participants circled "Improved". They commented that interior bezels separated the display area into smaller regions so that they could search them one by one, which seemed easier than with no interior bezel. In contrast, four participants reported that bezels hindered their performance because they were distracting and broke the continuity of search. Five participants thought bezels had no effect on the search task. These diverse answers indicated that effects of bezels on visual search might vary on different persons. According to participants' subjective opinions, bezels effects could be positive, negative, or even neutral in search process. It somehow explains why no significant main effect was observed for bezels on search time.

- "What search strategies did you use?" 11 participants reported that they were searching targets grid by grid in both the [2×2] and [3×3] conditions since the entire display surface was divided into smaller subareas. In the [1×1] condition, various search strategies were applied. Four participants reported that they searched the target by clusters on the display; two participants reported that they searched from left to right and top to bottom on the display; four participants reported that they searched the target circularly. This result indicates that the presence of bezels affects the decision of search strategies; most of participants searched targets grid by grid in bezel-present conditions ([2×2] and [3×3]), and their search strategies varied in no-bezel condition ([1×1]).

Visual Search: Conclusions

We conclude the first experiment with our results with respect to the two hypotheses we formulated.

> **H.1** *The presence of interior bezels is detrimental to visual search performance*. This hypothesis was not confirmed. The number of interior bezels did not show any main effect on either search time or error rate.

> **H.2** *Splitting data across interior bezels is detrimental to visual search performance*. This hypothesis is confirmed. Splitting symbols across an interior bezel(s) leads to a high rate. We reason that this is because separating symbols apart increases the difficulty of recognizing them.

TUNNEL STEERING EXPERIMENT

The objective of the second experiment is to investigate how interior bezels affect straight-tunnel steering performance and behavior – straight-tunnel steering is a canonical task for GUI interaction such as hierarchical menu invocation [1]. As interior bezels deflect tunnels and cursor trajectory (Figure 5), we hypothesize that interior bezels are detrimental to steering performances. To be specific, the major hypotheses in this experiment are:

> **H.3** *The presence of interior bezels hinders steering performance.*

> **H.4** *As the number of interior bezels increases, steering performance declines.*

Figure 5. Deflected straight tunnels in (a) [2×2] and (b) [3×3] tiled displays.

Tunnel Steering: Task

Participants perform a straight tunnel steering task (Figure 6). At the beginning of each trial, a red start circle appears at one of four home positions (Figure 6a). After clicking the circle, a 58-pixel wide, 480-pixel long straight green tunnel appears next to the start circle. The tunnel's direction is randomized with its start and end lines all residing within the display (Figure 6b). The subsequent cursor movement is shown as a red trajectory on the display (Figure 6c). When the cursor crossed the start line, a trial begins and the crossing time is recorded. When the cursor crosses the end line, the color of the tunnel turns to yellow, signaling the end of the trial (Figure 6d).

Crossing the side borders of the tunnel results in the cancellation of the trial, and an error is recorded. Participants are explicitly asked to perform the task as quickly and accurately as possible. The mapping speed of the cursor is adjusted through a pilot study to ensure that users can steer through any tunnel without clutching. The "Enhance pointer precision" function in Windows XP is turned on.

The tunnel length is fixed at 480 pixels to ensure that any tunnel crosses at least one interior bezel in the [2×2] condition and at least two in the [3×3] condition. Note that this study cannot be considered as a general steering law experiment [1] because we do not systematically vary tunnel length and width. Instead, by varying the number of interior bezels, it allows us to have an insight into interior bezel effects on general steering tasks.
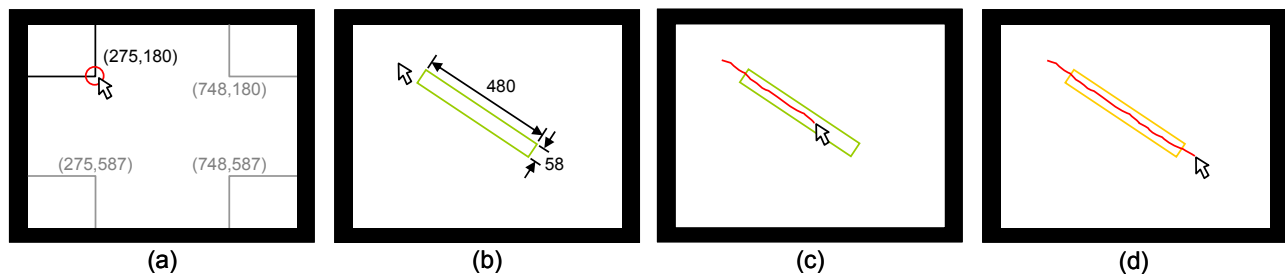

Figure 6. Steering task: (a) clicking the start circle appearing at one of the four home positions to start a trial, (b) a straight tunnel with a random direction, (c) crossing the start line, (d) crossing the end line (the color of tunnel changes from green to yellow).
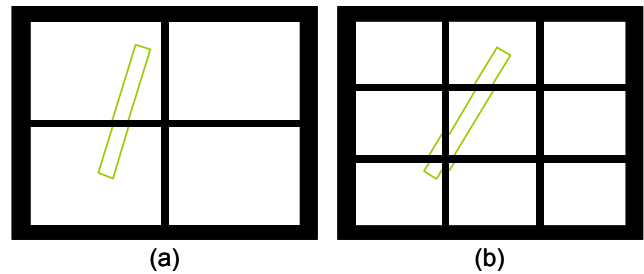
Tunnel Steering: Design

We used a within-subject, repeated measures design with steering time, error rate, and cursor speed as our dependent measures. The steering time is defined as the elapsed time from the moment when the cursor crosses the start line until when it crosses the end line. The error rate is the percentage of erroneous trials. The cursor speed is defined as the amount of movement over time. Although the task will result in cursor speed being directly proportional to steering time if the trajectory is perfect, in practice participants will create different trajectories each time they steer through a tunnel. Further, this might be affected by whether or not the tunnel crosses bezel(s). Thus, cursor speed provides a slightly more nuanced measure that considers both speed and trajectory as a whole.

The independent variable is the degree of tiling (1, 2, or 3). The presentation order of these three conditions was fully counter-balanced with 6 combinations among 12 participants. Within each degree of tiling condition, participants first performed 3 trials to familiarize themselves with the task. Practice trials were followed by the experiment sessions, which consist of 6 blocks with each one containing 6 trials. In short, our design was:

> 12 participants ×
> 3 degree of tiling (1, 2, 3) ×
> 6 blocks ×
> 6 repetitions =
>
> 1296 total trials.

Tunnel Steering: Results

Steering time

An ANOVA analysis of the collected data showed a significant main effect for the degree of tiling on the steering time ($F(2,22)=5.8$ $p<0.05$). The mean (SD) steering times for the [1×1], [2×2], and [3×3] conditions were 1542 (663), 2025 (869), and 2046 (815) ms, respectively. Pairwise mean comparisons showed significant differences in steering time for [1×1] vs. [2×2] ($p<0.01$) and [1×1] vs. [3×3] ($p<0.01$), but not for [2×2] vs. [3×3] ($p=0.8$) (Figure 7). No significant main effect of the number of blocks on the steering time was observed ($p=0.233$), indicating no main learning effects after the practice session.
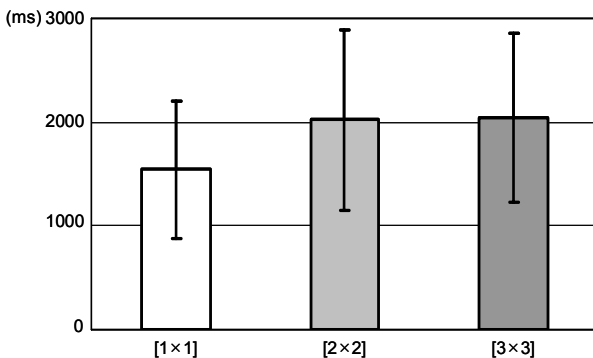

Figure 7. Mean (SD) steering time by the degree of tiling.

Error rate

The mean (SD) error rates for the [1×1], [2×2], and [3×3] conditions are 7.6% (5.3), 11.5% (4.9), 8.0% (3.9), respectively. No significant main effect of the degree of tiling on the error rate was observed ($F(2,22)=3.23$, $p=0.06$).

Cursor Speed

An ANOVA showed a significant main effect for the degree of tiling on the mean cursor speed. ($F(2,22)=8.4$, $p<0.05$). Pairwise mean comparisons showed significant differences for any pairs ($p<0.005$) except for [2×2] vs. [3×3] ($p=0.641$). The means (SD) of the cursor speed in the [1×1], [2×2], and [3×3] conditions were 0.34 (0.25), 0.26 (0.22), and 0.25 (0.26) pixel/ms, respectively, indicating that the users steered fastest in the no interior-bezel condition.

To further investigate steering behaviors, we divided each 480-pixel long tunnel into 15 32-pixel long segments and calculated the mean speed in each segment. As illustrated by Figure 8, the users steered fastest in the [1×1] condition across all the segments.
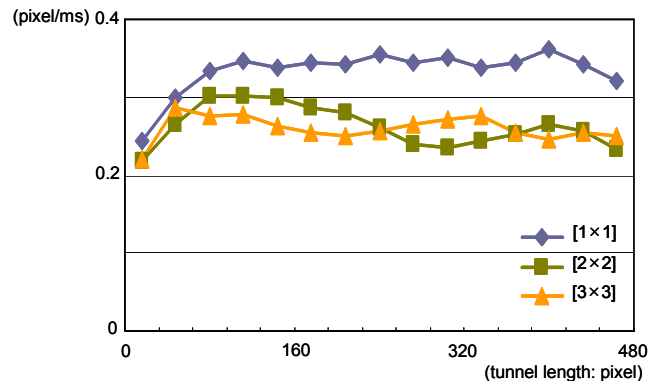

Figure 8. Mean cursor speed in each 32-pixel long segment along a tunnel.

Interestingly, Figure 8 also revealed different cursor speed distributions across the 15 segments. In the [1×1] condition, the cursor speed increased at the beginning of tunnels, kept a relative high value during the middle of operation, and slightly dropped down at the end. Participants commented that since the tunnels were relatively long, they sometimes lost control of the cursor at the end of tunnels thus leading to speed drop. Different from [1×1], strong wavy curves were observed for the [2×2] and [3×3] conditions. The cursor accelerated at the beginning of steering, but then sped up and down multiple times during the remaining steering process – one apparent (extra) deceleration for the [2×2] condition, and two for the [3×3] condition. Note that the average (SD) numbers of interior bezels the tunnels went through were 1.42 (0.49) and 2.88 (0.51), respectively.

We reason that this wave-shaped distribution might be attributed to the presence of interior bezels. Participants reported that since a tunnel was separated into several sub-tunnels by interior bezels, they conceptually broke the entire steering task into a combination of multiple sub-tunnel

steering tasks. Separating a tunnel into multiple sub-tunnels might break the continuity of cursor movement thus resulting in a wave shape in the cursor speed distribution.

Subjective Opinions

At the end of the experiment, the participants were asked to answer a short questionnaire.

• "Did interior bezels hinder steering performance?" Eight participants answered "Yes". Some of them explained that the visually broken tunnel and deflected cursor trajectory prevented them from quickly steering through. One of them said, "I saw the tunnel was horizontally offset when it crossed a vertical (interior) bezel, so I moved the cursor to compensate it. However, the tunnel was in fact straight in virtual space. My intentional compensation moved the cursor out of the tunnel." Four participants commented the bezels did not hinder their steering performance because they felt they could easily adjust mouse movement to meet the changes. In general, most participants indicated that bezels did hinder their steering performance, which is consistent with the *Steering Time* results – the presence of bezels significantly reduced the tunnel steering speed.

Tunnel Steering: Conclusions

We close this section with the results with respect to the hypotheses of the second experiment.

H.3 *The presence of interior bezels hinders steering performance*. This hypothesis was confirmed. Results showed a significant main effect for the degree of tiling on steering time, with the conditions having interior bezels leading to longer steering time. There are significant differences in steering time for [1×1] vs. [2×2], and [1×1] vs. [3×3]. Similarly effects were seen for cursor speed. Participants' subjective opinions also confirmed the negative effects caused by bezels on steering process.

H.4 *As the number of interior bezels increases, steering performance declines*. This hypothesis was not confirmed. No significant difference in steering time, error rate, or cursor size was observed between the [2×2] and [3×3] conditions. From the cursor speed data, however, we can surmise that a tunnel crossing a much larger number of bezels might well result in lower performance, but our current experiment did not have sufficient number of bezels to test that hypothesis fully.

Besides performance, our data indicates that interior bezels also affect steering behaviors. As a long straight-tunnel is visually broken into multiple sub-tunnels, users tend to treat the steering task as a combination of multiple sub-tunnel steering tasks.

TARGET SELECTION EXPERIMENT

The goal of the third experiment is to investigate how interior bezels affect user performance in a target selection task,

which is also canonical for GUI interaction. As target selection is path-free, cursor-trajectory deflection effects should be negligible. Thus, we set our hypotheses as follows:

H.5 *The presence of interior bezels does not affect user performance in target selection tasks.*

H.6 *As the number of interior bezels increases, the performance of target selection tasks remains constant.*

Target Selection: Task

We use a traditional 2D selection task consisting of repeated blocks of target selection trials. At the beginning of each block, a red circle appears at one of the four home positions (Figure 9a). Selecting the red circle starts a block, during which 10 blue circles appear sequentially. Participants are asked to select them in turn by clicking the mouse left-button while the cursor is in ther target (Figure 9b). Each target appears when the prior one is selected successfully, and disappears when it is selected correctly.

(a)   (b)
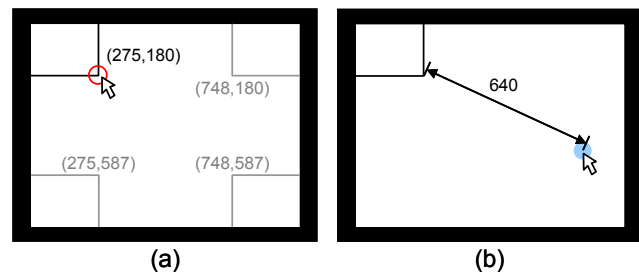
Figure 9. Target selection task: (a) clicking the start circle at one of the four home positions to start a block of 10 trials, (b) clicking a target circle 640 pixels away from the start position (or previous target position).

The radius of each target circle is 12 pixels, and the distance between two successive circles is 640 pixels to ensure a cursor trajectory crosses at least one interior bezel to select a target in the [2×2] condition, and at least two interior bezels in the [3×3] conditions. Note that because our study is not intended to be a general Fitts' law experiment [8], we do not systematically vary target width and distance – our purpose is to initially investigate interior bezel effects by varying the number of bezels, not target size and distance per se. The position of each target circle is randomly generated, but not across interior bezels since our main purpose is to investigate if the cursor-trajectory deflection caused by interior bezels affects selection performance and behaviors. Similar to the second experiment, the mapping speed of the cursor is adjusted through a pilot study to ensure that users can select any target without clutching, and the "Enhance pointer precision" function in Windows XP is turned on.

Target Selection: Design

We used a within-subject, repeated measures design with selection time, error rate, and cursor speed as our dependent measures. The selection time is the elapsed time between when a target is presented and when it is selected by clicking the left mouse-button. An error is recorded when par-

ticipants click outside the target. The error rate is the percentage of erroneous trials. The cursor speed is defined as the amount of movement over time. Unlike in the previous steering task experiment, we do not expect trajectories to significantly differ in this task, but nonetheless it would be useful to look at whether there is any deflection when crossing over bezel(s).

The independent variable is the degree of tiling (1, 2, or 3). The presentation order of these three conditions was fully counter-balanced among 12 participants. Within each degree of tiling condition, participants first performed a practice block consisting of 10 trials. The practice block was followed by the formal experiment, which consists of 6 blocks of 10 trials each. In short, our design was:

> 12 participants ×
> 3 degree of tiling (1, 2, 3) ×
> 6 blocks ×
> 10 repetitions =
>
> 2160 total trials.

Target Selection: Results

Selection Time
The mean (SD) selection times for the [1×1], [2×2], and [3×3] conditions were 1211 (312), 1244 (265), and 1311 (263) ms, respectively. An ANOVA did not show any main effect for the degree of tiling on the selection time (F(2,22)=2.43, p=0.11).

No main effects for number of blocks on selection time was observed (p=0.446), indicating no learning effect in the formal experiment after the practice block.

Error Rate
The mean (SD) error rates for the [1×1], [2×2], and [3×3] conditions are 3.5% (2.42), 4.6% (3.2) and 3.54% (3.14), respectively. No significant main effect for the degree of tiling on error rate was observed (F(2,22)=0.76, p=0.48).

Cursor Speed
The mean (SD) cursor speeds in the [1×1], [2×2], and [3×3] conditions are 0.7648 (1.4), 0.7567 (1.4) and 0.7109 (1.5) pixel/ms, respectively. An ANOVA did not show significant main effects for the degree of tiling on cursor speed (F(2,22)=3.39, p=0.052).

Figure 10 shows the cursor speed along normalized target selection time. In each of the three degree of tiling conditions, the cursor speed increased very quickly at the beginning, reached the peak soon, and then gradually dropped down during the rest of the trajectory. There were no other bumps caused by interior bezels as found in the tunnel steering experiment. This result is consistent with our observation – participants first moved the cursor a long distance regardless of intervening bezels, and then slowed it down to accurately select targets.
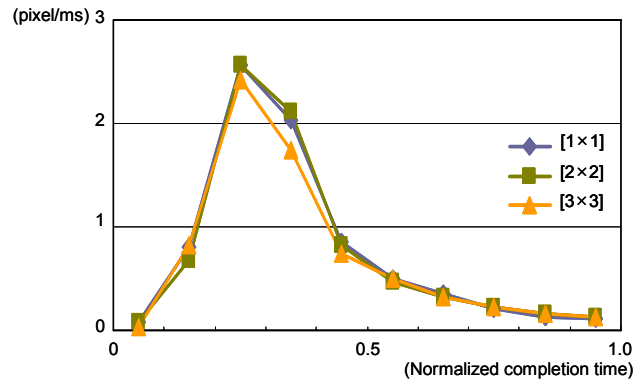

Figure 10. Mean cursor speed.

Pearson correlation tests showed strong positive correlations for cursor speed among these three conditions (Pearson correlation coefficient > 0.9 for every pair), indicating that the cursor speed distributions in the [1×1], [2×2], and [3×3] conditions were very similar.

Subjective Opinions
At the end of the experiment, we gave the participants a short questionnaire.

- "Did the bezels hinder selecting targets?" 11 participants answered "No", indicating that most participants felt that interior-bezel effects on target selection are negligible. It is consistent with the *Selection Time* and *Error Rate* results, which also show that interior bezels have negligible effects on selection performance.

Target Selection: Conclusions
We conclude the third experiment with our results with respect to the hypotheses.

> **H.5** *The presence of interior bezels does not affect user performance in target selection tasks*. This hypothesis was confirmed. The results showed no main effect for the degree of tiling on selection time, error rate, or cursor speed.

> **H.6** *As the number of interior bezels increases, the performance of target selection tasks remains constant*. This hypothesis was confirmed. The results showed no main effect for the degree of tiling on selection time, error rate, or cursor speed.

Both the cursor speed analysis and subjective opinions also supported that target selection behavior was not affected by interior bezels. Participants performed the tasks similarly across the three conditions.

DISCUSSIONS ON RESOLUTION EFFECTS
In our experiments, a single 1024×768 resolution projector was used to simulate all three tiling configurations. Thus, the resulting resolution of each grid in the [2×2] and [3×3] conditions is lower than that on real tiled-monitor displays (e.g., a 3×3 tiled-monitor display composed by nine 1024×768 LCDs). In this section, we discuss the feasibility

of applying our findings to real-world settings having higher display resolutions.

Since a pixel is the smallest unit of visualization on a display, we can assume that the maximum display error is at most one pixel. Given the large-display projection area (167 cm wide × 127 cm high), the physical size of each pixel is 0.16 cm wide × 0.16 cm high, thus the maximum error is at most 0.16 cm wide or high. In all the three experiments, the sizes of visual objects are all far beyond 0.16 cm: the rectangular tunnel is 9 cm wide × 77 cm long; the diameter of a circular target is around 4 cm; the VI/IV symbols are displayed in a 4 cm × 4 cm square area. Thus, the 0.16 cm pixel length can cause at most 1.8%, 0.2%, 4%, and 4% error with respect to the tunnel width, tunnel length, circle diameter, and symbol size, respectively. The cursor (arrow-shaped) is displayed in a 2.7 cm high × 1.8 cm wide rectangular area. 0.16 cm will cause at most 5.9% and 8.9% error with respect to cursor height and width. Because our experiments do not require precise operations across objects' boundary, we argue the current resolution does not substantially affect user performances. Subjective data also support this: all the participants reported that they could easily and comfortably view the tunnel, circular targets, VI/IV symbols and the cursor. In fact, given the 1.8 m sitting distance, 0.16 cm length leads to 0.05 degree visual angle, which is very close to the limit of a normal human's visual acuity, $1/60 = 0.01667$ degree.

Another difference between a 1024×768 projected screen with a higher resolution one is that the latter can show larger amounts of content. However, all the three experiments only involve simple geometric objects and a small number of symbols: the visual search experiment shows 15 or 30 VI/IV symbols; the tunnel steering experiment displays a rectangular tunnel; the target selection experiment shows a circular target. The visualization capability of a 1024×768 projected display is sufficient to clearly illustrate them. If we replace the 1024×768 display with a higher resolution one, we might get higher quality images, but not extra information such as more symbols/objects. Therefore, we argue the difference in visualization capability has minimal effect in the three experiments. The findings from these experiments can be generalized to higher resolution conditions with minimal changes.

CONCLUSIONS
We conducted three controlled experiments to investigate how interior bezels on tiled-monitor large displays affect user performance and behavior in visual search, straight tunnel steering, and target selection tasks. We summarize our findings as follows:

- Interior bezels are not detrimental to visual search performance; however, splitting objects across interior bezels leads to a higher error rate.

- The presence of interior bezels affects users' search strategies. As an entire surface is divided into grids by inte-

rior bezels, users tend to apply a grid-by-grid search strategy.

- The presence of interior bezels hinders straight-tunnel steering performance.

- The presence of interior bezels also affects steering behaviors – as a tunnel is visually separated into sub-tunnels, users tend to treat the steering task a combination of multiple sub-tunnels steering tasks with a multiple cursor acceleration-deceleration pattern.

- The existence of interior bezels does not affect target selection performance nor user behavior.

Based on the above findings, we can gain some insights that might help with tiled-monitor large display usage and interface designs:

- Tiled-monitor large displays are suitable for visual search tasks. However, if high accuracy is required, objects should not be placed across bezels.

- UI designers should take special care in designing steering-based elements (hierarchical menus, etc.) on a tiled-monitor large display so as not to place them across interior bezels. If it is not avoidable, techniques alleviating bezel effects such as Mouse ether [5] and OneSpace [12] might be worth considering.

- Selection-based UI elements (e.g., on-screen buttons or icons) can be adopted with no (or at most minor) adjustments on tiled-monitor large displays.

As an initial investigation into internal bezel effects, we did not vary steering/selection task parameters, such as tunnel shape/width/length, and target size/selection distance, as these would have overly complicated these studies. It might be worthwhile in followup work to conduct full Fitts' law [8] or steering law [1] experiments on tiled-monitor large displays to gain an even deeper understanding of the effect of interior bezels.

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