Effect of Bezel Presence and Width on Visual Search

James R. Wallace
Wilfrid Laurier University
73 George St.
Brantford, ON, Canada
jwallace@wlu.ca

Daniel Vogel
University of Waterloo
200 University Ave W.
Waterloo, ON, Canada
dvogel@uwaterloo.ca

Edward Lank
University of Waterloo
200 University Ave W.
Waterloo, ON, Canada
lank@uwaterloo.ca

ABSTRACT
We investigate how the presence and width of interior bezels impacts visual search performance across tiled displays. In spite of a potential benefit from structured segmentation, we do not find significant differences in visual search time, and note a small effect size of less than 0.5% for bezel width. However, we find participants are more accurate when searching for targets spanning a bezel. Based on these findings, we suggest two implications for the design of tiled displays: 1) that additional costs associated with thinner bezels may not provide significant return on investment; and 2) that bezels may act as visual anchors, and be useful for the placement of interface elements.

Author Keywords
Tiled Displays; Bezels; Perception; Visual Search;

ACM Classification Keywords
H.5.2 User Interfaces: Graphical user interfaces (GUI)

General Terms
Human Factors; Design; Measurement.

INTRODUCTION
The pixel density and physical size of digital displays continues to increase. These high resolution, wall sized displays will become ever more capable for viewing and interacting with 'Big Data' for applications such as sense making, information visualization, and navigation (e.g. [2, 28]). However, when deploying these wall-sized displays in practice, researchers and practitioners must choose between two imperfect approaches for their construction. They can buy a single, commercially available display at costs reaching hundreds of thousands of dollars, available in a limited number of sizes and aspect ratios, and at low standard pixel resolutions like 1080p or 4K. Or, they can tile many smaller displays together, at much lower cost, more flexibility in terms of size and shape, and significantly higher resolution, but this introduces interior bezels that may affect performance.

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Figure 1. Tiling multiple displays enables researchers to explore interactions on displays that are larger than those currently commercially available, of any shape, and at significantly higher resolution.

The extent to which the size of interior bezels affect tiled display use is largely unexplored, and it has been suggested that a lack of control over the many confounds in the design and use of tiled displays has led to a lack of understanding of their impact [5]. Purposeful investigation of fundamental tasks would assist in developing such an understanding [23]. Our previous work investigated the impact bezels have on human perception of data [25], and revealed that the presence of bezels led to only a 5% increase in human error. However fundamental aspects of attention, such as visual search [14, 5], have yet to be explored.

For visual search, understanding how the presence and width of bezels may impact performance is more nuanced: the discontinuities introduced by bezels may disrupt visual search, but may also provide a benefit with structured segmentation because bezels divide a large search task into many smaller, and potentially easier searches. Understanding the net impact on performance is beneficial in a number of practical settings. For example, manufacturers now offer display panels with 'ultra-thin' bezels, intended for use in video wall installations and priced at a premium when compared to their desktop counterparts. It is unclear what benefits these more expensive displays provide, and when the extra expenses are justified in developing tiled displays.

In this work, we evaluate the impact of interior bezel width on visual search. We conducted an empirical study investigating visual search while controlling for bezel presence and four widths between 0.5 cm and 4 cm. Our results suggest that visual discontinuities introduced by interior bezels have little negative impact on visual search, regardless of bezel width. We do not find any effect of bezel presence or width on search efficiency, and bezel width accounts for less than 0.5% of the variance in our model. However, our analysis suggests that people are *more* likely to find targets that span a bezel. Based on these findings, we provide two practical design implications when considering large, tiled displays for visual search tasks: that 1) the costs associated with bezel-less displays may only be warranted in scenarios where visual search performance is critical; and 2) bezels provide useful anchor points for GUI elements on tiled displays.

TILED DISPLAYS AND VISUAL SEARCH

Tiled displays provide a number of benefits over commercially available large displays. They can support resolutions that surpass human visual acuity [30], and allow people to view images and data an order of magnitude larger than is possible on traditional displays [28]. At the time of this writing, at pixel resolutions of up to 100 megapixels [20, 18]. Most importantly, tiled displays can support these resolutions at a physically large scale, and as they are constructed by combining many smaller displays, can be custom-made to any width, height, or combination thereof. That is, rather than relying on the commercially available predefined sizes and resolutions, practitioners can create tiled displays that support a desired resolution, at an appropriate size for the intended usage context.

In line with these opportunities, tiled displays have been constructed to support individuals and groups working in many fields, including analytics [23], information visualization [17, 28], and command and control [15, 12]. However, while these displays have been developed in accordance with their potential benefits for these tasks, the degree to which bezels interfere with tasks such as visual search [8] or target acquisition [9], and negatively impact user experience and aesthetic [1] remains largely unexplored, and when explored, results have been shown to be inconsistent or inconclusive.

Effect of Bezels

Research has reported a range of findings regarding the impact of bezels, including those citing a negative impact [7] , those citing no differences between bezel and no bezel conditions (e.g. [24, 29, 6, 16, 16]), those that found both positive and negative effects (e.g. [21]), and those that found that interior bezels may even improve performance [3, 4, 13]. Commenting on this lack of consensus, Bi et al. [5] argue that more controlled investigations into bezel effects are needed.

Our research evaluating the effect of bezels on specific task performance answers Bi et al.'s call. Previously, we explored the impact of bezels on magnitude judgement [25] and found that the presence of any bezel wider than 0.5cm affects judgement by approximately 4-7%, which we summarized as a simple "5% rule of thumb" useful for estimating the impact of bezels on magnitude judgement. However, when at arm's length, we found that length judgements in particular were susceptible to the presence of bezels, and error increased by up to an additional 15%. This paper complements our previous work with a systematic investigation of the impact of bezels for visual search tasks. Visual search is a particularly interesting task to evaluate because a tiled display may make visual search more difficult due the large display size and discontinuities from bezels, but the tiled structure may also provide a benefit through a phenomena called structured segmentation. Our overall aim is to provide guidance for designers and researchers towards how bezels may impact multiple aspects of human perception on tiled displays.

Visual Search and Structured Segmentation

As the physical size and pixel resolution of tiled displays increases, so do the attentional demands for people working with visualized data. People must be able to identify and monitor artefacts, and maintain workspace awareness when transitioning from one region of the display to another, between tasks, or between collaborative and individual stages of work. For example, someone may need to search for locations matching a description on a map, monitor a peer's progress in a shared task, or shift between editing different portions of a document. While each of these tasks may be demanding in traditional desktop settings, it is currently unknown how difficult they may be on wall-sized displays. Further complicating the issue is the degree to which bezels may affect a person's ability to direct their visual attention – it has been argued that the discontinuities introduced by bezels on large tiled displays may interfere with human perception and degrade an individual's visual search performance [21, 8].

Despite these potential disadvantages, there may be a benefit from *structured segmentation* when visual search across many small displays may be easier than searching a single large display of similar size. The literature suggests that people who can leverage structured segmentation in visual search tend to be more efficient. For example by encouraging a more structured visual search process, Sadasivan et al. [22] trained novices to search in a manner more similar to experts, thereby improving their own search performance. Similarly, user interfaces for radar operators have leveraged segmentation to guide visual search, improving performance [14]. Under certain conditions, structured segmentation has demonstrable benefits.

However, the degree to which segmentation introduced by tiled displays may benefit people is poorly understood. Forlines et al. [8] found no differences in performance based on the number of displays available for either individuals or groups. Ball and North [2] investigated two visual search tasks on 1, 3 and 9 display configurations, but found no effect on performance based on the number of displays. Qvarfordt et al. found that segmenting an image did not improve search performance [19]. Finally, Bi et al. [5] found no effect of number of bezels, but did find that when data was split across bezels error rate increased.

Thus, there is little consensus in the literature regarding the impact of bezels, or any consequent structured segmentation. The literature also lacks data relating to experimental control over bezel width, and there is currently little evidence to suggest whether there may be a threshold under which structured segmentation occurs; that is, there is little guidance towards what display characteristics may be desirable, worth investment, or critical when deploying tiled displays for use in settings where visual search performance is critical. Our work clarifies this lack of consensus regarding visual search on large tiled displays.

EXPERIMENTAL STUDY

The goal of this study is to measure the impact of interior bezels on visual search performance. We control for the presence and width of interior bezels on a large display to test the interaction between theoretical benefits of structured segmentation and theoretical problems caused by bezel discontinuities. We form the following hypotheses:

H1 The presence of bezels, and increased bezel width, will correspond with increased error rate.

H2 The presence of bezels, and increased bezel width, will correspond with increased search time.

H3 The placement of data across bezels, and increased bezel width, will correspond with increased error rate.

Experimental Design and Task

We based our study design on that of Bi et al. [5], and others that explored the reported benefits of structured segmentation [14, 22]. Each participant was tasked with searching a field of randomly positioned distractors (the characters '`VI`') for a single target, denoted by the characters '`IV`'. Participants were presented with a series of trials, where in each trial the target may or may not be present, and were asked to press the '`D`' key if the target was absent, and the '`J`' key if it was present. After each trial, participants were asked to take a short break if they wanted to, and when they were ready to proceed to the next trial pressed the space key. Our experiment utilized a 5 (Bezel Width) $\times$ 2 (Target Presence) $\times$ 2 (Bezel Split) within-subjects design.

Bezel Width

We included five bezel widths (0, 0.5, 1, 2, and 4 cm), chosen to represent a variety of different commercially available displays, and those used in the literature. With no bezels, there is no structured segmentation, and structured segmentation becomes more pronounced as bezel width increases.

Target Presence

As in [5], a single target was either present or absent in each trial. Pilot testing revealed that participants often completed this basic task without errors so two changes were made to increase the difficulty. First, we reduced the number of 'present' targets so that they appeared in only 25% of trials. This ratio of present to absent targets has been reported to result in an average error rate of 10% in the literature [27]. Second, where [5] had participants complete trials with both 15 and 30 distractors, we used a single, higher difficulty level of 40 distractors. Distractors and target locations were randomly generated for each trial, and the experimental software ensured that no overlaps occurred.

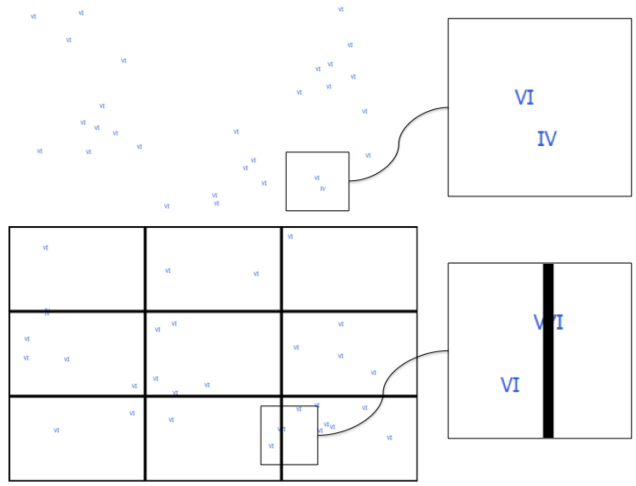

Figure 2. Participants searched a screen full of distractors ('`VI`') for a single target ('`IV`'). An example of the No Bezel condition is shown top, whereas a 1cm bezel is shown bottom.

Bezel Split

Finally, we controlled whether or not targets and distractors crossed a bezel, which we denote as *split* or *not split*. In split cases, at least one target or distractor was placed so that it spanned a bezel, whereas in not split cases, all targets and distractors were positioned without crossing a bezel.

Figure 2 illustrates two trials from the study in which targets are present. The experimental design can be summarized as:

20 Participants $\times$

5 Bezel Widths (0, 0.5, 1, 2, and 4cm) $\times$

2 Target Present / Absent (1:3 ratio) $\times$

2 Split Present / Absent $\times$

6 Repetitions

For a total of 2400 comparisons. Participants completed one block of trials for each of the bezel width conditions, the order of which was balanced using a latin-square design. Within each block, the order of target presence/absence and where targets or distractors were split by a bezel were randomized.

Participants, Procedure, and Apparatus

20 participants (16 men and 4 women) between the ages of 21 and 40 ($\bar{x} = 26.5$) were recruited to participate in this study. Participants were all Science, Technology, Engineering, and Mathematics students who were enrolled at the University of Waterloo, and received a $5 gift card for their participation.

Participants were seated in an adjustable chair at a conference table within reach of a keyboard and performed the visual search task on a large, projected display approximately 3m in front of them (Figure 3). The display measured 2m wide by 1.5m tall, and was projected at a resolution of 1024 $\times$ 768 pixels. While the resolution of the display was lower than those on other tiled displays, task difficulty was calibrated during pilot testing to provide a level of difficulty consistent with related research [27, 5].

Figure 3. Participants interacted with the experimental software via keyboard, while seated at a distance of approximately 3m in front of a large display.

After being seated, participants were instructed to adjust the chair and position themselves so that they were comfortable. Participants were then briefed on the task, and asked to complete an informed consent form and brief demographic questionnaire. Participants then completed a series of practice trials to ensure that they understood the task. Finally, participants were instructed to complete the trials as accurately and as quickly as possible, and completed a block of trials for each bezel condition. During each trial, software logged when each stimulus was shown and time-logged input submitted by the participant.

Analysis

The primary experimental measures are *error rate* and *task time*. Error rate is the number of incorrect answers submitted (either false negatives or positives) as a proportion of the overall trials. Trial time is measured as starting from when the stimuli first appeared on screen until the participant pressed a key to submit their answer. Repeated measures analysis of variance (RM-ANOVA) statistical tests were conducted to examine differences between bezel conditions, with post-hoc pairwise comparisons made using the Bonferroni adjustment. All statistical tests used an alpha-value of 0.05.

Results

On average, participants completed each visual search trial in 10.3 ($\sigma = 5$) seconds, with an error rate of 6% ($\sigma = 2.38$). Our analysis included all collected data; no outliers were removed. We now discuss our analyses of the experimental factors, and how they influenced the two quantitative measures collected during each trial: error rate and trial time.

Error Rate

Overall, participants made a total of 147 errors, which, as reported in similar studies [5], were predominantly false negatives. In cases where targets were present, participants averaged an error rate of 22.7% ($\sigma = 47$), whereas when targets were not present, participants averaged an error rate of 0.6% ($\sigma = 7.7$). This difference was found to be significant ($t_{2398} = 21.2348, p < .0001, d = 0.730$).

No differences were found in error rate based on interior bezel width ($F_{4,76} = 1.916, p = 0.116, \eta_p^2 = .092$). Error rates for each bezel width condition were: 0cm ($\bar{x} = 7.1\%, \sigma = 6.2$), 0.5cm ($\bar{x} = 4.4\%, \sigma = 3.5$), 1cm ($\bar{x} = 8.1\%, \sigma = 7.6$), 2cm ($\bar{x} = 5.4\%, \sigma = 5.3$), 4cm ($\bar{x} = 5.6\%, \sigma = 6.7$). However, our analyses did reveal differences in error rate based on whether data crossed an interior bezel ($F_{1,19} = 8.260, p = 0.01, \eta_p^2 = .303$). Participant error rates were consistently lower in the conditions where data crossed a bezel ($\bar{x} = 3.9\%, \sigma = 1.77$) than in conditions where no data crossed a bezel ($\bar{x} = 7.4\%, \sigma = 1.89$). Error rate data is summarized in Figure 4.

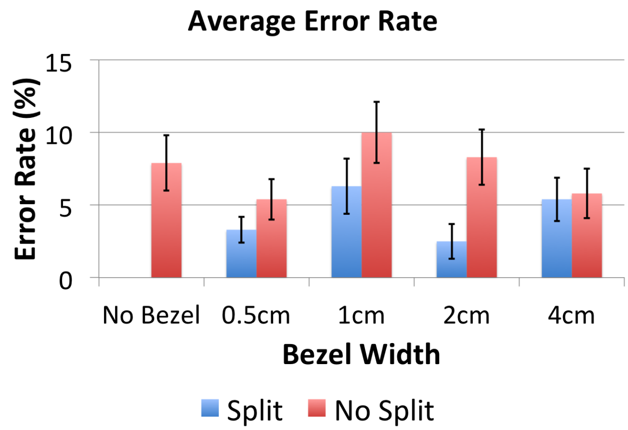

Figure 4. Error rate results. Averages and standard deviations (error bars) are shown for each of the bezel width and split/not split conditions.

Visual Search Time

As expected, we observed differences in trial time based on whether targets were present or absent ($t_{2398} = 18.1417, p < .0001, d = 0.802$), with participants taking 11.4s ($\sigma = 7.3$) for trials without a target, and 7.3s ($\sigma = 5.6$) for trials with a target. No differences were found based on the width of interior bezels ($F_{4,76} = .086, p = .986, \eta_p^2 = .005$), with participants completing trials on average in similar times for all conditions: 0cm ($\bar{x} = 10.3s, \sigma = 3.24$), 0.5cm ($\bar{x} = 10.3s, \sigma = 2.3$), 1cm ($\bar{x} = 10.3s, \sigma = 3.47$), 2cm ($\bar{x} = 10.5s, \sigma = 2.82$), 4cm ($\bar{x} = 10.2s, \sigma = 2.6$). Our analyses also did not reveal any differences based on whether data crossed a bezel ($F_{1,19} = 0.238, p = .631, \eta_p^2 = .012$). Trials in which data crossed a bezel averaged 10.4s ($\sigma = 2.6s$), whereas trials in which no data crossed a bezel averaged 10.3s ($\sigma = 2.7s$). Figure 5 summarizes trial time data across each of the conditions.

Discussion

We found no effect of the presence or width of bezels on visual search, and thus reject hypothesis **H1**. These results add to the growing consensus in the literature that structured segmentation as a consequence of display tiling may not improve visual search performance [5]. Our analysis of effect size suggests that the presence and width of bezels accounts for less than 10% of the variance encountered in our observed error rate, an effect size traditionally interpreted as "medium" in magnitude. We interpret these results as suggestive that structured segmentation that leverages characteristics of the task domain, such as in [19] and [22], may provide a more robust

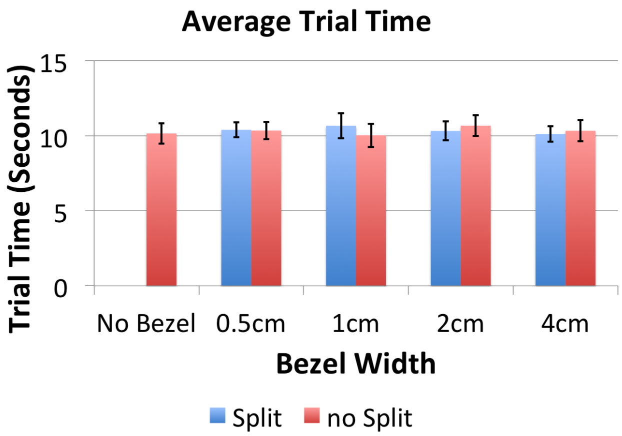

Figure 5. Trial time results. Averages and standard deviations (error bars) are shown for each of the bezel width and split/not split conditions.

benefit to people when considering visual search, however a study focused on this effect would be required to validate its impact. For visual search time, bezel width accounted for even less of the observed effect; our analysis estimates less than 0.5% of the variance in our model. The lack of a difference between conditions, and this extremely small effect size lead us to reject **H2**.

Furthermore, our results suggest not only that **H3** can be rejected, but that participants were *more* accurate in searching for targets that crossed a bezel. This result is particularly striking in that it contradicts previous work, and in particular, the findings of Bi et al. [5], who found that people were more likely to miss targets that spanned an interior bezel. A plausible explanation for this finding may be that participants were expecting targets to be located on the bezel, and therefore directed their attention to this portion of the display. However, participants received no special instructions, and the number of times that data crossed a bezel was controlled to occur in only 5% of their trials. Our analyses did not reveal any difference in search times based on whether interior bezels were present, and thus it is difficult to conclude that participants' visual search patterns differed between those conditions.

IMPLICATIONS FOR THE DESIGN OF TILED DISPLAYS

There are currently mixed messages regarding the impact of interior bezels on tiled display use within the HCI community. Our controlled, empirical investigation directly studied the effect of interior bezel width on visual search, and our analyses help to quantify the impact of bezels on those tasks. We suggest two implications for the design of large, tiled displays: 1) cost and performance trade-offs of thin bezelled displays, and 2) interior bezels as visual anchors for interface elements.

Cost and Performance Tradeoffs

Our initial motivation for this work was to explore design trade-offs during the development of our own tiled display, and to understand how beneficial premium display technology, like 'ultra-thin' bezels, are for efficiently locating data. This understanding is crucial in making informed design decisions for large displays. Tiling enables the development of displays at virtually any size and aspect ratio, at a fraction of the cost of an individual screen. However, the degree to which bezels interfere with the perception of on-screen data has only begun to be studied rigourously in a scientific context [5, 25], and the therefore it was unclear under what conditions the use of commercially available 'ultra-thin' bezel displays is justified.

Our findings suggest that bezel presence and width have a minimal impact on visual search performance on large displays, accounting for less than 0.5% of the variance in our observed search times. We further quantified the impact of bezels on visual search error rate as accounting for less than 10% of the observed variance, including the noted *positive* effect of bezels. These results, taken into consideration with similar studies of aspects of human perception such as magnitude judgement [25, 26, 4] and three dimensional navigation [10, 2], suggest that tiled displays may be used in contexts such as scientific visualization and analysis without compromising performance. Further, additional expenses associated with assembling these displays using 'ultra-thin' bezel displays are unlikely to provide a significant return on investment in all but the most demanding settings.

Interior Bezels as Visual Anchors

We also found that participants were more accurate when searching for targets that were split across a bezel. Notably, these findings contradict those of [5], who found that participants found split targets more slowly than those located wholly within a single display. We hypothesize that this improved performance may be a result of participants performing a two-phase search: one pass of the screen as a whole, and one pass to check if any targets had been placed on a bezel. These behaviours are consistent with those reported by Bezerianos et al. [4], and highlight the advantages of having established anchor points for onscreen targets.

Our results raise the question of whether this phenomenon may be leveraged to support interactions on large, tiled displays. For example, bezel menus have been explored on mobile devices with small displays [11], however research directed at developing tiled displays has largely sought to eliminate bezels for more aesthetic design. Our findings suggest that interior bezels may provide an opportunity to provide access to menu interactions on large displays that may not be otherwise available. Further, when taken into consideration with our previous work that revealed only a 5% increase in magnitude judgement errors [25], our findings suggest that such placements will only minimally interfere with other tasks performed on the display. Thus, future research may benefit from exploring bezel-activated menus on large, tiled displays.

LIMITATIONS AND FUTURE WORK

As with any experimental design, the study presented in this work has limitations that lead to future investigations. For example, even with 20 participants, there may not have been sufficient power to detect very small differences between bezel widths; but our analysis does suggest that bezel width may account for a moderate amount of variance observed in our study – further explorations may yield such an effect. Similarly, our analysis suggests an extremely small effect of bezel width on visual search time that could be more fully explained in a follow-up study. We also feel that the interesting result surrounding the placement of stimuli across bezels could warrant further exploration. In particular, future work would benefit from more fully examining human perception of stimuli that span bezels, drawing on additional quantitative data. As one approach, eye tracking hardware may help to explain the disparity between our results and those of Bi et al. [5].

CONCLUSION

Our study did not reveal any negative effects related to the presence or width of interior bezels on a person's ability to perform visual search across tiled displays. Our analysis further quantifies the impact of bezel presence and width as small, accounting for less than 0.5% of the variance in our observed search times and less than 10% of the variance in observed error rates, suggesting a minimal impact of bezels on visual search performance. However, we also noted, that participants were *more* likely to locate targets that spanned bezels. Based on these findings we suggest two implications for the design of tiled displays: 1) 'ultra-thin' bezel displays may provide minimal benefits when performing visual search tasks, and therefore may not warrant the additional expenses associated with their purchase, and 2) that bezels may provide useful anchor points for user interface elements since they are more likely to be found. As displays reach new sizes, shapes, and resolutions it is becoming increasingly important to understand how humans can perceive and interact with data at scale. Underlining the importance of such an understanding are the tasks that these displays are designed to support; tasks such as scientific visualization, emergency response and command and control, health care, and myriad other forms of decision-making with 'Big Data'.

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