

# The Effect of Several Tradeoffs in the Implementation of Large Displays on the Performance of the Users of the Displays

by

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## **Author's Declaration**

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

## Abstract

A large display can be constructed in two different ways:

1. a rectangular grid, or tiling, of many small screens with seams, or bezels, at the boundaries between the screens and
2. one large screen with no bezel inside the screen.

The first way costs significantly less than the second way. However, the first way creates a discontinuity in the image because of the bezels, and this discontinuity may impact a user's performance.

There are two different ways to implement the first, tiling way of constructing a large display:

1. tiled, multiple projections onto one large screen and
2. tiling of actual LC displays.

With the first way, bezels are avoidable, but there is the necessity of continuous, precise coordination of multiple projectors. With the second way, once the displays are mounted, no coordination is necessary, but bezels are unavoidable.

While it might seem preferable to avoid bezels and incur higher construction or coordination costs, the reality is that if no user's performance is negatively affected by bezels, then there is no reason not to use the cheaper methods of constructing large displays.

Therefore, the aim of this study is to determine how bezels affect a user's task performance. We conducted two controlled experiments in order to determine

- how varying the width of bezels affects a user's performance;
- how varying the number of bezels affects a user's performance; and
- how the choice between tiled, multiple projections and tiling of actual LC displays affects a user's performance.

In each experiment, the participants solved a puzzle within a given time. The findings from this study are that user performance is not affected by variation in the width of bezels and by variation in the number of bezels. However, the tiling of actual LC displays is better for user performance than tiled, multiple projections.

Therefore, it is more acceptable to use a rectangular grid of actual LC displays to implement a large display.

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## **Dedication**

In loving memory of my grandmother.

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# Chapter 1

## Introduction

Large and high resolution displays have become ubiquitous. They are becoming common in various fields such as geo-spatial, military, and automotive design [18], among other fields. They are useful in navigation [13], advertising/public display [25], 3D viewing without glasses [46], displaying large data sets in scientific visualization [39], conferences, meetings [28], and many other applications in which data sets are required to be visualized minutely and in large contexts. Displays can be low resolution<sup>1</sup>, high resolution<sup>2</sup>, and ultra high resolution<sup>3</sup>. The range of pixels in display varies from a few thousand pixels to billions of pixels. Examples of displays include mobile phones, tablets, laptops, desktop displays, tiled monitor displays, and billboard displays. This thesis uses the following terminology for describing displays:

- Size of a screen is measured diagonally in inches or centimetres.
- Resolution is the number of vertical pixels multiplied with the number of horizontal pixels.

The advantage of greater resolution is having more information displayed at once. However, arbitrarily increasing the resolution of a display and keeping the size of the display fixed is not reasonable because at some point, the visual acuity of the user cannot make use of the increased resolution. We limit the resolution of the display so that a user's visual acuity can utilize the information on the display. The world's current highest resolution wall has

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<sup>1</sup>at current standards, 2-4 million pixels approximately

<sup>2</sup>at current standards, 5-8 million pixels approximately

<sup>3</sup>at current standards, more than 8 million pixels

been developed by the University of California at San Diego. It is the Highly Interactive Parallelized Display Space (HIPerSpace) [6] featuring 286.7 million pixels, which is 30 million pixels more than the NASA hyper-wall-2 (256 million pixel system) constructed by NASA Ames Research Centre [48].

Large displays are gaining importance because of their affordability and their ability to display granularity. Having a large display does not mean covering only one wall and displaying information. There are displays covering five walls [58] and those covering six walls [44]. There are also screens which can support the weight of a user.

There are two ways to construct a large displays.

1. A single continuous screen.
2. A collection of smaller displays laid out in a rectangular grid with all the needed pixels. The boundaries of the smaller screens create a discontinuity in the display. One such boundary is called a *bezel*, and it has a non-zero width.

An example of each is

1. A single 9600X5400 display with 51.8 million pixels, and
2. A 5x5 grid of 25 1920X1080 displays with the same 51.8 million pixels.

Observe that they have the same resolution and that the second has four horizontal bezels and four vertical bezels. The first kind of display is available in limited pixels up to a few million and costs around \$25,000 to \$500,000. LG's 84 inch diagonally and 8.3 million pixel display costs around \$25,000. Tiling five monitors, each of size 21 inch diagonally and of resolution 1680 by 1050 per monitor, for a total of 8.8 million pixels costs around \$2,500. The cost of a tiled-monitor display is one tenth of the cost of single display with almost the same resolution.

In the second way to implement a large display, the discontinuity in the image at the bezels might bother the users. However, if the users are in fact not affected by the presence of bezels, then the choice is clear. Go for the cheaper method of making a grid of smaller displays and make the seams as small as possible.

Within the second choice of a grid of smaller displays, there are yet two more tradeoffs:

1. The grid is made of liquid crystal (LC) displays with physical bezels, and

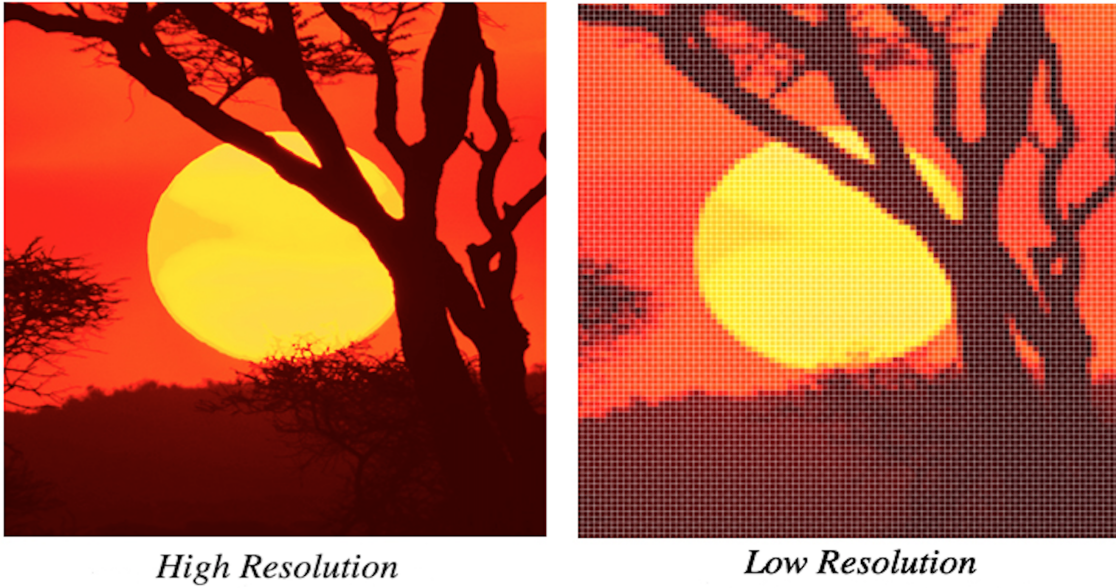


Figure 1.1: High and low resolution image [2]

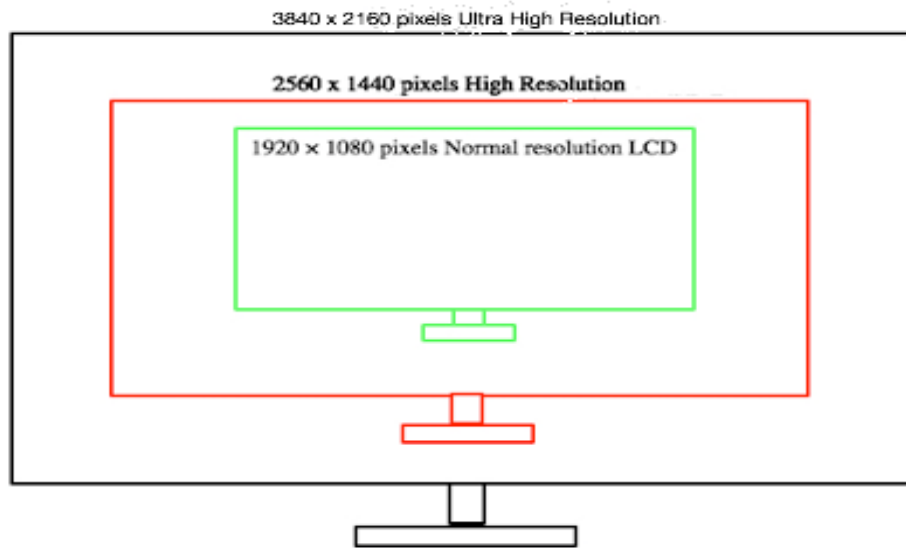


Figure 1.2: The difference in the resolution of one single contiguous display

2. The grid is made of projectors projecting on to a large enough undivided screen with virtual only bezels in it.

The tradeoffs between these two choices are:

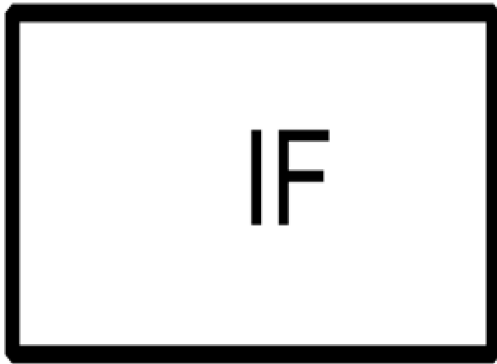
1. With a projector display, we can achieve a display with almost no bezels, but it comes with the cost of calibration of the positions and brightness of the individual projectors [39], many projectors, and a large projection screen. The setup is bulky and the cost of setting up a projector display is higher than tiling LC displays [39].
2. A tiled LC display has physical bezels in it, which are displeasing [15], but it is easier to build because there are fewer calibration issues than for a projector display. These displays can be vertical as mounted on wall displays or horizontal as on table tops.

There are two ways of implementing the discontinuity of the image caused by the bezels.

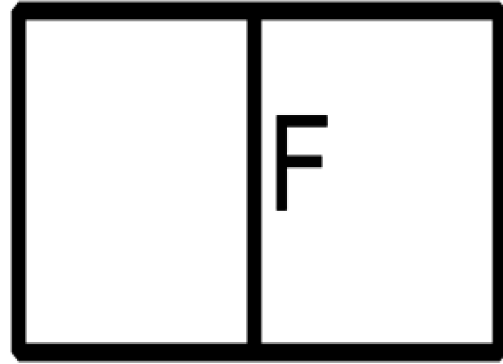
1. Offset: In offset, the pixels to the left or the top of a bezel are adjacent in the image to the pixels to the right or the bottom of the bezel. Thus, there is a gap between adjacent pixels in the image at each bezel.
2. Overlay: In overlay, there is no gap between adjacent pixels in the image, and a bezel hides a strip of the bezel's width of the image.

In overlay, as shown in Figure 1.3, parts of the image are hidden behind the bezels, and that might create a problem in a user's understanding the displayed image. Overlay is described by Almeida's *French Window* is discussed in Chapter 2. In our experiments, we use the overlay implementation of bezels because this implementation is the most common in commercial large displays.

In offset, Figure 1.4, the path of a mouse is deflected because of the gap in the image [43]. Offset not only deflects the mouse's path, but it also distorts images and it may make documents confusing [15]. Robertson et al. tried to eliminate the warping effect and keep the trajectory of the mouse in line with the previous screen [43]. Similarly, an image that is distorted by bezels is corrected by a technique called OneSpace. In OneSpace, a user adjusts an image once for a given display to inform the system about the exact bezel placement. This technique hides the part of image located behind the bezel but lets the user to see a distortion-free image [43]. See Figure 1.6 and Figure 1.5. Offset does not

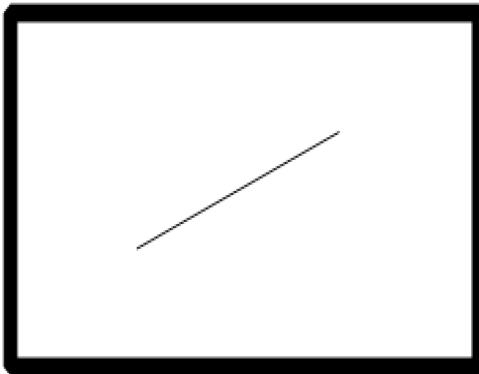


Display without bezel  
(object is visible)

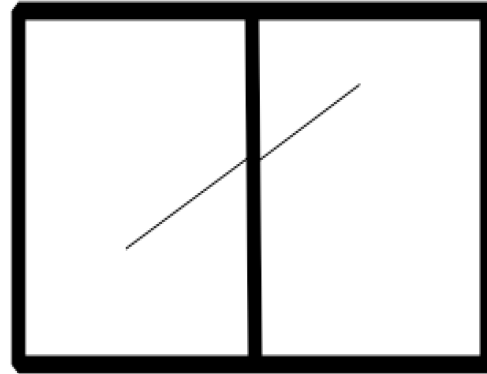


Display with bezel  
(object "I" is located behind the bezel)  
Overlay approach

Figure 1.3: Overlay approach



Display without bezel  
(Object is visible)



Display with bezel  
(Object is distorted)  
Offset approach

Figure 1.4: Offset approach





Figure 1.5: Image before OneSpace adjustment

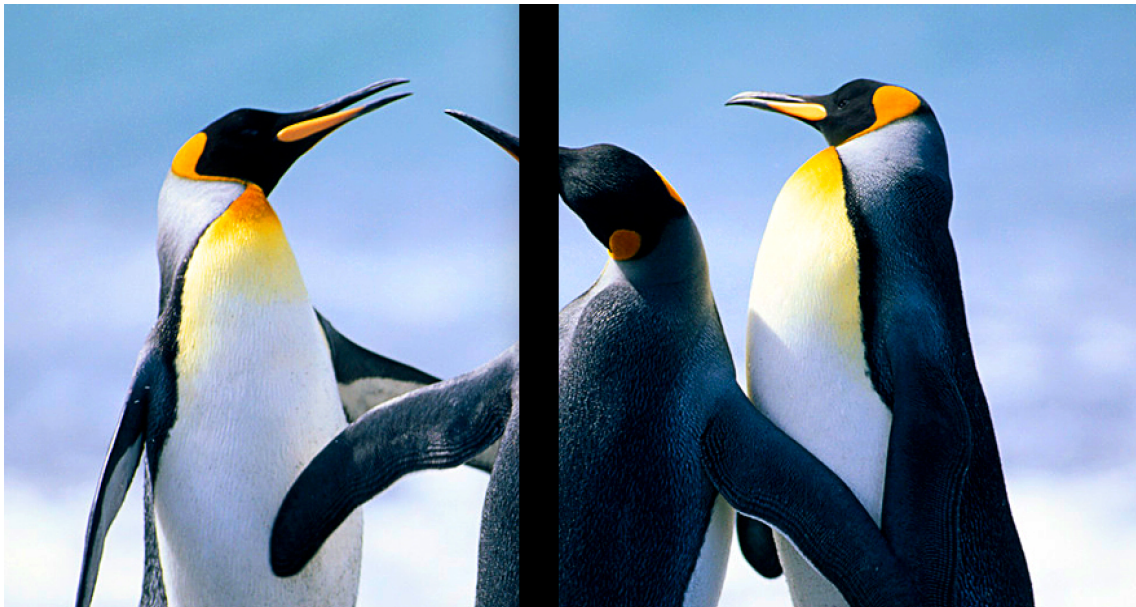


Figure 1.6: Image after OneSpace adjustment

create much distortion when there is some video-related task. The human brain can make up the portion hidden behind the bezel.

How these tradeoffs affect users gives rise to the following research questions:

- How worthwhile is it to invest in eliminating bezels?
- In a situation in which a large high-resolution display is needed by humans to perform a task with images, does the presence of bezels affect the users' performance of the task?
- How does the width of the bezels affect the users' performance?
- How does the number of bezels affect the users' performance?
- Which implementation of a grid of displays is better from the users' viewpoint: LC display or projection?

The rest of this thesis uses “performance” to include all aspects of a user’s performance of his or her task, including throughput, task completion time, and error rate. A higher performance means a greater throughput, a shorter task completion time, and a lower error rate. There are yet other issues, but addressing them is declared beyond the scope of this research. These research questions give rise to the following hypotheses to be tested by experiments:

- $H1_0$ : User task performance is not affected by increasing the width of bezel.
- $H1_1$ : User task performance is affected by increasing the width of bezel.
- $H2_0$ : User task performance is not affected by increasing the number of bezels.
- $H2_1$ : User task performance is affected by increasing the number of bezels.

For any  $Hn$ ,  $Hn_0$  is the null hypothesis, and  $Hn_1$  is its corresponding non-null hypothesis. We present the results of two user studies that investigate the effect of *bezel width* and *number of bezel* on users' performance and compare LCD and projector display from users' view point.

The following sections provide an overview of the related work, explain issues related to bezel display, and describe the experiments. The thesis concludes with the results, discussion, and future work.

# Chapter 2

## Related Work

Extensive research has been done on large displays, but there is a lot more that can be done regarding bezel width and how users perceive bezels when performing a task on a large display [43, 12, 23]. Bezel interference is largely unexplored, and careful understanding of the design would help manufacturers to create optimal software [56]. Various tasks are used in the related work to analyze bezels, such as a visual-search task<sup>1</sup>, a magnitude-judgement task<sup>2</sup>, a navigation task, a virtual-navigation task, among others [15, 56, 12, 39, 9, 43]. We discuss navigation tasks later this section.

We would like to shed some light on some of the issues and solutions regarding large display that are discussed in the literature such as construction, overlay/offset, navigation, aesthetics of the display, bezel, among others. We would also like to discuss whether we view these issues individually as pros or cons.

### 2.1 Construction

Bi et al. and Robertson et al. have explained that the construction of a large display can be done in two ways: tiling multiple projectors or tiling LC display monitors [15, 43]. Tiling multiple projectors is less advantageous than tiling monitors because it requires calibration of projectors and a screen every time<sup>3</sup> [15]. Bi et al. conducted three experiments to

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<sup>1</sup>it is to find the specific object on a large display

<sup>2</sup>it is to make an estimate the relative sizes of the stimulus shapes on the basis of Stevens' Power Law[51]. To understand more, we direct readers to [51, 55]

<sup>3</sup>

investigate the effect of tiled-monitor bezel on visual search, straight-tunnel steering, and target selection tasks. They used one display with simulated bezel drawn on it and kept factors such as brightness and contrast constant. They constructed the display using these configurations: 1x1 (no bezel), 2x2 (display divided into four parts), and 3x3 (display divided into nine parts). The conclusion from their experiment is that the interior bezels do not affect visual search time. We decided to expand on this idea and divide our task into four screen configurations: 1x1, 2x2, 3x3, and 4x4. We add the last 4x4 configuration to see, if increasing the number of tiles affects user performance.

## 2.2 Overlay and offset

Bezel obstruction was dealt with very carefully in one of the studies conducted by Almeida et al. [23]. The problem they encountered was that the part of the image was hidden behind the bezel. They proposed two techniques, ePan and GridScape, to reveal the portion of the image hidden behind the bezel, thus eliminating the problems of overlay.

- ePan: User can drag the image using finger drag gesture and they can comfortably read all the information behind bezel. User can drag the image either on the wall directly or on handheld device. When releasing the finger after the drag, the virtual canvas can revert back to its original position or it can stay at the same place depending upon the requirement.
- GridScape: Part of an image or text is revealed progressively as the user moves or leans relative to the orientation of screen.

Our work used the similar approach of overlay to introduce the discontinuity created by bezel. We studied the impact of discontinuity and to determine if it is worthwhile to invest on these techniques to remove the impact. Robertson et al. talk about one of the strategies they used, called OneSpace, which is used to deal with the problem cause by offset [43]. OneSpace adjust the computer’s geometric model to show the actual distance between the monitor and lets the user to view images hidden behind the bezels without distortion. We have not used offset in any of our experiment. See Figure 1.6 and Figure 1.5.

## 2.3 Navigation

Ball and North studied user behaviour and showed that more physical navigation (hand and head movement) is required for high resolution display, and that more virtual navigation

(zooming and panning) is required for low resolution display [12]. They proved that virtual navigation has a greater negative impact on visual-search task performance than physical navigation. During the experiment conducted by Ball and North, users were asked to search a house and its attributes, once they have figured out where the house is located on the large display. This visual-search task, followed by a pattern-finding task helped them to reach to their conclusion. They also found that as the display size increases, virtual navigation and performance time decrease [13]. Lauren et al. observed some physical movement when users performed a task on large display even when virtual navigation devices like a keyboard and/or mouse were used [49].

Robertson et al. conducted a user study and provided a detailed analysis of various issues caused by large displays [43]. Out of the issues which are discussed in the literature, we discuss two of them namely, bezel problems and losing the cursor (explained later in this section). If an object is too big to fit on single monitor, it might be displayed on more than two monitors. We have discussed this issue as one of our research question. Robertson discussed the techniques to overcome these problems. The Table Cloth approach has been used to reduced physical navigation: the desktop is dragged until the target appears in front of the user. This eliminates body movement and effort to move to the other side of the display [43]. Also, GroupBar will help create a list of all open tabs or windows on a large display (similar to a menu), eliminating large movements of the head or hands [43]. Navigation has been explored in great detail by researchers [14, 36, 23]. Moreland et al. and McNamara et al. produced results which align with our result that bezels do not affect users' task performance [37, 36]. In the experiment conducted by McNamara, users were asked to navigate through five different routes indicated by a start and a end point on the display with different bezel widths. Users had to navigate on the display to find the correct route. McNamara studied if the users are impacted by the introduction of bezels in the tasks and they found that there was no significant difference in the task completion time when bezels were introduced. Ball et al. performed experiments on the navigation of maps [14]. They showed that object location can be done twice as fast on a large display than on a conventional display [12, 14]. Large displays that are made up of nine monitors have 70% fewer mouse clicks and 90% less window management than a one monitor configuration. Data on a large display can be more easily viewed than on a small screen when the object to screen ratio is maintained [9].

## 2.4 Aesthetics of the display

In an experiment conducted in 2011, Andrews et al. studied large display design as well as various parameters such as the background colour of an image or text on the display, the distance from screen, space, bezels, and wide-field views [9]. The purpose of this study was to determine how visualization on a large display differs from visualization on a small display. There should be contrast between the background colour of an image or text on the display and the colour of bezels, otherwise the details can be embedded into visualization that can be seen in detail when the user is close to the display. Therefore, we used light coloured images in contrast with the black coloured bezels. Wallace et al. studied the impact of bezel width at a distance and at arm's length. Their results showed that, when the magnitude-judgement task is performed at arm's length, the users were less prone to make errors than when the task is performed at a distance [32, 56]. Therefore, we used arm's length as the distance for the experiments which is approximately 40 cms from the display.

Another problem which Robertson et al. have studied is the delay caused when a mouse/cursor is dragged to other side of a large display. If the speed of the mouse is accelerated, then it strays off its original path. This problem of losing trajectory and delay can be solved by using a mouse missile [43]. When using the mouse missile, the user presses a special key and moves the cursor in the desired direction. This continues until the user changes the direction or moves the cursor. This eliminates the need to move the cursor if an object is at other side of the display. We encountered the same issue in the pilot run of our experiments and solved it by providing a tail indicating the direction of the mouse. See Figure 2.1.

## 2.5 Effects of bezel

Many researchers suggest that Bezel has both positive and negative effects. Ball et al. stated that in two type of configurations consisting of nine tiled monitors and four tiled monitors, users tried to segregate their task within the boundaries made by the bezels. This division improved their ability to keep track of maps they were finding [14]. On the other hand, Almeida et al. showed that bezels negatively affected user performance; the task was to navigate through the display using a starting point and several ending points. Users had to follow the line on the touch display and to reach to a named exit. At the bezels, lines were intersecting, users used one of ePan and GridScape to find the correct line to follow [23].

There is always a question of investment when considering bezel elimination. One of our own research questions is, *How worthwhile is it to invest in eliminating bezels?*. With respect to this question, we would like to elaborate on a few technologies developed by various authors and would like to see their financial and practical feasibility. Researchers have suggested many techniques to eliminate the effect of bezels [23, 25, 12, 34]. Ni et al. stated that building a truly seamless tiled display is one of the important research areas for high resolution displays [39]. Additionally, various authors have conducted experiments that attempt to remove the effects of bezels:

- Ball removed the seam frame surrounding the display in one of the experiments. However, seam has a control element that regulates heat and helps the display work properly [25]. Even though the cost of removing seam is not very high, removing the control element is not advisable.
- Ebert et al. [25] suggested an approach to overcome the problems of offset and overlay, called Tiled++. Tiled++ is a technique that shows information hidden by bezel on a large display. This technique uses a separate projector to project missing parts of an image on the large display so that there appears to be one smooth picture. A low resolution image will project on the bezels. Brushed aluminum is used as the bezel, which provides a perfect screen for projection. Thus far, this technique has reduced the calibration problems that can occur when producing a seamless large display using projectors. Tiled++ removes the problems of offset and overlay. There is no need to remove the bezel frame which acts as a heat control element. Problems with Tiled++ are related to the brightness and colour of the image projected on the bezel because the reflection of the image on the bezels is displayed on low brightness. The width of bezel does not affect a Tiled++ display because the image produced by projector is adjusted according to the width of the bezels. There is a tolerance of 5 mm in the dimension of low brightness image projected on bezel, which is nearly ignored by every user when he or she works on screen [25]. Major issue in this technique is its cost. Tiled++ requires both LC displays with coated aluminium on the bezels and a projector to project the missing portion of the image on the bezels from the front. There is also a requirement of separate software that has to be installed as well as sensors and cameras that are used as an additional object help in projecting the image in the Tiled++ technique. All of this increases the manufacturing costs of the whole display setup.
- Mackinlay et al. suggested a technique to create a seam-aware application that helps to identify gap created by seam between monitors. It automatically moves the text

off the seam, creates a gap between words or images that are the same size as the seam, and displays them as a continuous image [34]. Seam awareness mainly depends on the gap between the screens and measuring it in display pixels. Unfortunately, it is not self adjusting. Every time we deploy screens, we have to modify the seam aware application according to our needs. Consequently, modifying an application every time is one of the factors that is in the best interest of the experimenter to avoid. It is our understanding that this application is mainly for images and text. Videos may be problematic because for videos running in real time, it may be difficult to modify every frame according to the width of seam in real time. Also, manufacturing wideband display is expensive, as stated by Mackinlay [34].

## 2.6 Conclusion

Most of the related work does not deal with the research questions of this thesis and none address the specific hypotheses. From this related work, we make the following decisions about the design of the experiments:

- The task in both of our experiments is based on visual search. Puzzle pieces pop up randomly on a large display and participants are required to find and join those pieces correctly to complete the puzzle in a given amount of time.
- Physical navigation is required in our experiments because it helps the user to interact with the bezels on a large display. As a result, we entertain physical navigation not as an issue as did many researchers, but simply as part of our experiment.
- We propose that adding a tail to the cursor on a touch display will be helpful. See Figure 2.1. The tail might be helpful when using virtual navigation devices such as a mouse, keyboard, or light pen to work on large display (we have yet to test this).
- We consider the factors such as background color, wide field view and distance from screen, while designing the experiments. The puzzle pieces are scattered all over the display and the user employs physical navigation to find all the pieces. At the beginning of the experiment, users can take a wide field view of the large display to figure out where the pieces are positioned.



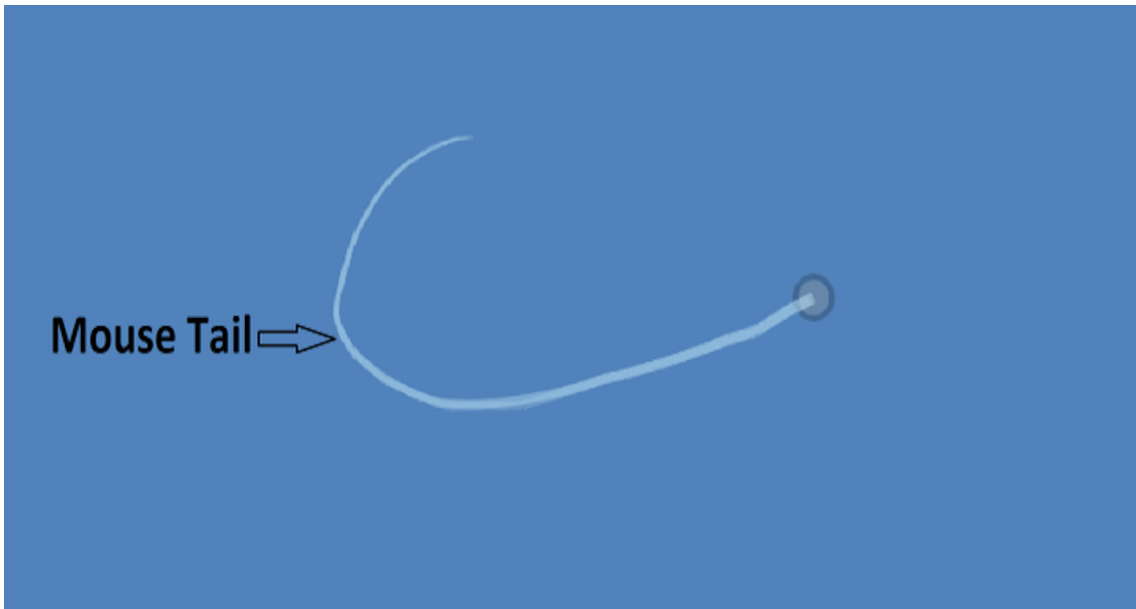


Figure 2.1: Mouse tail

# Chapter 3

## Experimental setup

In this section, we explain the set-up of our experiments.

### 3.1 Bezel experiment

We did two experiments on a projector display and a LC display respectively. The goal of the experiments was to determine if the users are impacted by bezel widths and the number of screens. We simulated the bezels on a projector display and on a LC display to identify the interference of bezels on users' performance. The projector display and the LC display were used in the experiment to simulate the tiled monitors with bezels. The setup of two experiments is discussed below. First, we discuss the projector display setup in Section 3.1.1 and next we discuss the LC display setup in Section 3.1.2. Later this section we discuss the type of display preferred from users' viewpoint: LC display or projector display.

#### 3.1.1 Projector display

The display that we used in this setup was a back-projected projector display. Our goal was to identify the interference of bezel from the users' perspective. We simulated the bezels of widths 0, 0.5, 1.0, and 2.0cm on the display. One important variable in the experiment was the configuration of a screen, which explains how many horizontal and vertical bezels show up on large projector display. We used the following configurations in the experiment:

- 1 x 1: This configuration is a large display without bezel.
- 2 x 2: This configuration has one horizontal and one vertical bezel rendered on screen. It is to simulate four monitors joined together and making one large display.
- 3 x 3: This configuration has two horizontal and two vertical bezel rendered on screen. It is to simulate nine monitors joined together and making one large display.

The resultant resolution of each grid in the [2x2] and the [3x3] configurations is lower than that of real high resolution tiled monitor. Our findings are based on the simulation of the real tiled monitors. The experimental design for this setup can be summarized as:

24 Participants x

10 Bezel Variations =

240 comparisons

Each participant received a random task out of 10 variations. The randomization shows the unbiased behaviour of author towards participants in the experiment.

The projector that we used in the experiment was a Panasonic with 1024 horizontal and 768 vertical pixels. The image produced by the projector is 167 cms x 116 cms. Bezels are drawn on a projector display to simulate the plastic boundary which surrounds the LC display from four sides. We designed the experiment to simulate the overlay effect.

### 3.1.2 LC display

In this section we discuss the setup of second experiment. We used LC display with 1024 horizontal and 768 vertical pixels for the experiment. The experiment consisted of various combinations of bezel width and number of bezels. We simulated the bezels of widths 0, 0.5, 1.0, 2.0, and 4.0cm on the display. Configurations that we used in this set up are explained below:

- 1 x 1: This configuration is a large display without bezel.
- 2 x 2: This configuration has one horizontal and one vertical bezel rendered on screen. It is to simulate four monitors joined together and making one large display.
- 3 x 3: This configuration has two horizontal and two vertical bezel rendered on screen. It is to simulate nine monitors joined together and making one large display.

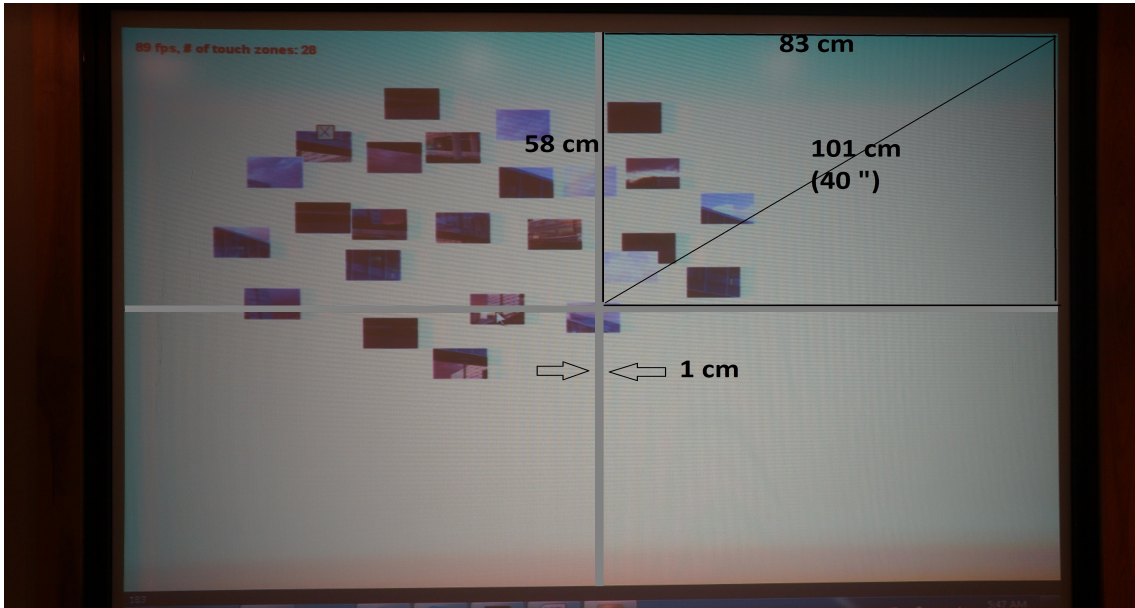


Figure 3.1: Tiled monitor configuration used in experiment [2x2]

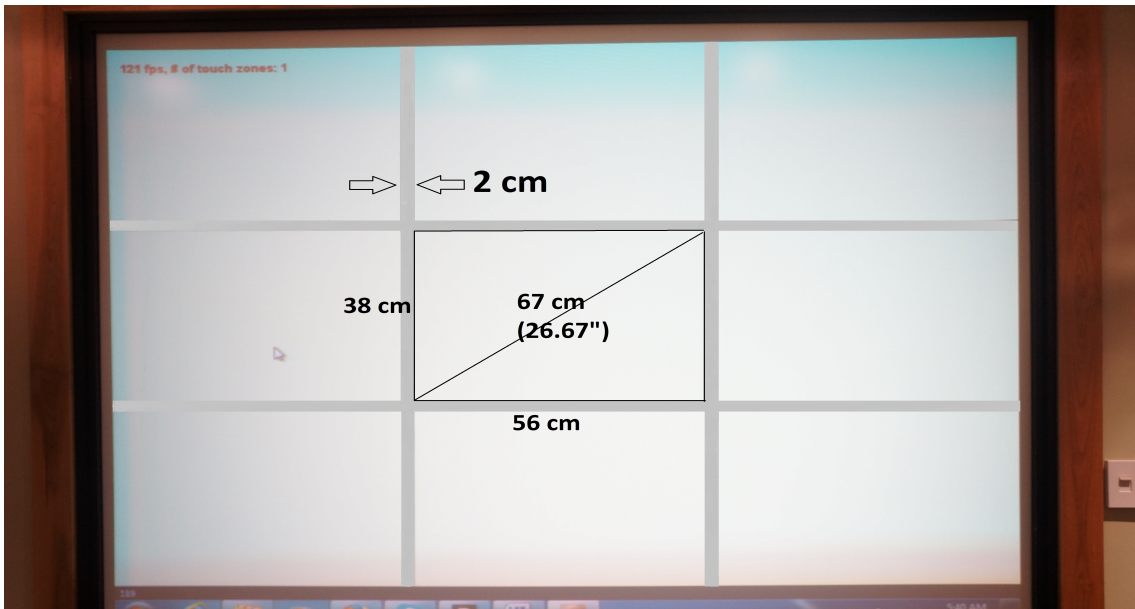


Figure 3.2: Tiled monitor configuration used in experiment [3x3]

- 4 x 4: This configuration has three horizontal and three vertical bezel rendered on screen. It is to simulate sixteen monitors joined together and making one large display.

The resultant resolution of each grid in the [2x2], the [3x3], and that [4x4] configurations is lower than that of real high resolution tiled monitor. Our findings are based on the replication of the real tiled monitors. The above four configuration with five bezel widths (0, 0.5, 1.0, 2.0, and 4.0cm) make a total of 13 tasks that each user suppose to do on a LC display.

The experimental design for this set up can be summarized as:

24 Participants x

13 Bezel Variations =

312 comparisons

Each participant received a random task out of 13 variations. The randomization in tasks shows the unbiased behaviour of the author towards the participants in the experiment.

## 3.2 Bezel width

In the first experiment we took four bezel widths: 0, 0.5cm, 1.0cm, 2.0cm, and in the second experiment we took a new bezel width of 4.0cm in addition to all the above. So, in total, five bezel widths were tested in the second experiment. According to a market survey, typically the available border width of an LC display for video wall is 2.0cm [56]. When two monitors are joined, the total width of the bezel is 4.0cm. Most of the tiled monitor displays available in market have less than 4.0cm bezel width. That is the reason we used a 2.0cm bezel width in the first experiment. The literature shows that experiments have been conducted with 0, 0.5, 1.0, 2.0 and 4.0cm bezel width to show how bezel width affects visual search and steering task [15, 56]. The quantity of data and the nature of the tasks that we used differentiate us from rest of the studies done in the past. There were 24 participants for each experiment and the experiments consisted of 10 and 13 tasks respectively. The puzzle-solving task involves the visual search for an image and placing the image at its specific location through navigation on the display. The tasks we have seen in the past research is either a directed task in which participants are directed to follow a path or to search for an object. In our experiments, participants locate an object and place it at its correct location. The order is randomized which means there is no unique image and there is no specific location. We designed the experiments according to the survey we did regarding the ratio of bezel width to display size.

### 3.3 Experimental task

The first experiment was a task in which participants were asked to solve a puzzle that popped up on a large display. The puzzle included the pictures of buildings from a local university. There were 13 pictures and they were totally randomized to maintain the unbiased nature of task.

The second experiment was exactly same as the first experiment, except that there was one more configuration of screen with bezel width of 4.0cm. Each experiment took approximately 30 minutes to complete all of its tasks. After the experiment, each participant was asked to fill a feedback form, which included a demographic questionnaire and questions about bezels.

### 3.4 Participants

Twenty four participants (nineteen men and five women) between the ages of 18 and 27 (median age 22) were recruited to participate in this study. Participants were Technology, Engineering, and Mathematics students who were enrolled at the University of Waterloo. Participants were daily computer users, and each has interacted with smart touch displays before. Each participant had either normal or corrected-to-normal vision and was right handed. Each participant was asked to sign an informed consent form. Upon arrival in the room, tasks were explained to participants, and they were allowed to get comfortable with the large display during a practice period for about 2-4 minutes. Practice period entailed the interaction with the display, solving an easy dummy puzzle, comfortably stand themselves in front of the display, signing a consent form. Each participant performed a puzzle solving task on a projected display approximately 200cm wide and 150cm tall. Each maintained a distance of approximately 40cm from the display which was at a resolution of 1980 x 1024 pixels on both the projector display and the LC display. See Figure 3.4.

Each puzzle used in the experiments has 25 unsorted pieces and for every participant, a new puzzle popped up on the display. We measured each participant's task completion percentage (TCP), which is defined as the number of pieces in an unsorted puzzle he or she managed to join correctly in the time of 120 seconds. If out of 25 pieces, a user manages to join 16 pieces correctly, then his TCP is 64%. After every task, the number of pieces joined correctly is noted down. Table 3.1 shows the combinations of tasks performed using the projector display. Table 3.2 shows the combinations using the LC display. Table 3.2 and Table 3.1 do not show the sequence of tasks performed because the sequence is randomized and it is different for every participant.

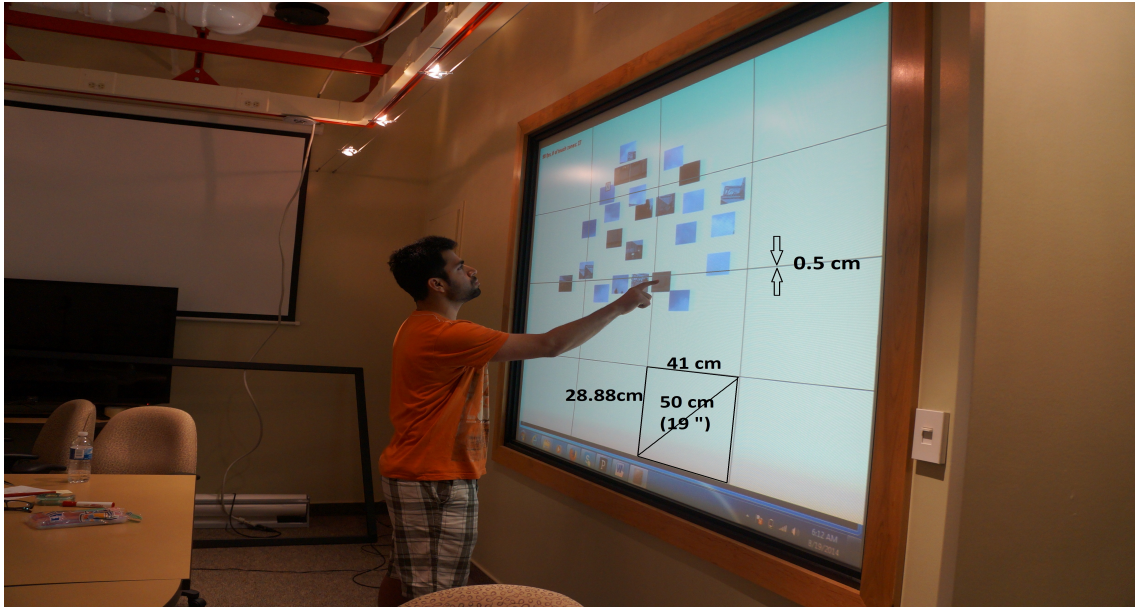


Figure 3.3: Tiled monitor configuration used in experiment [4x4]

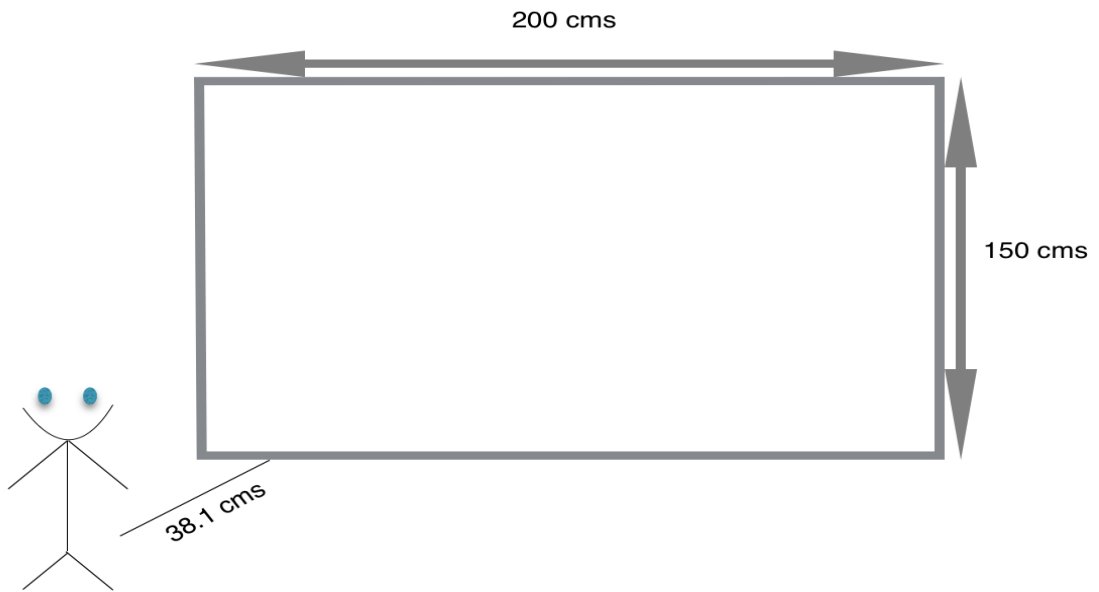


Figure 3.4: Dimension of large projector display

### 3.5 Justification for the randomized behaviour of the tasks

In the experiments, we randomly shuffled the images to generate a puzzle and each image is split into 25 equal sized pieces scattered on the display to generate a  $5 \times 5$  matrix. A user is then required to solve the puzzle, i.e, to arrange the shuffled pieces of an image to its original position. We calculated the average of the times taken by the users to complete this task. When the tasks were distributed to the users, there were two options:

- The image is randomly shuffled once. Each user is given the same randomly shuffled image and then the average and other statistics are computed.
- The original image is randomly shuffled for each user. The drawback of this approach is that different users may get tasks of different difficulties.

In this thesis, we used the second approach for our experiments. Since each user solved a different task and then we computed the average statistics. We should justify why this approach makes sense. In our experiments, the users were required to arrange a  $5 \times 5$  image. This was repeated for 24 users.

We modelled the task as follows. An image can be thought of as the vector  $\mathbf{V} = (1, \dots, 25)$ . We randomly permute the vector  $\mathbf{V}$  to get a new vector  $\mathbf{V}'$ . The task of the user is then to rearrange  $\mathbf{V}'$  to get  $\mathbf{V}$ . However, this arrangement can be done using only swap operations. The difficulty of this task can be measured by the number of swaps it takes to achieve  $\mathbf{V}$  when we start from  $\mathbf{V}'$ .

$$\text{Difficulty}(\text{Task}) = \# \text{ Swaps to rearrange } \mathbf{V}' \text{ to } \mathbf{V}.$$

To justify our experiment and show that our results are meaningful, we should show that on an average each user solved a task of similar difficulty. To verify this, we ran the following computer simulation.

- Generate a random permutation  $\mathbf{V}'$  of the vector  $\mathbf{V} = (1, \dots, 25)$ .
- Count the number of swaps needed to transform  $\mathbf{V}'$  to  $\mathbf{V}$ .
- Repeat the above for 50 iterations and calculate the average and the standard deviation.



Experiment Description	Bezel Width	Number of Screen
Without Bezel	0 cm	1
With Bezel	0.5 cm	4
With Bezel	0.5 cm	9
With Bezel	0.5 cm	16
With Bezel	1.0 cm	4
With Bezel	1.0 cm	9
With Bezel	1.0 cm	16
With Bezel	2.0 cm	4
With Bezel	2.0 cm	9
With Bezel	2.0 cm	16

Table 3.1: Design of Experiments - Projector Display

We ran the simulation and observed that the mean is  $\sim 21$  and standard deviation of about  $\sim 1.5$ . The small value of standard deviation shows that on an average each user solved a task of equal difficulty.

Before, we started the tasks, the touch screen was calibrated for each participant to maintain equality and to rectify errors. The hypotheses that were tested are:

- $H1_0$ : User task performance is not affected by increasing the width of bezel.
- $H1_1$ : User task performance is affected by increasing the width of bezel.
- $H2_0$ : User task performance is not affected by increasing the number of bezels.
- $H2_1$ : User task performance is affected by increasing the number of bezels.

Experiment Description	Bezel Width	Number of Screen
Without Bezel	0 cm	1
With Bezel	0.5 cm	4
With Bezel	0.5 cm	9
With Bezel	0.5 cm	16
With Bezel	1.0 cm	4
With Bezel	1.0 cm	9
With Bezel	1.0 cm	16
With Bezel	2.0 cm	4
With Bezel	2.0 cm	9
With Bezel	2.0 cm	16
With Bezel	4.0 cm	4
With Bezel	4.0 cm	9
With Bezel	4.0 cm	16

Table 3.2: Design of Experiments - LC Display

# Chapter 4

## Results

This section discusses the results of the two experiments. Section 4.1 discusses the results produced using the projector display. Section 4.2 discusses the results produced using the LC display.

### 4.1 Projector display analysis

We did the experiment with 240 comparisons, arising from 10 experimental tasks x 24 participants. The TCP of the 24 participants for each task is shown in Table 4.1. First, we compare and analyze the whole experimental data and determine which hypotheses are supported. For each analysis, we use one-way ANOVA with an  $\alpha$ -value of 0.05. The mean and variance of each task is shown in Table 4.2. Distribution of data is showed in box and whisker plot in Figure ??

Bezel Width (No. of Screens)	Participants																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0 (1)	36	32	44	24	40	32	52	36	32	60	32	52	44	36	48	44	44	48	44	36	32	40	32	40
0.5 (4)	40	32	40	36	40	36	40	56	44	32	36	48	32	40	32	44	44	48	40	24	32	40	52	44
1.0 (4)	38	40	40	44	32	44	56	44	32	32	36	44	52	44	52	44	48	52	36	52	60	44	28	36
2.0 (4)	44	32	48	32	32	28	44	48	32	36	40	56	40	40	36	40	48	52	40	28	40	40	48	44
0.5 (9)	44	48	40	48	36	44	48	32	40	44	44	48	40	36	32	48	48	40	40	48	48	48	44	48
1.0 (9)	44	48	40	36	32	44	60	40	36	32	36	48	48	48	48	44	40	36	36	52	32	44	48	40
2.0 (9)	44	32	40	40	40	48	32	28	48	40	44	44	40	36	36	36	48	40	48	40	40	40	40	52
0.5 (16)	32	40	40	36	40	48	32	36	36	52	40	48	40	48	40	52	44	44	36	44	36	36	44	28
1.0 (16)	40	60	44	36	36	48	44	36	36	32	40	48	40	48	28	44	48	40	40	44	32	36	44	44
2.0 (16)	36	36	44	40	44	40	44	40	44	52	48	48	52	44	36	52	48	44	40	40	38	44	32	36

Table 4.1: Participants' Task Completion Percentages - Projector Display

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0 (1)	24	960	40	69.56
0.5 (4)	24	952	39.66	52.75
1.0 (4)	24	1030	42.91	69.21
2.0 (4)	24	968	40.33	55.53
0.5 (9)	24	1036	43.16	27.79
1.0 (9)	24	1012	42.16	50.05
2.0 (9)	24	976	40.66	32.92
0.5 (16)	24	972	40.5	39.39
1.0 (16)	24	988	41.17	46.57
2.0 (16)	24	1022	42.58	30.77

Table 4.2: ANOVA Mean and Variance for complete data set

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	356.26	9	39.58	0.83	0.58	1.92
Within Groups	10915.67	230	47.45			
Total	11271.93	239				

Table 4.3: ANOVA Analysis for complete data set

There are two variable, *bezel width* and *number of screens*<sup>1</sup>, which vary and are mutually exclusive. Tables 4.2 and 4.3 gives the mean and  $\sigma$  of the complete data set and the ANOVA analysis of the same data set respectively. From the above analysis, the hypotheses might be supported or not, but concluding at this point is not justifiable until we go into details by fixing one variable out of the two. To make it more clear, we did several more analyses using the same data, but this time we fixed the *number of screens* and varied the *bezel width*. So, in total there are three data sets as shown in Table 4.4, 4.6, and 4.8.

In Tables 4.4 and 4.5, we fix the number of screens to be 4 and vary the width of a bezel to be 0.5cm, 1.0cm, and 2.0cm. The ANOVA shows that  $F_{2,69} = 1.1953$ ,  $P - value = 0.3087$ , and  $F_{crit} = 3.1296$ . Clearly,  $F_{2,69} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the null hypothesis  $H1_0$  is accepted, and its corresponding non-null hypothesis  $H1_1$  is rejected.

<sup>1</sup>*Bezel width* and *number of bezels* are the two variables mentioned in the hypotheses. An increase in the *number of screens* results in an increase in the *number of bezels*. In order to make the discussion understandable, we will use the *number of screens* instead of the *number of bezels* in this section.

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0.5 (4)	24	952	39.66	52.75
1.0 (4)	24	1030	42.91	69.21
2.0 (4)	24	968	40.33	55.53

Table 4.4: Mean and Variance of data set keeping number of screens = 4 and varying width of Bezel

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	141.44	2	70.72	1.19	0.30	3.12
Within Groups	4082.5	69	59.16			
Total	4223.94	71				

Table 4.5: ANOVA Analysis of 4.4

Therefore, we conclude that a user's performance is not affected by variation in the bezel width.

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0.5 (9)	24	1036	43.16	27.79
1.0 (9)	24	1012	42.16	50.05
2.0 (9)	24	976	40.66	32.92

Table 4.6: Mean and Variance of data set keeping number of screens = 9 and varying width of Bezel

In Tables 4.6 and 4.7, we fix the number of screens to be 9 and vary the width of a bezel to be 0.5cm, 1.0cm, and 2.0cm. The ANOVA shows that  $F_{2,69} = 1.0290$ ,  $P - value = 0.3627$ , and  $F_{crit} = 3.1296$ . Clearly,  $F_{2,69} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the null hypothesis  $H_0$  is accepted, and its corresponding non-null hypothesis  $H_1$  is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the bezel width.

In Tables 4.8 and 4.9, we fix the number of screens to be 16 and vary the width of a bezel to be 0.5cm, 1.0cm, and 2.0cm. The ANOVA shows that  $F_{2,69} = 0.6980$ ,  $P - value = 0.5010$ , and  $F_{crit} = 3.1296$ . Clearly,  $F_{2,69} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the

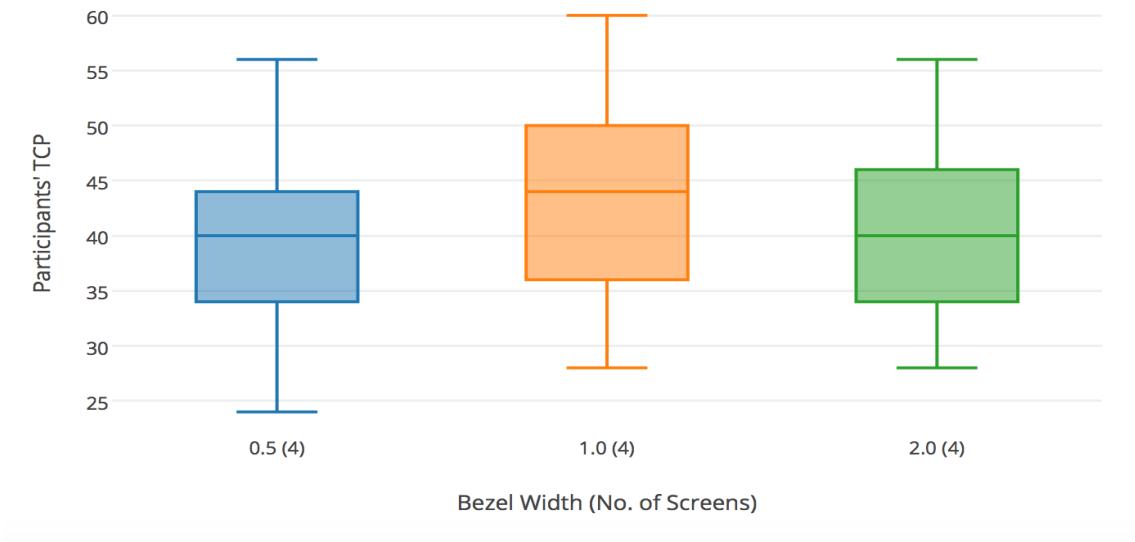


Figure 4.1: Distribution of data set 4.4 keeping the number of screens = 4 and varying the width of bezels

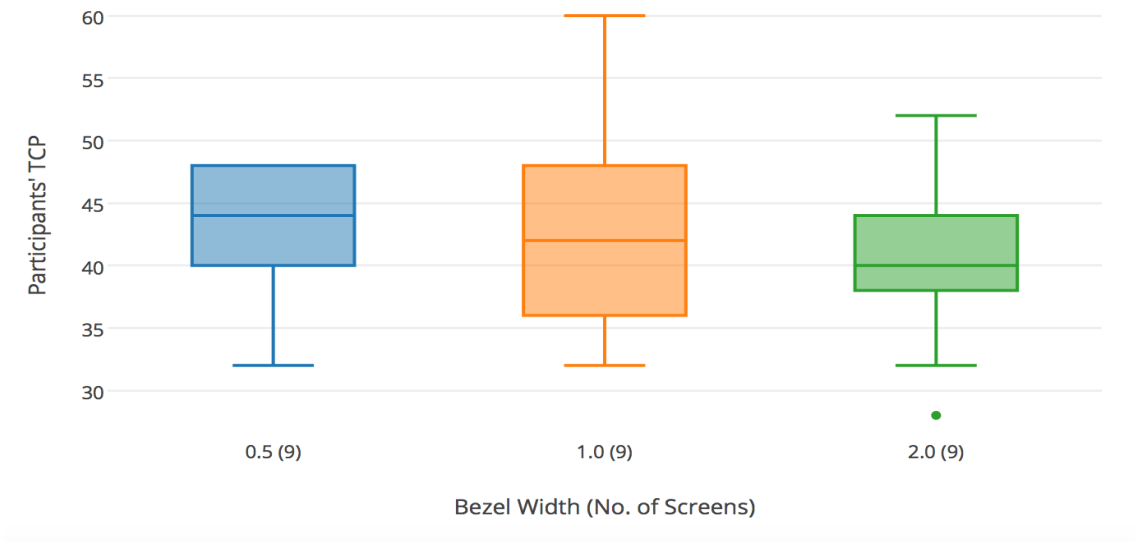


Figure 4.2: Distribution of data set 4.6 keeping the number of screens = 9 and varying the width of bezels

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	76	2	38	1.02	0.36	3.12
Within Groups	2548	69	36.92			
Total	2624	71				

Table 4.7: ANOVA Analysis of 4.6

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0.5 (16)	24	972	40.5	39.39
1.0 (16)	24	988	41.16	46.57
2.0 (16)	24	1022	42.58	30.78

Table 4.8: Mean and Variance of data set keeping number of screens = 16 and varying width of Bezel

null hypothesis  $H1_0$  is accepted, and its corresponding non-null hypothesis  $H1_1$  is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the bezel width.

From the above discussions of Tables 4.5, 4.7, and 4.9, the null hypothesis  $H1_0$  is accepted, that is, *user task performance is not affected by increasing the width of bezels.*

In the next discussion, we examine the data set in which we fix the *bezel width* to determine if there is any effect in a participant performance when we vary the *number of screens* as 1, 4, 9, and 16. An increase in the *number of screens* results in an increase in the number of bezels. In the discussion, we have Table 4.10, 4.12, and 4.14 with three different bezel widths, 0.5, 1.0, and 2.0, respectively.

In Tables 4.10 and 4.11, we fix the bezel width to be 0.5cm and vary the number of screens to be 1, 4, 9, and 16. The ANOVA shows that  $F_{3,92} = 1.2852$ ,  $P - value = 0.2841$ , and  $F_{crit} = 2.7035$ . Clearly,  $F_{3,92} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the null hypothesis  $H2_0$  is accepted, and its corresponding non-null hypothesis  $H2_1$  is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the number of screen.

In Tables 4.12 and 4.13, we fix the bezel width to be 1.0cm and vary the number of screens to be 1, 4, 9, and 16. The ANOVA shows that  $F_{3,92} = 0.6520$ ,  $P - value = 0.5836$ , and  $F_{crit} = 2.7035$ . Clearly,  $F_{3,92} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the null



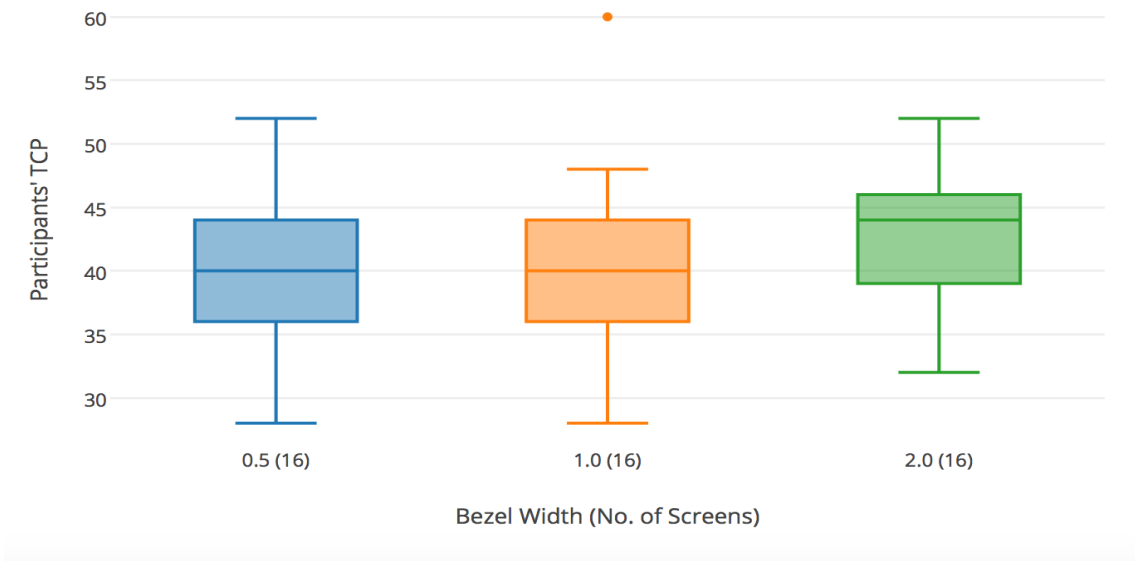


Figure 4.3: Distribution of data set 4.8 keeping the number of screens = 16 and varying the width of bezels

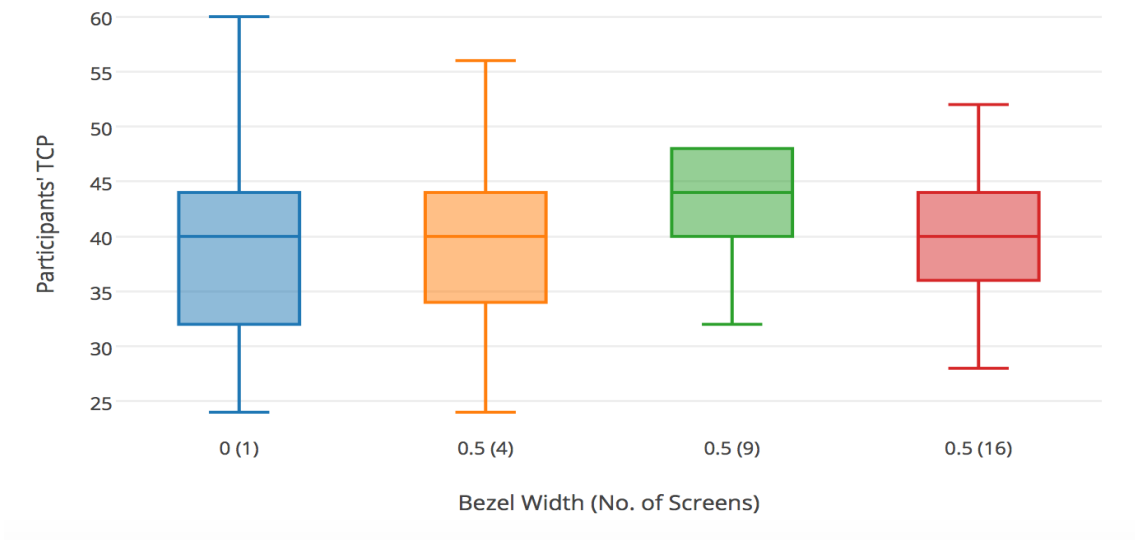


Figure 4.4: Distribution of data set 4.10 keeping the width of the bezel = 0.5cms and varying the number of screens

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	54.33	2	27.16	0.69	0.50	3.12
Within Groups	2685.16	69	38.91			
Total	2739.5	71				

Table 4.9: ANOVA Analysis of 4.8

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0 (1)	24	960	40	69.56
0.5 (4)	24	952	39.66	52.75
0.5 (9)	24	1036	43.16	27.79
0.5 (16)	24	972	40.5	39.39

Table 4.10: Mean and Variance of data set keeping width of the Bezel = 0.5cms and varying number of screens

hypothesis  $H2_0$  is accepted, and its corresponding non-null hypothesis  $H2_1$  is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the number of screen.

In Tables 4.14 and 4.15, we fix the bezel width to be 2.0cm and vary the number of screens to be 1, 4, 9, and 16. The ANOVA shows that  $F_{3,92} = 0.6811$ ,  $P - value = 0.5657$ , and  $F_{crit} = 2.7035$ . Clearly,  $F_{3,92} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the null hypothesis  $H2_0$  is accepted, and its corresponding non-null hypothesis  $H2_1$  is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the number of screen.

From the above discussions of Tables 4.11, 4.13, and 4.15, the null hypothesis  $H2_0$  is accepted, that is, *user task performance is not affected by increasing the number of bezels.*

## 4.2 LC display analysis

We did the experiment with 312 comparisons, arising from 13 experimental tasks x 24 participants. The task completion percentage (TCP) of 24 participants for each task is shown in Table 4.16. First, we compare and analyze the whole experimental data and

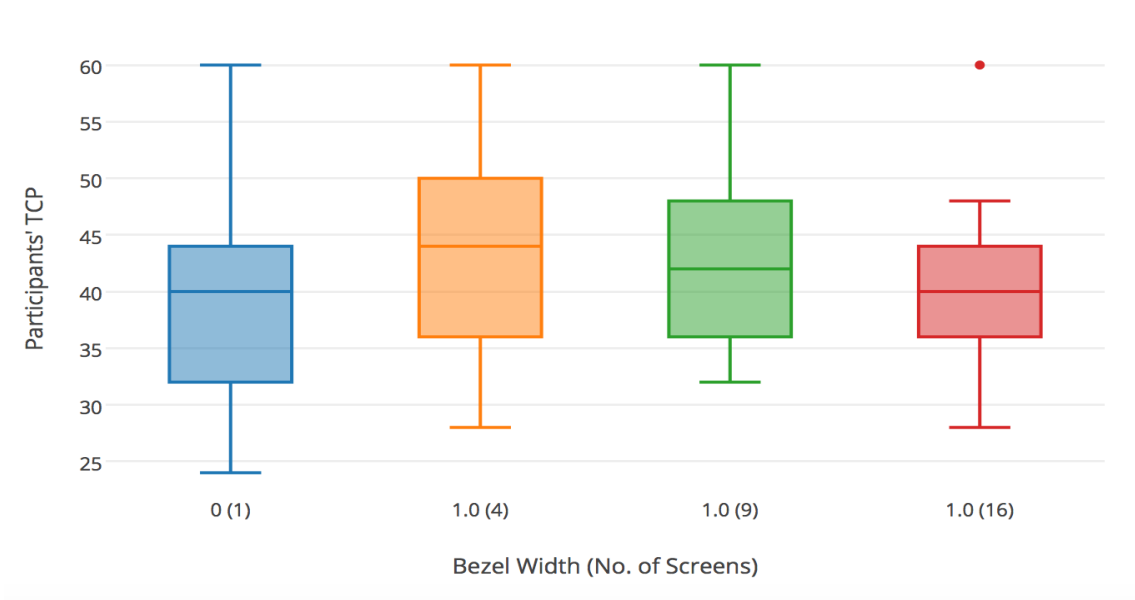


Figure 4.5: Distribution of data set 4.12 keeping the width of the bezel = 1.0cm and varying the number of screens

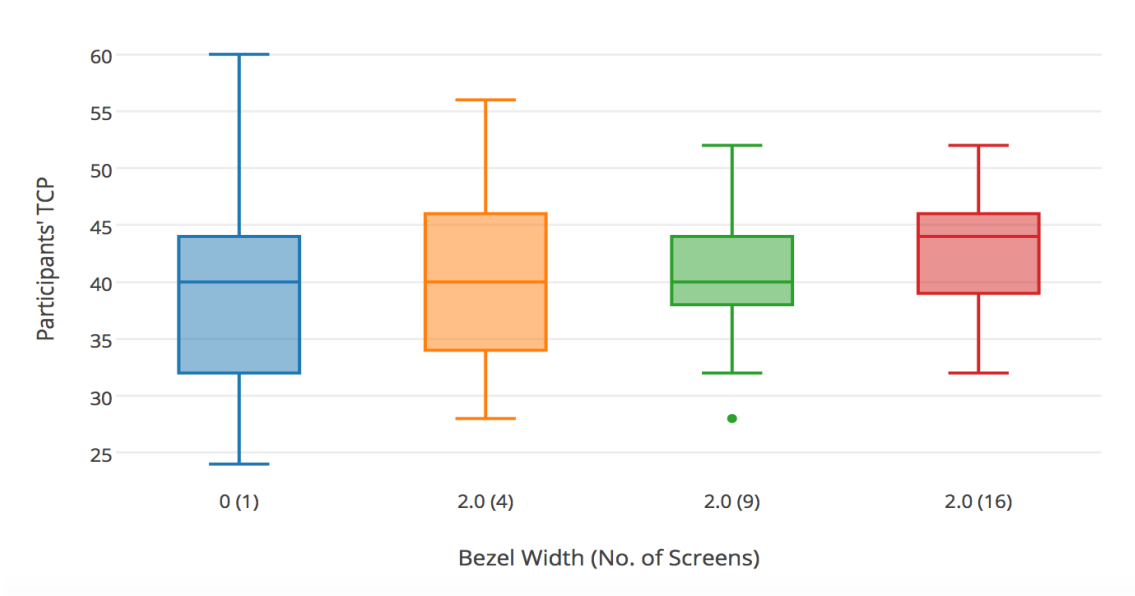


Figure 4.6: Distribution of data set 4.14 keeping the width of the bezel = 2.0cms and varying the number of screens

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	182.66	3	60.88	1.28	0.28	2.70
Within Groups	4358.66	92	47.37			
Total	4541.33	95				

Table 4.11: ANOVA Analysis of 4.10

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0 (1)	24	960	40	69.56
1.0 (4)	24	1030	42.91	69.21
1.0 (9)	24	1012	42.16	50.05
1.0 (16)	24	988	41.16	46.57

Table 4.12: Mean and Variance of data set keeping width of the Bezel = 1.0cm and varying number of screens

determine which hypotheses are supported. For each analysis, we use one-way ANOVA with an  $\alpha$ -value of 0.05. The mean and variance of each task is shown in Table 4.17. Distribution of data is showed in box and whisker plot in Figure ??

There are two variable, *bezel width* and *number of screens*, which vary and are mutually exclusive. Tables 4.17 and 4.18 gives the Mean and  $\sigma$  of the complete data set and the ANOVA analysis of the same data set respectively. Similar to the discussion in Section 4.1, we did several more analysis using the same data but first, we fix the *number of screens* and varied the *bezel width*. So, in total there are three sets as shown in Table 4.19 ,4.21, and 4.23.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	115.125	3	38.37	0.65	0.58	2.70
Within Groups	5414.5	92	58.85			
Total	5529.625	95				

Table 4.13: ANOVA Analysis of [4.12](#)

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0 (1)	24	960	40	69.56
2.0 (4)	24	968	40.33	55.53
2.0 (9)	24	976	40.66	32.92
2.0 (16)	24	1022	42.58	30.77

Table 4.14: Mean and Variance of data set keeping width of the Bezel 2.0cms and varying number of screens

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	96.45	3	32.15	0.68	0.56	2.70
Within Groups	4342.5	92	47.20			
Total	4438.95	95				

Table 4.15: ANOVA Analysis of [4.14](#)

Bezel Width (No. of Screens)	Participants																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0 (1)	48	48	72	60	76	44	72	52	80	64	44	72	44	40	72	60	64	72	32	76	24	72	68	84
0.5 (4)	84	64	64	76	64	20	60	52	64	72	52	20	72	64	68	64	68	72	64	72	76	72	72	48
1.0 (4)	56	56	84	72	76	60	48	60	72	84	72	60	68	68	72	64	68	76	28	72	72	76	60	72
2.0 (4)	84	60	52	84	84	64	28	84	84	64	72	84	40	68	44	68	72	76	52	68	60	68	24	68
4.0 (4)	84	64	48	76	16	48	56	64	36	84	68	84	36	72	60	72	40	76	44	44	56	56	40	72
0.5 (9)	84	84	48	40	64	16	40	72	84	52	44	52	52	72	64	72	52	84	48	40	60	60	40	72
1.0 (9)	60	60	72	84	80	40	32	68	64	84	56	44	56	72	68	84	60	84	60	56	52	40	60	84
2.0 (9)	64	72	68	48	76	52	48	68	48	60	60	48	64	60	76	84	60	80	40	60	64	48	56	80
4.0 (9)	84	60	56	56	64	40	48	52	76	84	44	80	72	56	48	76	64	80	60	64	64	32	64	48
0.5 (16)	80	48	60	40	64	48	64	80	60	76	84	48	36	68	48	80	68	84	60	72	72	60	68	60
1.0 (16)	60	60	80	72	84	68	60	68	48	84	84	68	64	84	60	76	72	80	72	76	68	24	72	80
2.0 (16)	84	72	52	52	60	84	56	52	64	64	68	72	40	76	72	76	36	84	44	56	68	68	44	56
4.0 (16)	68	80	84	84	56	64	48	68	80	84	64	76	60	64	68	68	48	84	64	64	84	28	68	72

Table 4.16: Participants' Task Completion Percentages - LC Display

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0 (1)	24	1440	60	262.95
0.5 (4)	24	1504	62.66	238.84
1.0 (4)	24	1596	66.50	144.43
2.0 (4)	24	1552	64.66	301.44
4.0 (4)	24	1396	58.16	322.75
0.5 (9)	24	1396	58.16	311.62
1.0 (9)	24	1520	63.33	234.66
2.0 (9)	24	1484	61.83	144.66
4.0 (9)	24	1472	61.33	201.27
0.5 (16)	24	1528	63.66	189.10
1.0 (16)	24	1664	69.33	183.18
2.0 (16)	24	1500	62.50	194.52
4.0 (16)	24	1628	67.833	188.49

Table 4.17: ANOVA Mean and Variation for complete data sets

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	356.26	9	39.58	0.83	0.58	1.92
Within Groups	10915.67	230	47.45			
Total	11271.93	239				

Table 4.18: ANOVA Analysis for complete data set

In Tables 4.19 and 4.20, we fix the number of screens to be four and vary the width of a bezel to be 0.5cm, 1.0cm, 2.0cm, and 4.0cm. The ANOVA shows that  $F_{3,92} = 1.22$ ,  $P - value = 0.30$ , and  $F_{crit} = 2.7$ . Clearly,  $F_{3,92} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the null hypothesis  $H_{10}$  is accepted, and its corresponding non-null hypothesis  $H_{11}$  is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the bezel width.

In Tables 4.21 and 4.22, we fix the number of screens to be nine and vary the width of a bezel to be 0.5cm, 1.0cm, 2.0cm, and 4.0cm. The ANOVA shows that  $F_{3,92} = 0.50$ ,  $P - value = 0.67$ , and  $F_{crit} = 2.70$ . Clearly,  $F_{3,92} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the null hypothesis  $H_{10}$  is accepted, and its corresponding non-null hypothesis  $H_{11}$

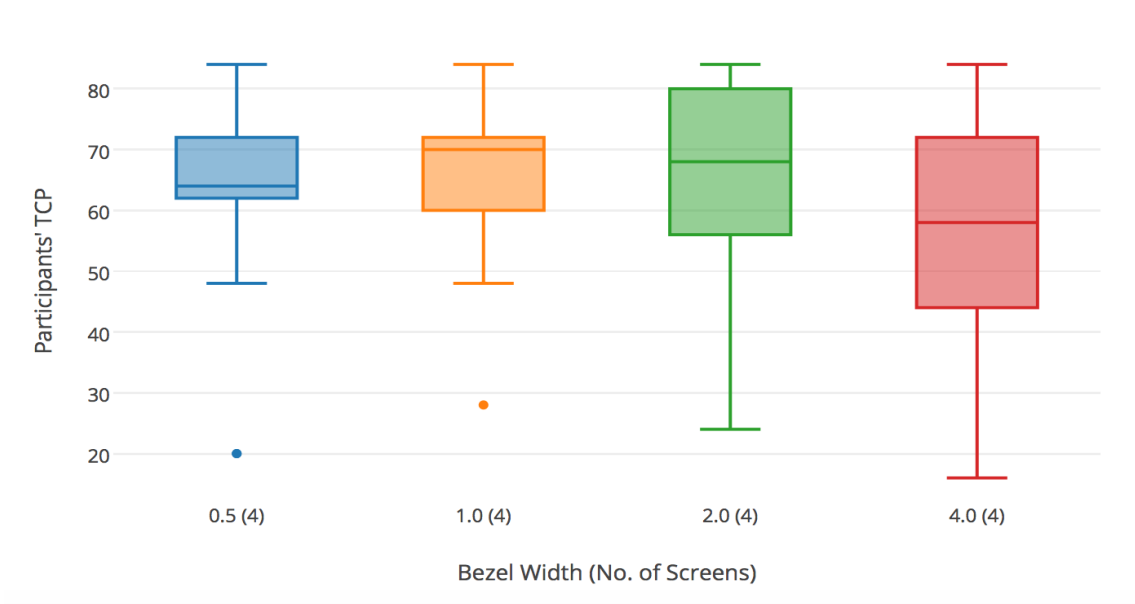


Figure 4.7: Distribution of data set 4.19 keeping the number of screens = 4 and varying the width of bezels

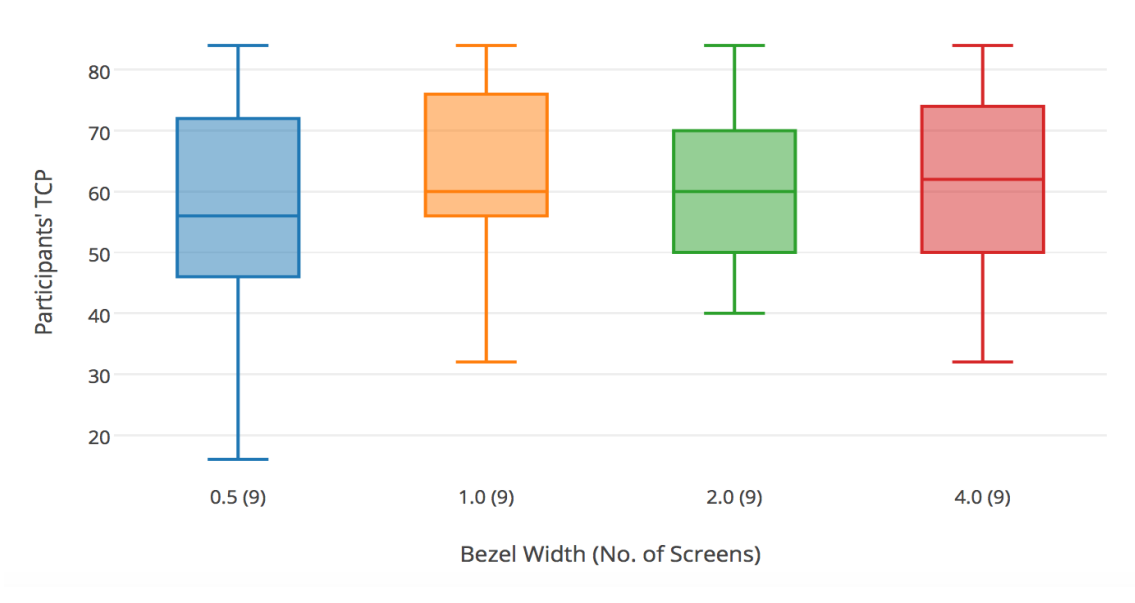


Figure 4.8: Distribution of data set 4.21 keeping the number of screens = 9 and varying the width of bezels



Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0.5 (4)	24	1504	62.66	238.84
1.0 (4)	24	1596	66.50	144.43
2.0 (4)	24	1552	64.66	301.44
4.0 (4)	24	1396	58.16	322.75

Table 4.19: Mean and Variance of data set keeping number of screens = 4 and varying width of Bezel

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	924	3	308	1.22	0.30	2.7
Within Groups	23172	92	251.86			
Total	24096	95	I			

Table 4.20: ANOVA Analysis of 4.19

is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the bezel width.

In Tables 4.23 and 4.24, we fix the number of screens to be 16 and vary the width of a bezel to be 0.5cm, 1.0cm, 2.0cm, and 4.0cm. The ANOVA shows that  $F_{3,92} = 1.35$ ,  $P - value = 0.26$ , and  $F_{crit} = 2.70$ . Clearly,  $F_{3,92} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the null hypothesis  $H_{10}$  is accepted, and its corresponding non-null hypothesis  $H_{11}$  is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the bezel width.

From the above discussions of Tables 4.20, 4.22, and 4.24, the null hypothesis  $H_{10}$  is accepted, that is *participant task performance is not affected by increasing the width of bezels*.

In the next discussion, we examine the data set in which we fix the *bezel width* to determine if there is any effect in a participant performance when we vary the *number of screens* as 1, 4, 9, and 16. An increase in the *number of screens* results in an increase in the number of bezels. In the discussion, we have Table 4.25, 4.27, 4.29, and 4.31 with four different bezel widths, 0.5, 1.0, 2.0, and 4.0cm respectively.

In Tables 4.25 and 4.26, we fix the bezel width to be 0.5cm and vary the number of screens to be 1, 4, 9, and 16. The ANOVA shows that  $F_{3,92} = 0.60$ ,  $P - value = 0.61$ , and  $F_{crit} = 2.70$ . Clearly,  $F_{3,92} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is

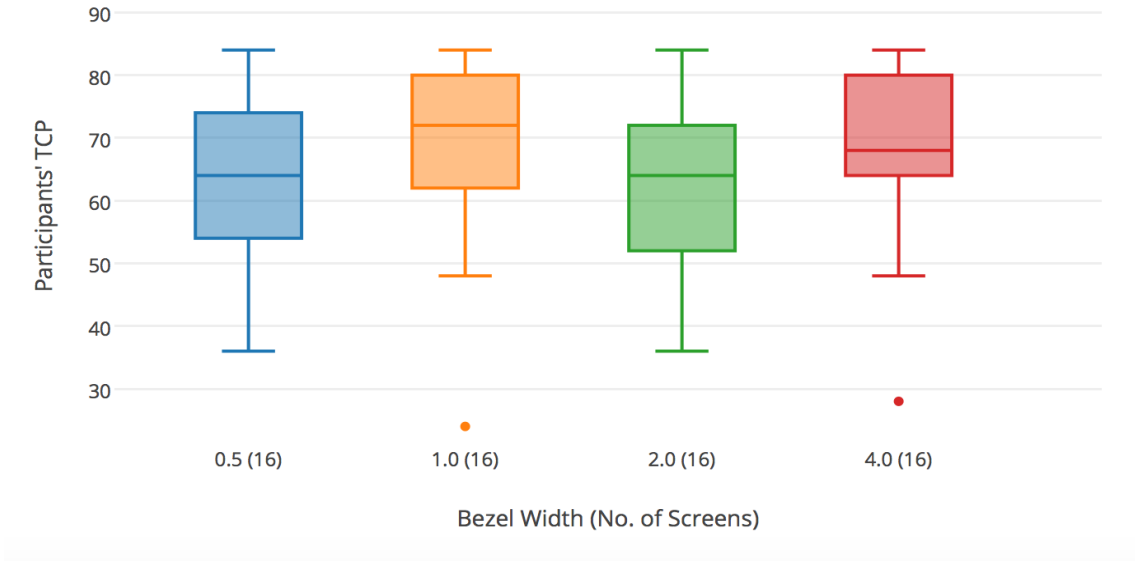


Figure 4.9: Distribution of data set 4.23 keeping the number of screens = 16 and varying the width of bezels

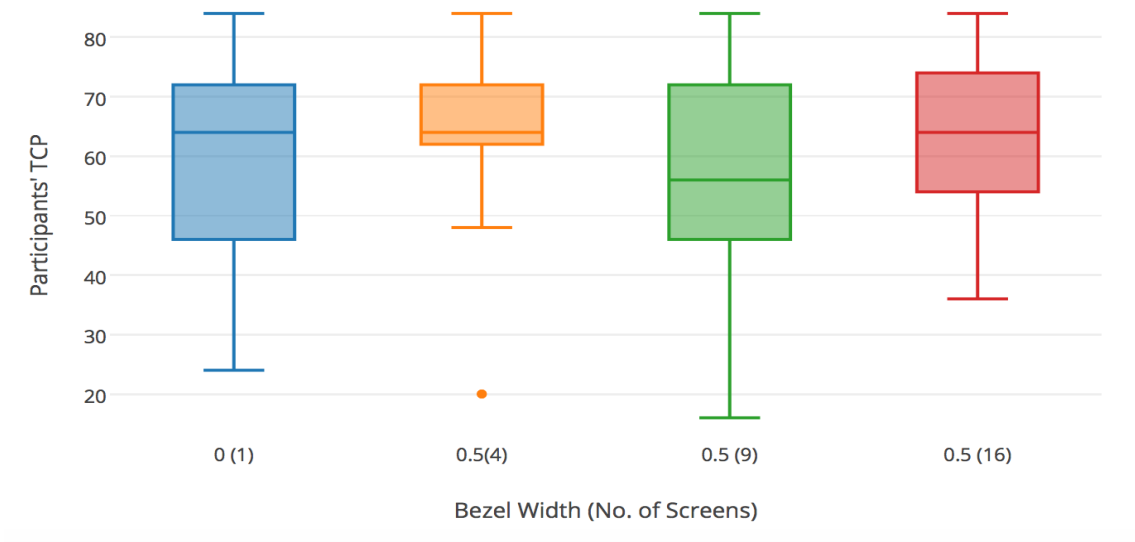


Figure 4.10: Distribution of data set 4.25 keeping the width of the Bezel = 0.5cms and varying the number of screens

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0.5 (9)	24	1396	58.16	311.62
1.0 (9)	24	1520	63.33	234.66
2.0 (9)	24	1484	61.83	144.66
4.0 (9)	24	1472	61.33	

Table 4.21: Mean and Variance of data set keeping number of screens = 9 and varying width of Bezel

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	340	3	113.33	0.50	0.67	2.7
Within Groups	20521.33	92	223.05			
Total	20861.33	95				

Table 4.22: ANOVA Analysis of 4.21

no significant difference among the participants in their performance. Hence, the null hypothesis  $H2_0$  is accepted, and its corresponding non-null hypothesis  $H2_1$  is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the number of screen.

In Tables 4.27 and 4.28, we fix the bezel width to be 1.0cm and vary the number of screens to be 1, 4, 9, and 16. The ANOVA shows that  $F_{3,92} = 1.88$ ,  $P - value = 0.13$ , and  $F_{crit} = 2.70$ . Clearly,  $F_{3,92} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the null hypothesis  $H2_0$  is accepted, and its corresponding non-null hypothesis  $H2_1$  is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the number of screen.

In Tables 4.29 and 4.30, we fix the bezel width to be 2.0cm and vary the number of screens to be 1, 4, 9, and 16. The ANOVA shows that  $F_{3,92} = 0.39$ ,  $P - value = 0.75$ , and  $F_{crit} = 2.70$ . Clearly,  $F_{3,92} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the null hypothesis  $H2_0$  is accepted, and its corresponding non-null hypothesis  $H2_1$  is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the number of screen.

In Tables 4.31 and 4.32, we fix the bezel width to be 4.0cm and vary the number of screens to be 1, 4, 9, and 16. The ANOVA shows that  $F_{3,92} = 1.74$ ,  $P - value = 0.16$ ,

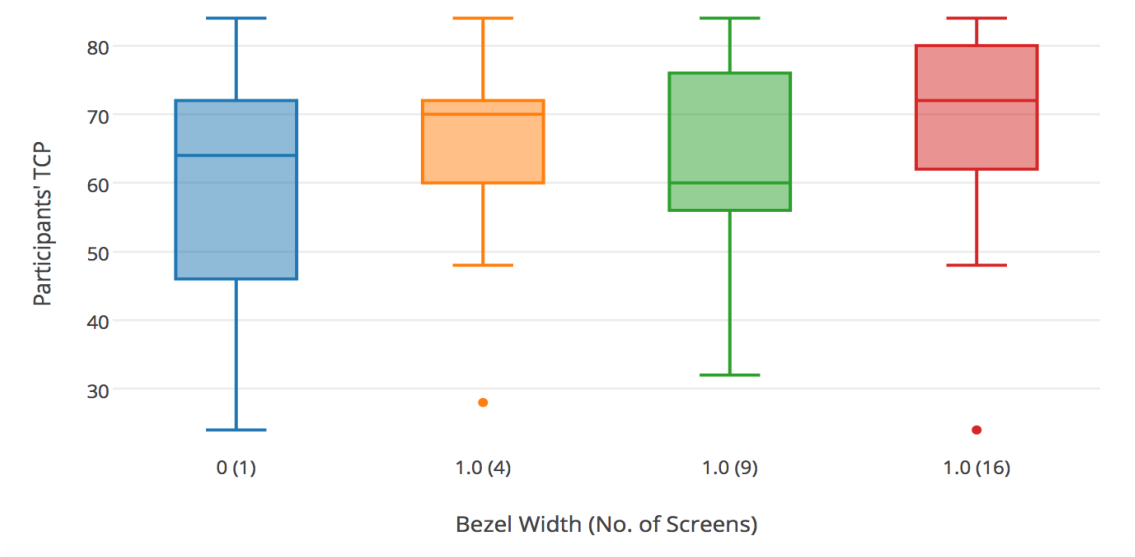


Figure 4.11: Distribution of data set 4.27 keeping the width of the Bezel = 1.0cm and varying the number of screens

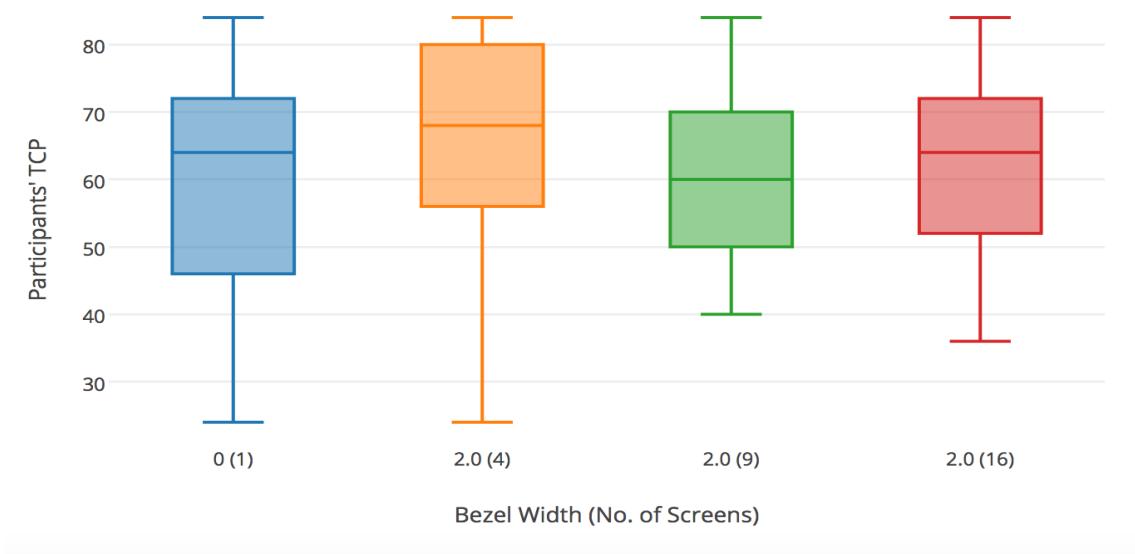


Figure 4.12: Distribution of data set 4.29 keeping the width of the Bezel = 2.0cms and varying the number of screens

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0.5 (16)	24	1528	63.66	189.10
1.0 (16)	24	1664	69.33	183.18
2.0 (16)	24	1500	62.50	194.52
4.0 (16)	24	1628	67.833	188.49

Table 4.23: Mean and Variance of data set keeping number of screens = 16 and varying width of Bezel

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	769.33	3	256.44	1.35	0.26	2.70
Within Groups	17372	92	188.82			
Total	18141.33	95				

Table 4.24: ANOVA Analysis of 4.23

and  $F_{crit} = 2.70$ . Clearly,  $F_{3,92} < F_{crit}$ , and  $P - value > \alpha$ , which mean that there is no significant difference among the participants in their performance. Hence, the null hypothesis  $H_0$  is accepted, and its corresponding non-null hypothesis  $H_1$  is rejected. Therefore, we conclude that a participant's performance is not affected by variation in the number of screen.

From the above discussions of Tables 4.26, 4.28, 4.30, and 4.32 the null hypothesis  $H_0$  is accepted, that is *participant task performance is not affected by increasing the number of bezels*.

We introduced the new bezel width of 4.0 cm in the LC display. The analysis showed that its behaviour is similar to that of the other bezel width. That is,  $H_0$  is accepted and  $H_1$  is rejected. Combining the analyses of projector displays and LC displays, we reach the following results:

- A user's performance is not affected by increasing the bezel width.
- A user's performance is not affected by increasing the number of bezels.

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0 (1)	24	1440	60	262.95
0.5 (4)	24	1504	62.66	238.84
0.5 (9)	24	1396	58.16	311.62
0.5 (16)	24	1528	63.66	189.10

Table 4.25: Mean and Variance of data set keeping width of the Bezel = 0.5 cms and varying number of screens

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	452.50	3	150.833	0.60	0.61	2.7
Within Groups	23058	92	250.63			
Total	23510.50	95				

Table 4.26: ANOVA Analysis of 4.25

### 4.3 LC display versus projector display

We analyzed both projector display and LC display, considering a participant performance as the important parameters. We know that a projector display can produce an image which is free from bezel, and this cannot be achieved completely in a LC display. The best that we can have in a LC display is a very thin bezel, but such display are on the expensive side. In addition to bezel interference, there are other factors such as brightness, contrast, calibration, colour and resolution. The effort to calibrate a LC display is lower than calibrating a projector display. Although we keep brightness, contrast, resolution, and colour of both displays the same in the experiments, the display created with a projector appears to be different from a LC display. The projector display has slightly different colour range because of the bulb and colour filter [52]. The projector does not illuminate the screen uniformly, and that is why the projector display is slightly different from the LC display. It is difficult to come to conclusion that one display is better than other with the data we have, but we try to give a direction for future research. We take a LC display and projector display without bezel for the data analysis of this experiment. We use the same data that we gather for bezel width and utilize it towards a new aspect which is: a LC display is better than a projector displays when a single participant interacts with it.

Figure 4.14, the X-axis is the number of participants perform an experiment and the Y-axis is the task completion percentage. The graph shows the variation in task completion percentage of the LC display and the projector display of 24 participants. For 83.3% of the

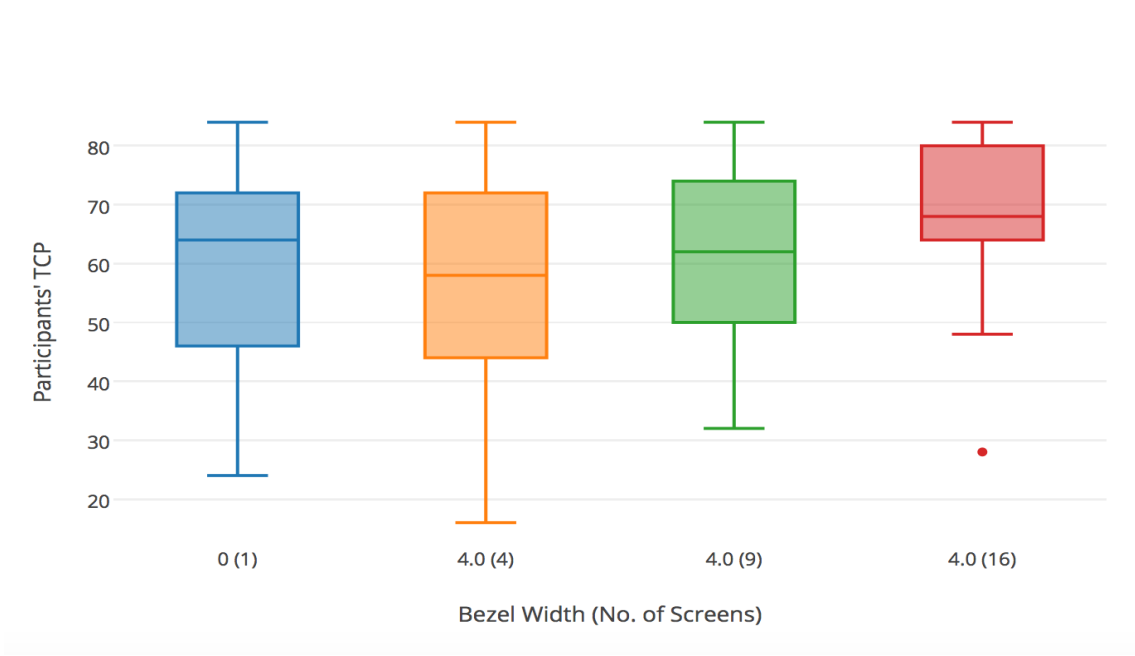


Figure 4.13: Distribution of data set 4.31 keeping the width of the Bezel = 4.0cms and varying the number of screens

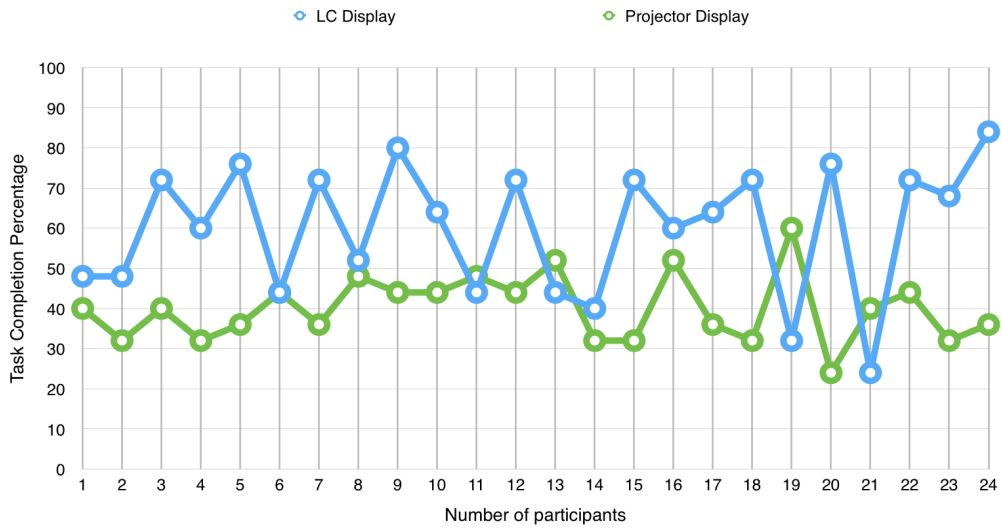


Figure 4.14: Task completion percentage in LCD and projector display

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0 (1)	24	1440	60	262.95
1.0 (4)	24	1596	66.5	144.43
1.0 (9)	24	1520	63.33	234.66
1.0 (16)	24	1664	69.33	183.18

Table 4.27: Mean and Variance of data set keeping width of the Bezel = 1.0 cms and varying number of screens

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1167.16	3	389.05	1.88	0.13	2.7
Within Groups	18980.67	92	206.31			
Total	20147.83	95				

Table 4.28: ANOVA Analysis of 4.27

participants, the TCP for the LC display is more than for the projector display. It is clear from the above evidence that with LC displays, participants are more comfortable than with projector displays. Every participant except *participant 11, 13, 19 and 21* shows more completion with LC displays. It is clearly visible that the average of 24 participants with the LC display  $\succ$  average of 24 participants with the projector display, and it is because of the factors such as brightness, colour contrast, attractiveness of the display, aesthetics of the displays, among others, as we observed in feedback. Some participants are more comfortable with the greater brightness that a LC display has. On the contrary, a smaller number of them said that the LC display's brightness is too high. So, talking about the other factors at this point will not take us anywhere unless we do the experiments by taking individual factors into account and focussing on one at a time. We leave that for future work. We do another analysis by plotting a graph with the data from Table 4.2 and 4.17. We plot the mean of every task performed by each participant with the LC display and the projector display. We eliminate the bezel width 4.0 cm for this analysis because this bezel width is not present in projector display. In the analysis, we are trying to determine the effect of the projector display and the LC display on the participants. So, for this analysis, we eliminate the effect of bezel width, as this is the common factor in both displays. Technically, participants did 10 tasks under the influence of the same factors such as variation in *bezel width* and *number of bezels* with the different displays. We can ignore the effect of variation in bezel width and number of bezels because their variation is the same in both experiments. From the Figure 4.15, in all the cases, participants are more



Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0 (1)	24	1440	60	262.95
2.0 (4)	24	1552	64.66	301.44
2.0 (9)	24	1484	61.83	144.66
2.0 (16)	24	1500	62.50	194.52

Table 4.29: Mean and Variance of data set keeping width of the Bezel = 2.0 cms and varying number of screens

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	267.33	3	89.11	0.39	0.75	2.70
Within Groups	20782.67	92	225.89			
Total	21050	95				

Table 4.30: ANOVA Analysis of [4.29](#)

efficient with the LC display than with the projector display. In all 10 task variations, the mean for the LC display  $\succ$  mean for the projector display. Hence, participants are more comfortable with a LC display than with a projector display under certain conditions.

Bezel Width (No. of Screen)	Total No. of Participants	Sum	Mean	Variance
0 (1)	24	1440	60	262.95
4.0 (4)	24	1396	58.166	322.75
4.0 (9)	24	1472	61.33	201.27
4.0 (16)	24	1628	67.83	188.49

Table 4.31: Mean and Variance of data set keeping width of the Bezel = 4.0 cms and varying number of screens

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1273.33	3	424.44	1.74	0.16	2.70
Within Groups	22436	92	243.86			
Total	23709.33	95				

Table 4.32: ANOVA Analysis of 4.31

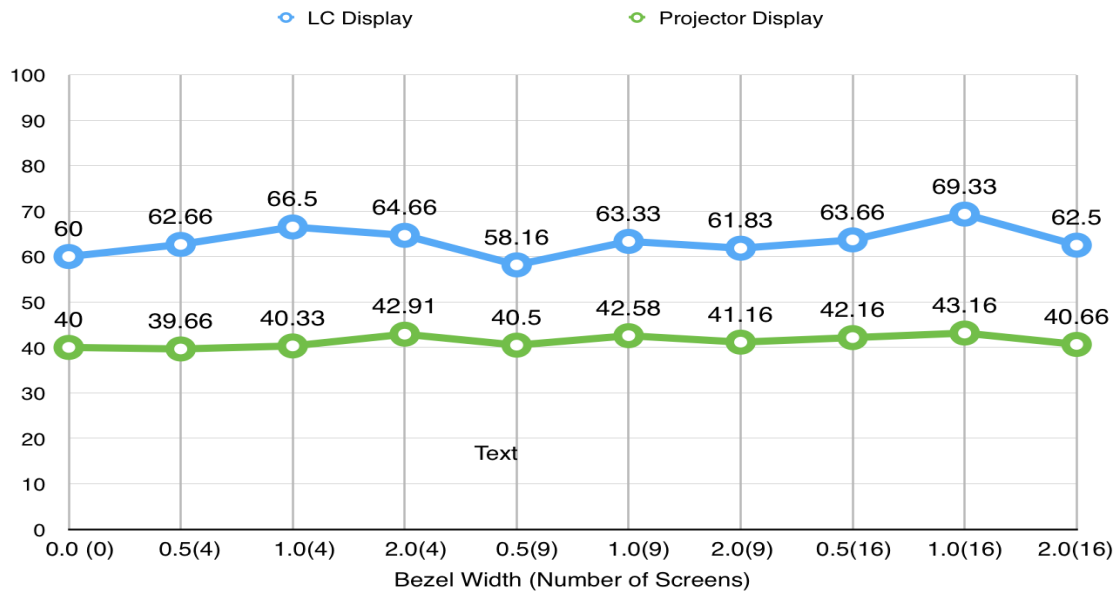


Figure 4.15: Task completion percentage in LCD and projector display

# Chapter 5

## Discussion

The data that we collected during the experiments help us to quantify the impact of bezel width and the number of bezels on user performance. Our null hypotheses  $H1_0$  and  $H2_0$  are supported. Thus the user is not affected by the bezel width and the number of bezels. Our results are aligned with those of the study conducted by Wallace et al. in which they show that bezels have no effect in visual task performance [56]. Some users in their feedback mentioned that the bezels seemed to be an obstacle. However, when we quantified the results, we did not find any problems caused by the bezel. It is plausible that users are expecting a delay in performance from the bezels, but when they actually performed on a large display, there was not any.

Decreasing the width of bezels and making them thin is costly for a LC display. Our study addresses the following question<sup>1</sup>:

1. *How worthwhile is it to invest in eliminating bezel?* The results show that it is not worthwhile to invest in eliminating bezels. It is clear that participants were not impacted by the bezel interference. There is hardly any viable and cheap option available other than tiling monitors.
2. *In an situation in which a large display is needed by humans to perform a task with images, does the presence of bezels affect the users' performance of the task?* The results show that in the above situation, the participants' performance was not affected by presence of bezels. Feedback from the participants show that they were

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<sup>1</sup>All the conclusions that we made are very specific to the visual search puzzle solving task and we have not considered tiled, beveled display which might require more cognitive or physical effort by the user

trying to keep the image away from bezels but in the quantification of the results, we did not find any effect of bezel width or the number of bezels on the participant's performance.

3. *How does the number of bezels affect the users' performance?* The results show that the users' performance was not affected by number of bezels. As we increased the number of bezels, the participants seemed to be more comfortable. This is because they could segregate their work space on the display. In the experiments, they were able to separate the pictures, place it on different screens and then merge them later to solve the puzzle. Manufacturers of large displays can take an advantage of the results, because more the bezels the lower the cost of production.
4. *How does the width of the bezels affect the users' performance?* The results show that bezel width did not affect participants' performance. We know that the bezels are unpleasing and a LC displays with very thin bezel is the expensive display of one of its kind. From the analysis in Section 4, the choice is clear. Even if bezels were unpleasing, they did not interfere in participants' task performance. Choose the cheaper method of tiling monitors.
5. *Which implementation of a grid of displays is better from the users' viewpoint: LCD or projection?* The results show that a LC display was better than a projector display, keeping contrast, brightness, resolution constant. We did analysis using the displays without bezel. In the experiment, participants were more comfortable with a LC display than with a projector display. We noticed that participants were more concerned about the aesthetics of the display, such as display quality, that it should not give off too much light and colour contrast ratio. As they were standing at a distance of approximately 40 cm from the display, the above factors were expected to come into play.

Based on our findings, we suggest the following :

- Bezel width and the number of bezels do not affect a user's performance in a visual-search task.
- An LC display is better than a projector display in a visual-search task.

Eight-three percent of the participants felt that the puzzle solving task was involving and fun at the same time. This matched up with the motivation for choosing puzzles as a visual search task. A major issue observed during the task was dragging a piece of the

puzzle from one end to another with a bezel in between. Almost 96% of the participants managed this issue by slowly dragging the puzzle piece without any loss of contact. The background of the screen was chosen such that there was a contrast between the puzzle colours and the background. However, two of the participants were not able to focus because of the high contrast. Seventy-two percent of the participants started the tasks from the top left corner of screen. About 64% of the participants tried to segregate the task when they saw bezels. About 28% of the participants said that bezels did not help them much. Only 8% of the participants said that they did not notice any bezels. We quote user statements as recorded during our tasks:

- User 3: *“I found that there is a small effect of this black line in my task but I completed the given task on time”*
- User 22: *“It’s normal for me because I worked on this type of display before. I didn’t know you were focusing on bezel. For me its was just a task no bezel nothing”*
- User 13: *“More focused on hand movement and body movement, I did not think about seam at all”*
- User 7 : *“I did not notice the width of task varying”*
- User 8 : *“It helped me in segregation. I was trying to bring pieces to center”*

Participants had mixed opinions about bezel and their performance. We gathered quantitative evidence to prove that bezels have no effect in task performance. This study contributes to other researchers who wish to understand this field and develop software and hardware and also to build assumptions based on our research. In addition to the above mentioned questions, there are several other issues and addressing them here is beyond the scope of this research<sup>2</sup>

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- touch input:
  1. Tiling monitors and present a unified touch surface to the operating system.
  2. Tiling projectors and present a unified touch surface to the operating system.

We did not measure how hard or easy to assemble the above two configurations.

- pixel density: The tiled monitors may provide much higher pixel density at a lower cost than the projected displays. If the size of display is fixed and resolution is increased by increasing pixel density, then there is a point after which the visual acuity simply cannot make use of increased resolution

# Chapter 6

## Future Work

By conducting two experiments in a controlled environment, we concluded that bezel width does not affect a user's performance in a visual-search task. However, this result is only a first step towards understanding the interaction of bezels with user performance. We need more experiments under different settings to generalize these results to a broader context. For instance, parameters such as the resolution of the displays and nature of the task, were fixed during the experiment. One direction for future work can be to vary these parameters and observe their effect on participants' performance. We can extend the research by using a magnitude-judgement task or a virtual-navigation task instead of a visual-search task and examine the effect of bezels on user performance in these tasks.

While we compared a LC display and a projector display, we set brightness, colour, contrast, resolution as constant. To generalize which display is better in terms of user performance, we should vary one factor while keeping the others constant.

Another important aspect one can think of is to synthesis the result of this study and to use in various other task such as video, reading, games, writing, among others. These results can be extended by including participants of varying height, age, and hand dexterity.

We conducted an analysis on the number of bezels. Our experiments had up to four bezels in each direction. Future research can use better resolution displays to examine the effect of number of bezels in more depth. We expect that in the near future, advances in display technology is going to drive down the cost of displays even further. This research aims to provide guidelines to design software and hardware within an affordable range and contribute to the human-computer interaction community and demonstrate the importance of large display with bezels.

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