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Performance and interaction behaviour during visual search on large, high-resolution displays

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Abstract

Large, high-resolution displays (LHRDs) allow orders of magnitude more data to be visualized at a time than ordinary computer displays. Previous research is inconclusive about the circumstances under which LHRDs are beneficial and lacks behavioural data to explain inconsistencies in the findings. We conducted an experiment in which participants searched maps for densely or sparsely distributed targets, using 2 million pixel (0.4m × 0.3m), 12 million pixel (1.3m × 0.7m) and 54 million pixel displays (3.0m × 1.3m). Display resolution did not affect the speed at which dense targets were found, but participants found sparse targets in easily identifiable regions of interest 30% faster with the 54-million pixel display than with the other displays. This was because of the speed advantage conferred by physical navigation and the fact that the whole dataset fitted onto the 54-million pixel display. Contrary to expectations, participants found targets at a similar speed and interacted in a similar manner (mostly short panning movements) with the 2- and 12-million pixel displays even though the latter provided more opportunity for physical navigation, though this may have been because panning used velocity-based control. We are applying these findings to the design of a virtual microscope for the diagnosis of diseases such as cancer.

Keywords

Large high-resolution displays, gigapixel images, interaction behaviour, physical navigation, visual search, histopathology

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Introduction

Large, high-resolution displays (LHRDs) are typically constructed from a matrix of ordinary computer displays, providing an overall display that is the physical size of the one that is produced by a classroom projector, but with a resolution that is orders of magnitude greater. This means LHRDs have great potential for large-scale data visualization[1], and example applications have been developed for domains such as the earth sciences[2], engineering[3], astronomy[4], national security[5] and medicine[6].

Our interest centres on the possibility of histopathologists using LHRDs to diagnose diseases such as cancer. Histopathology is the science of diagnosing diseases by examining thin sections of tissue, which histopathologists perform by sectioning the tissue onto glass slides and examining the tissue under a microscope. Histopathologists navigate a slide by changing microscope lenses to zoom and turning knobs on the microscope stage to pan. Microscope navigation resembles 'virtual' navigation on a computer (navigating with an interface device such as a keyboard, mouse or gamepad) because lens changes are discrete like pressing a key, and turning the knob on a stage is similar to using a mouse scroll wheel (indeed some stages are motorized). Glass microscope slides can be digitally scanned to show the cellular detail that is necessary for diagnosis, but the resulting images are extremely large (up to 180,000 × 100,000 pixels for standard-sized (75 × 25 mm) glass that is scanned at 400× magnification). The process is high-volume (in our region's cancer centre the 39 consultants inspect 250,000 slides per year[7]) and virtual slides have the potential to make it more efficient by streamlining workflows and avoiding the need to physically transport glass slides to another hospital to obtain specialist second opinions[8, 9]. However, one show-stopper that currently prevents histopathology from 'going digital' is that histopathologists take substantially longer to make a diagnosis from a virtual slide than with a glass slide[10]. One key reason for this is that a computer display would need to contain at least seven million pixels (and possibly more) to show the same amount of tissue in the same detail as a conventional microscope[11].

This paper describes an experiment that investigated how display resolution affects participants' ability to find target objects in large images. The experiment was conducted to help determine the resolution that is needed if virtual microscopes are to be used effectively in histopathology. However, the targets were places of worship on maps (see Figure 1) rather than histological specimens, so that non-specialists (university students) could participate instead of the experiment requiring hospital consultants. The targets were either densely distributed or in easily identifiable regions of interest, mimicking the characteristics of two common types of histopathology case (see *Experiment*), and compared 2 vs. 12 vs.

54 million pixel displays. These display resolutions were chosen because one screen on our display wall is 2 million pixels, the whole display wall is 54 million pixels (28 screens), and 12 million pixels is approximately half way between the other resolutions and occupies a whole number of screens (6 screens). The following sections summarise previous research into the benefits of LHRDs for different types of visualization task, and then reports the experiment.

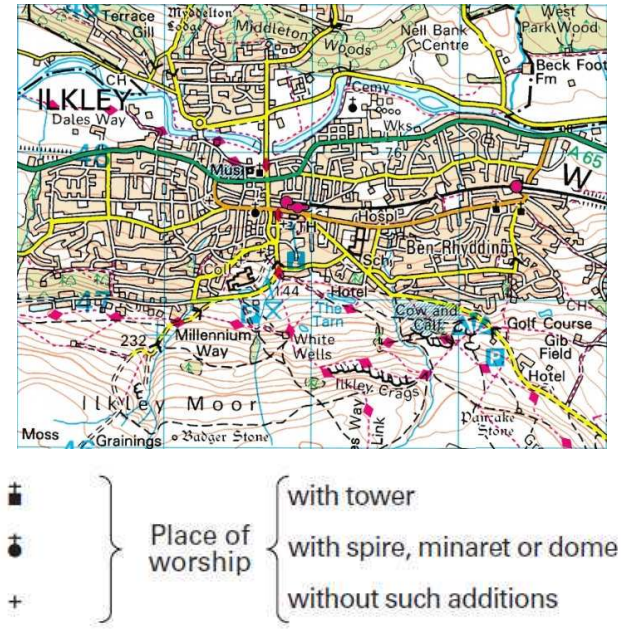

Figure 1. A 4 × 3 kilometre extract of a 1:50000 Ordnance Survey map with 10 places of worship marked. The map legend shows the three symbols that are used for places of worship. © Crown Copyright ED 100018888.

Large high-resolution displays

Compared with an ordinary computer display, the extra resolution of LHRDs can be used to show more data, levels of detail, abstractions, and/or stages of analysis[12]. Rather than always having to virtually navigate with an interface device, a key advantage of LHRDs is that users can exploit 'physical' navigation (moving their head or body) to find and compare data[13]. With workstation-based LHRDs (e.g., a 6-screen matrix of 30-inch monitors; 31 megapixels) this physical navigation involves head movements, whereas on display walls physical navigation involves body movements as well.

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Three broad categories of visualization tasks are finding, following, and comparing information. Finding involves locating a feature or pattern, following involves moving along a feature (e.g., from one end of a road to another), and comparing involves identifying similarities or differences between two or more features/patterns[14]. Studies that investigated the effect of display resolution on users' performance in these types of task are summarized in Table 1. The sometimes contrasting findings of these studies and theoretical benefits of LHRDs are discussed below. As well as display resolution, other factors that affect performance include the interaction devices and techniques that participants use, the scale of the data, the number and distribution of interesting features, and the details of the tasks that participants perform. The studies below do not report sufficient information for a complete assessment to be made about these factors, but some key details are noted.

Study	Display resolution(s) / megapixels	Dataset	Tasks
Ball et al. (2007)[13]	4, 8, 12, 16, 20, 24 & 31	Housing data superimposed on 131 megapixel map	Find, compare
Ball & North (2008)[15]	2 & 96	Housing data superimposed on map	Find, compare
Shupp et al. (2009)[16]	1, 16 & 31	Satellite imagery	Find, compare, follow
Yang et al. (2010)[17]	2 & 96	64 page document	Find, compare
Jakobsen & Hornbæk (2011)[14]	0.2, 1.5 & 14	17280 x 7200 pixel map	Find, compare, follow
Yost et al. (2007)[18]	2, 8 & 31	Abstract information	Find, compare
Singh et al. (2011)[5]	25	Cyber-security data	Find, compare
Anslow et al. (2010)[19]	49	3000 × 9000 pixel images of software structure	Find, compare

Table 1. Studies that have investigated the effect of display resolution on users' performance. Every study used displays constructed from LCD computer screens.

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For finding tasks LHRDs may be advantageous in two main ways. First, if highly salient information is being sought then displaying more data increases the likelihood that the information concerned will be within the display's bounds and, therefore, is seen to visually 'pop out' without the display having to be systematically searched. That was the case in a subjective study where participants commented on the way that a 49 megapixel display let interesting features stand out at a glance of an eye[19]. Second, the greater a display's resolution the faster that users will be able to dismiss uninteresting parts of a dataset, and focus their efforts on regions of interest, again without having to make a detailed search of the whole display.

A generally reported result is that participants find targets significantly faster as the display resolution increases, but the details of specific studies' results are worthy of comment. In some studies[13, 15] participants panned and zoomed to find any one of several targets on a map that matched certain criteria (e.g., a house within a certain price range). At full resolution the map contained 20 – 27 houses/megapixel, but the percentage of houses that matched the criteria is not reported. The time that participants took decreased steadily as the display resolution increased, and it was on this basis that the advantage of physical navigation compared with virtual navigation was highlighted,. In another study participants searched satellite imagery for a unique target. A significant difference only occurred when the target was salient, and was caused by participants taking more than twice as long with a 1 megapixel display compared with 16 or 31 megapixel displays[16]. When the targets were less salient participants failed to complete 26% of the trials and there was no significant difference between displays. Thus, the evidence suggests that LHRDs may only be advantageous for finding when targets are salient and, therefore, straightforward to find. It is also worth noting that studies which did not find significant differences either involved a text (rather than graphical) dataset[17], or required participants to pan and zoom to an indicated target rather than find an unknown one[14].

In principle at least, following tasks are likely to benefit from LHRDs because in some circumstances both the start and end point fit within the increased display resolution, and in others fewer steps are required to navigate from start to end. In one study participants had to follow a road that fitted within the highest resolution display (14 megapixels) but not a lower resolution (1.5 megapixel) display that was tested. Despite this, there was no significant difference in participants' performance, and only with a very low resolution display (0.2 megapixel) did participants take significantly longer to complete the task[14]. In another study participants marked under/overpasses along a road that covered a distance

that was three times larger than the width of the highest-resolution display[16]. When the road was salient participants performed significantly faster with a 31 megapixel display than with a 16 megapixel display, but performance with a 1 megapixel display was, surprisingly, in-between. When the road was less salient and required close inspection, participants failed to complete the task in almost half the trials, irrespective of the display resolution. In other words and contrary to expectations, neither of these studies shows that a high-resolution display is advantageous for following tasks compared with an ordinary desktop display.

For comparison tasks the increased resolution may reduce the cognitive effort that is involved because comparisons can be made with small, rapid physical movements of a user's head or body, rather than requiring virtual navigation. Despite this, most studies reported non-significant differences[13, 14, 16, 17], and in only one study did participants complete comparison tasks faster as the display size increased[15]. The nature of the comparison varied. One study allowed participants to move pages of a document together to facilitate comparison[17]. Other studies' all involved attributes of houses (e.g., price or number of bedrooms), and the tasks ranged from involving a direct comparison of three houses[14], to identifying localised patterns[15] and global patterns among many houses[13]. Additional studies that employed comparison tasks had different aims. One increased the quantity of abstract data in proportion to the display size to investigate the scalability of visual encoding, which meant that task performance times cannot be directly compared[18]. A second gathered subjective feedback that highlighted the potential benefit of LHRDs for helping users refer back to previous steps during extended sessions of visual cybersecurity data analysis[5].

In the following experiment, participants used different resolutions of display to search for targets. The display resolutions (2 vs. 12 vs. 54 million pixels) covered a range that is comparable with most of the above studies. Like several of the above studies[13-15], the datasets were maps but the targets were places of worship (see Figure 1) rather than houses with attributes such as price and number of bedrooms. Like previous studies, participants navigated virtually and/or physically, depending on the display resolution[13-16], but our participants only performed 'finding' tasks, and did not have to compare data or follow paths. The primary contribution of our experiment is detailed behavioral data that explain the performance differences that were observed, and help to explain inconsistencies in previous studies' findings.

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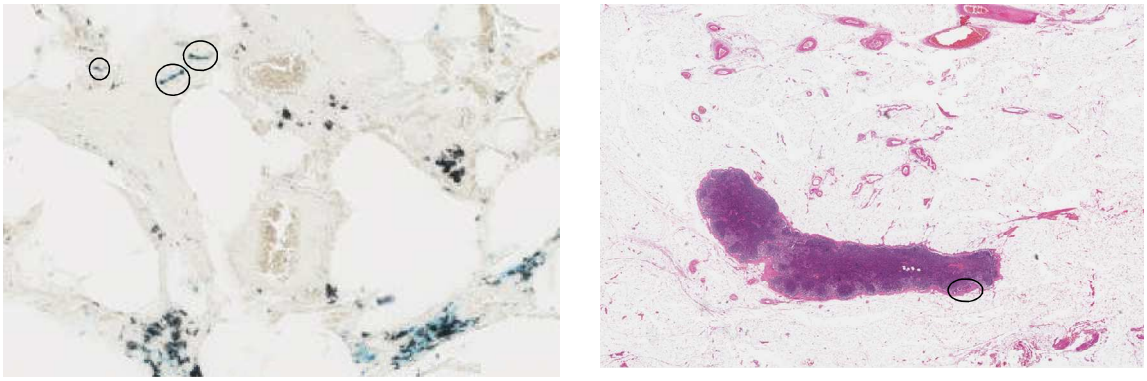
Experiment

The experiment used a within-participants design to investigate the effect of display resolution (2 vs. 12 vs. 54 million pixels) on participants' ability to find targets under two distinct sets of circumstances. These were when targets were: (a) densely distributed (exhaustive search required), or (b) in easily identifiable regions of interest. The targets were places of worship on maps, but the circumstances have similarities with common types of histopathology case. The dense circumstance occurs when histopathologists look for asbestos particles on a lung biopsy (see Figure 2a), conducting a comprehensive search using a lawnmower pattern (searching systematically in adjacent strips) because it is not possible to predict where on a slide the particles are likely to be. On the other hand, when searching a lymph node for metastatic cancer (a cancer that has spread from another place in the body) a histopathologist typically identifies regions of interest at a medium magnification (see Figure 2b), and then inspects those regions at a high magnification to confirm or deny the presence of cancer. A hematoxylin and eosin (H&E) stain (the most widely used chemical stain in medical diagnosis) marks both normal and cancerous tissue pink/purple, but the cancerous tissue has a different texture.



(a) (b)

Figure 2. Extracts from histopathology slides: (a) three asbestos particles (circled; typically 20 – 50 microns long) at 40× magnification, and (b) region of interest (circled; 1.1 × 0.1 mm in size) in a lymph node at 5× magnification.

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Our hypothesis was that, as identifiable regions of interest became more apparent, participants would find targets faster with increased display resolutions. In other words, there would be a significant target density × display resolution interaction for the time participants took to find targets.

Method

Participants. Thirteen individuals (11 men; 2 women) with a mean age of 31 years (SD = 13.9) took part, one being a replacement for a participant who missed a large percentage of targets (see *Results*). All the participants gave informed consent and were paid for their participation. The study was approved by the Faculty Ethics Committee.

Materials. The experiment was carried out on a display wall that consisted of 28 DELL 20-inch monitors, driven by a cluster of 7 PCs (see Figure 3). The PCs all ran the CentOS 5 Linux operating system. The map data used during the experiment was stored on a server and accessed via a gigabit network.

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Figure 3. An Ordnance Survey map shown on the display wall used in the experiment. © Crown Copyright ED 100018888.

Three display conditions were used during the experiment: 28 screens (the whole display; 11,200 × 4,800 pixels; 54 million pixels in total; display dimensions 3.0m × 1.3m), six screens at the centre of the display (4,800 × 2,400 pixels; 12 million pixels in total; 1.3m × 0.7m), and a single screen at the centre of the display (1,600 × 1,200 pixels; 2 million pixels in total; 0.4m × 0.3m). All three display conditions required participants to stand. In the 2 and 12 megapixel conditions the map needed to be panned on the display (see below). In the 54 megapixel condition the whole map was shown at once on the display and panning was disabled so that participants had to use a physical navigation strategy.

Eight maps of regions of UK were extracted from digital 1:50,000 scale Ordnance Survey data. Each map was 11,200 × 4,800 pixels (the same resolution as the 54 megapixel display), and covered a 56 × 24 kilometre area that was primarily land (lakes were permitted, seas were not). Four of the maps were densely populated with places of worship, and four were sparsely populated with places of worship and contained few roads (see Table 2). On all the maps, the places of worship were located alongside roads. The locations of the places of worship were recorded in a text file prior to the commencement of the experiment. One dense and one sparse map were used for training, and the other three maps of each type were used during the test phase of the experiment. From here onward, places of worship are termed *targets*.

Participants were tracked using an Ascension Flock of Birds (Ascension Technology Corporation, Milton, VT, USA) with two sensors. One of the sensors was attached to a head band that participants' wore to track their position and orientation in 3D space, so the part of the display they looked at could be determined.

Map type	**National Grid square**		**Number of places of worship**
	Bottom left	**Top right**	
Sparse	NC 9811	NC 4232	4
	NN 2346	NN 7046	6
	NG 8940	NH 4564	8
	NC 6938	ND 2562	8
Dense	SO 4960	SN 9384	134

	TL 6187	TG 1711	214
	SO 1183	SJ 6707	161
	SN 1222	SN 4668	220

Table 2. Location of each map within the UK National Grid (for a detailed explanation, see[20]), and the number of places of worship on each map. The first sparse and dense maps in the table were used for training.

The second sensor was mounted within a Virtual Presence 3D mouse (see Figure 4), which had a thumb-operated joystick, a trigger, and three buttons. In the 2 and 12 megapixel display conditions, participants could pan the map at a fixed speed of 1000 pixels/second by moving the joystick to the left, right, up or down. Movement of the 3D mouse controlled a 60 pixel diameter, 50% transparent, red "aiming" disk on the display (see Figure 5), which participants used to indicate the target locations on the map. When participants pressed the 3D mouse trigger a marker of the same size and colour as the "aiming" disk was placed on the map. One of the 3D mouse buttons acted as a clutch, to allow the participants to adjust the offset between the 3D mouse's physical position and the aiming disk. This avoided participants having to stretch to reach targets at the extremes of the display and allowed participants to compensate for any tracking drift that occurred. Another button reset the offset. The experimenter remained present throughout the experiment to monitor the attachment of the tracking sensors.

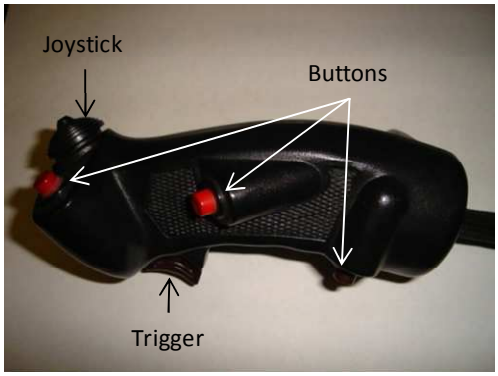

Figure 4. The 3D mouse. Position and orientation were tracked by an Ascension Bird sensor contained within the mouse.

Figure 5. The red aiming disk positioned on top of one of the targets.

Procedure. Each participant first performed the experiment with one display condition (e.g., 2 megapixels), then a second (e.g., 12 megapixels) and then the third (e.g., 54 megapixels). For each display condition, the participant performed some training and then conducted two test trials (sparse then dense, or dense then sparse). A Latin square design was used to balance the order in which participants performed the three display conditions and target densities (sparse vs. dense), and the particular map that a participant used with a given display condition. Participants took a five minute break after the training and test trials with each display condition, and took an average of three hours to complete the whole experiment.

The training for each display condition was as follows. First, a participant was shown the controls to be used for the display. Then the participant searched a quarter of the sparse training map and a quarter of the dense training map for targets. A different quarter was used for each display condition. The participant was told the strategy that they should use, which with sparse maps was to find the roads and search along them to identify the targets, and on dense maps was to conduct an exhaustive search of the map by examining each grid square (200 × 200 pixels on the display) in turn. After searching each training map the 54 megapixel display was used to show participants the targets they had successfully found (circled in green), had missed (black) and places they had selected that were not near a target (red).

There was no time limit for the test trials, which stopped when a participant said that they had completed the task. During each test trial a log file was recorded at 60 Hz for subsequent analysis. The log file contained data relating to the position of the map on the display, time elapsed since the start of the trial, button presses, and Flock of Birds position/orientation data from both sensors.

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Results

The results are divided into two parts. First we report participants' performance in terms of accuracy and time in the three sparse and three dense test trials that each participant conducted. Then for the sparse trials we report participants' interaction behaviour, to explain the underlying causes of significant differences in the performance data.

Accuracy and time. The following procedure was used to determine the number of targets that a participant correctly identified during a trial. Software was written to render the map on the 54 megapixel display, with markers superimposed on the map to indicate every target and the centre of the aiming disk each time the 3D mouse trigger was pressed. Due to the locations of the targets, sometimes the trigger position was close to just one target, whereas on other occasions there was a cluster of targets and trigger positions (typically the same number of trigger positions as targets). Through a partly automated process, trigger positions were allocated to targets provided the distance between the target and the trigger position was within a 200 pixel threshold. This left a total of only 20 'false' trigger positions across the 39 test trials, compared with 6901 that were matched to a specific target. Four of the false trigger positions occurred in one trial when the participant selected large cross-shaped symbols that were not targets.

One participant missed more than 30% of targets on four of the six test trials, and was replaced in the experiment. The remainder of the Results only report data for the 12 participants who were retained. Those participants found an average of 87% of targets in the dense trials (SD = 9.4%) and an average of 89% in the sparse trials (SD = 13.0%). Most of the missed targets were of the type that had no tower, spire, minaret or dome (see Figure 1).

The percentage of targets that participants successfully found was analysed using an analysis of variance (ANOVA) that treated the display (2 vs. 12 vs. 54 megapixels) and target density (sparse vs. dense) as repeated measures. This showed no significant difference between the displays, $F(2, 22) = 1.27$, $p > .05$, $\eta_p^2 = .10$, or target densities, $F(1, 11) = 1.30$, $p > .05$, $\eta_p^2 = .10$. Means for the dense targets were 90%, 85% and 86% (2, 12 and 54 megapixel displays, respectively), and for the sparse targets were 88%, 86% and 93% (2, 12 and 54 megapixel displays, respectively).

Across all the display conditions, participants took an average of 34.8 minutes (SD = 10.6) to complete a dense trial, and 6.5 minutes (SD = 2.4) to complete a sparse trial. Clearly, the greater the number of targets that were found the longer a trial is likely to have taken. Two ways of adjusting for this are to: (a) take account of the percentage of targets that were found (divide the trial time by the percentage of successes), or (b) calculate the time per

target (divide the trial time by the number of targets found). The former is sensitive to differences between the numbers of targets that were on the maps, whereas the latter does not directly take account of the distribution of the targets across a display (participants are 'rewarded' more for finding a cluster of targets than a single outlying target). Data for both methods were analysed using an ANOVA that treated the display (2 vs. 12 vs. 54 megapixels) and target density (sparse vs. dense) as repeated measures. The pattern of results was the same for both methods, so only method (b) is reported here. Means for the dense targets were 12.5, 10.7 and 13.9 seconds (2, 12 and 54 megapixel displays, respectively), and for the sparse targets were 69.9, 69.6 and 49.1 seconds (2, 12 and 54 megapixel displays, respectively). There was not a significant difference between the displays, $F(2, 22) = 3.08$, $p > .05$, $\eta_p^2 = .22$, but there was a significant effect of density, $F(1, 11) = 66.80$, $p < .001$, $\eta_p^2 = .86$, and a significant display × density interaction, $F(2, 22) = 3.65$, $p < .05$, $\eta_p^2 = .25$. This was caused by participants taking substantially less time to find targets on the 54 megapixel display than on the other displays (see Figure 6), which was partially consistent with our hypothesis (to be fully consistent, the 12 megapixel display time should have been faster than the 2 megapixel display time but slower than the 54 megapixel display time).

Interaction behaviour in sparse trials. A distinguishing feature of the 54 megapixel condition was that participants did not virtually navigate, whereas in the 2 and 12 megapixel conditions they did. To investigate how this could account for the similar performance in the 2 and 12 megapixel conditions, and step change improvement in the 54 megapixel condition, we analysed participants' interaction behaviour in the sparse trials.

As the display resolution increased more of the map was visible, which we expected to reduce the time that participants took to identify regions they needed to closely inspect and, therefore, to find targets faster. This was investigated by using the following method to calculate heat maps of where participants gazed. The head sensor position and orientation data in each log file record were used to project a participant's gaze onto the plane of the display, which was divided into 200x200 pixel cells (equivalent to a 1km grid square on the map) that stored cumulative gaze time. The cells were treated as point masses, with mass equal to the cumulative duration of the gazes that fell within that cell, and entered into a centre of gravity calculation that was then used to find the display-sized region that contained the maximum amount of gaze time. Gazes outside the bounds of the display (2, 12 or 54 megapixels) were then culled. The remaining gazes (an average of 89% of the trial time) were then integrated with the joystick panning data to calculate where on a map (rather than just the display) participants looked. The distribution of the heat map data was

similar for all three display conditions (see Figure 7), indicating that participants were able to dismiss large areas of the map with a small (2 megapixels) display as quickly as they could on the large (54 megapixels) display. In other words, although participants did find targets faster with the 54 megapixel display, the underlying reason was contrary to our expectation.

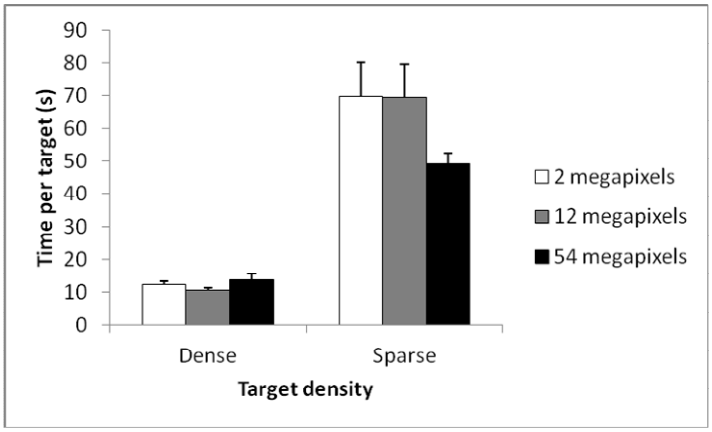

Figure 6. Average time taken to find each target. Error bars show the standard error of the mean.

An alternative explanation was that the need to virtually pan the map caused participants to detect targets slower with the 2 and 12 megapixel displays than with the 54 megapixel display. Comparison of the time during which the map was stationary vs. being panned supports this explanation, because the panning time accounts for half of the difference between the 12 and 54 megapixel displays and all of the difference between the 2 and 54 megapixel displays (see Table 3).

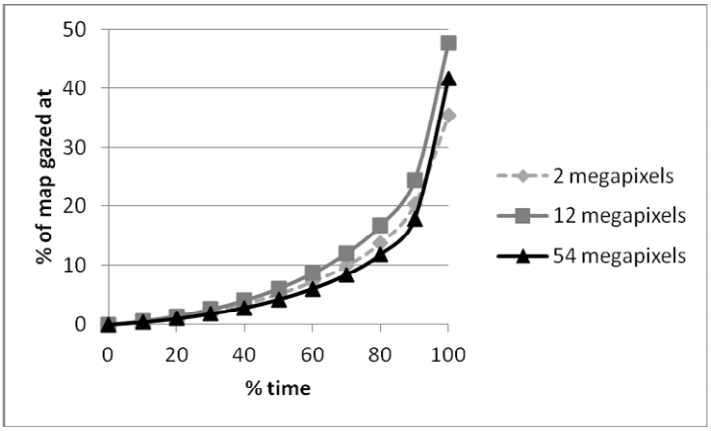

Figure 7. Percentage of a sparse target map that participants had gazed at as a test trial progressed.

Display resolution (megapixels)	Mean trial time (expressed as % of 54 megapixel mean)	Mean % of trial spent panning the map
2	127	26.1
12	125	12.7
54	100	-

Table 3. Trial time and % time spent panning (sparse trials only). The 54 megapixel trials took an average for 333 seconds.

Finally, to investigate the similarity in the rate at which targets were found with the 2 and 12 megapixel display we analysed the duration of each pan and the periods between pans when the map was stationary on the display. The majority of panning movements took less than 0.5 seconds (see Figure 8), indicating that even with the 12 megapixel display participants made many small movements rather than larger, occasional movements. This was consistent with anecdotal observations made by the experimenter, and confirmed by the analysis of panning distance data, which showed that with the 2 and 12 megapixel displays 75% of pans were less than 500 pixels (the maximum distance the map could be panned in 0.5 s) and 92% of pans were less than 1600 pixels (the width of one monitor). The periods between pans (i.e., when the map was stationary) were equally split between

brief intervals (< 0.5s) and longer periods (> 2.0s), with similar distributions for the 2 and 12 megapixel displays (see Figure 9). Therefore, our explanation of the similarity between participants' behaviour with the 2 and 12 megapixel displays is as follows. If participants made large pans with the 12 megapixel display then they would have to search the whole display each time it was stationary and, after the next pan, physically move to reposition their gaze from one corner of the display to the opposite corner. However, by making small pans participants reduced to a minimum the physical movements that they had to make.

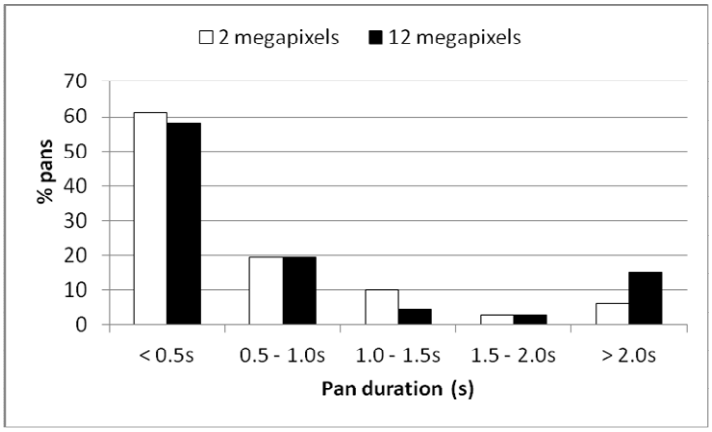

Figure 8. Histogram of the pan durations during the sparse trials.

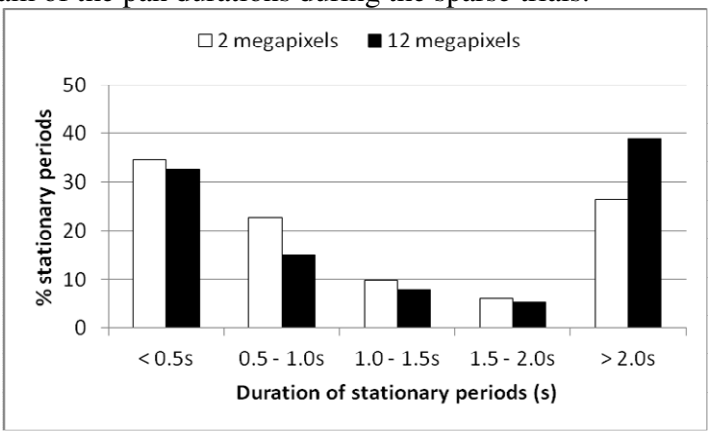

Figure 9. Histogram of the durations of the periods between panning movements in the sparse trials, when the map was stationary.

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Discussion

The most important finding of the experiment was the step change reduction in the time participants took to find sparse targets with the 54 megapixel display compared with the other display configurations, and the behavioural data that provides an explanation for this finding. Previous studies where participants had to find targets in unknown positions showed either a gradual decrease in search time as display resolution increased[13, 15] or a step change improvement at a much lower resolution (between 1 and 16 megapixels)[16]. These studies and ours all used geographic data (maps or satellite imagery), but differed in terms of the target density, target saliency, nature of the finding task that participants performed, and the navigation interfaces.

In the study by Shupp et al.[16], participants were asked to find salient and non-salient targets. Participants took 3 – 6 times longer to find salient targets with a 1 megapixel display than 16 or 31 megapixel displays. The reason for this may have been that participants had to search systematically with the 1 megapixel display, but the other displays' resolutions meant that participants were almost guaranteed to see the target after making a few panning and zooming movements. In other words, it is likely that the 16 and 31 megapixel displays were well-suited to the task, but the 1 megapixel display was not. The non-salient targets are likely to have required participants to search systematically irrespective of the display resolution, as with the dense targets in the present study, but participants failed to complete 26% of the trials. This may have been because the five minute time limit was not sufficient.

In Ball's studies[13, 15] participants performed some virtual panning and zooming, as well as physically navigating, even with the highest resolution display. A high target density (20 – 27 houses per megapixel) was accommodated by using semantic zooming to vary how the attributes of the targets were displayed (e.g., bar chart vs. text). Given that participants only had to find one of several targets that matched a given criterion, this semantic zooming is likely to have helped participants to concentrate on the parts of the dataset that were most likely to contain a target, and those parts became progressively faster to identify as the display resolution increased. It should also be noted that caution needs to be taken when interpreting these two studies' findings because, although the data (e.g., mean times) that are provided support the findings, the statistical analyses appear to be flawed (the degrees of freedom are far too large for the studies' designs).

The present study was different to the above ones because participants only panned the dataset (virtually or physically), rather than panning and zooming. The advantage of the 54 megapixel display stemmed from the fact that physical navigation is faster than virtual navigation, evidenced by the difference between that display (virtual navigation disabled)

and the 2 megapixel display (too small to involve physical navigation). The lack of a difference between the 2 and 12 megapixel configurations may have been caused by the type of virtual navigation interface we implemented. This interface used velocity-based control (joystick movement controlled the speed of panning, rather than the distance panned), so it took three times longer to pan across the whole 12 megapixel display than across the 2 megapixel display. This is one reason why 92% of participants' panning movements were less than the width of a screen (1600 pixels). If as in previous studies[13, 15] the panning interface had used displacement-based control (like the virtual hand on Google maps), then participants could have made large pans quickly, which may have reduced the time required to find targets with the 12 megapixel display.

Conclusions

The above behavioural differences highlight a special class of visualization problem, where it is feasible to use a display with the resolution to show the entire dataset in detail at once. LHRDs promise clear benefits for this class of problem, because of the speed and precision with which users can navigate physically. When the whole dataset can be displayed at once the problem is reduced to visualizing a space that in spatial cognition is termed *small-scale*[21], as opposed to *large-scale* spaces that have to be travelled through (panned or zoomed) to be viewed in their entirety. It is well-known that people learn spatial layouts much faster from small-scale representations than large-scale representations[22], and physical navigation greatly improves efficiency when people search room-sized (small-scale) spaces[23].

For larger datasets, LHRDs have proved beneficial when semantic zooming was provided[13, 15]. Greater benefit is expected when items of data need to be compared rather than just found or multiple abstractions of data need to be displayed, but experimental evidence to support these predicted benefits is currently lacking.

Finally, we return to histopathology. Histopathology virtual slides are extremely large – up to 18 gigapixels, which far exceeds the resolution of any computer display. At any moment, a user will only see a small amount of a slide in detail, a situation that is more similar to the 2 and 12 megapixel configurations used in the present experiment than the 54 megapixel configuration. To make a diagnosis, histopathologists navigate from one part of a slide to another, making many small panning actions. Sometimes the histopathologists' path is systematic (e.g., a lawnmower pattern), but more often it is informed by tissue features. Some parts are viewed at increased magnification but, apart from that, each part of a slide is typically inspected no more than once. Histopathologists rarely explicitly compare different parts of a slide, so there is limited need for a virtual slide visualization system to leverage

physical navigation. Therefore, a display that provides a seven million pixel detail view (plus additional resolution for an overview(s)) is likely to be sufficient for a virtual microscope, because that provides a similar field to a conventional microscope. As a result, our research has shifted emphasis from the application of display-walls for medical diagnosis[24] to virtual slide interfaces that allow histopathologists to make diagnoses almost as quickly with multi-million pixel workstations as they can with a microscope[25].

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