Redirecting Research in Large-Format Displays for Visualization

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Fig. 1. Texas Advanced Computing Center's Stallion, weighing in at over 300 million pixels, is currently the world's largest display. Image courtesy of Greg Abram, Texas Advanced Computing Center.

Abstract—Large-format displays, in particular tiled displays, remain actively used and researched today after almost two decades since their conception. Many government, academic, and commercial entities have invested considerably in the construction and use of large-format displays. During this time we have developed new applications but have also discovered faulty assumptions. This position paper evaluates the most important lessons learned from early and recent research in large-format displays. Each lesson suggests a direction for future research, which generally takes the form of a more user- and application-centric focus.

Index Terms—tiled display, large-format display.

Display technology is an integral part of any visualization system. It is therefore no surprise that the visualization community has spent over fifteen years designing and exploring displays with larger images and greater pixel counts. Large-format displays are most commonly built by tiling several conventional displays. This technique was pioneered by Paul Woodward when his team demonstrated a 2×2 tiled display (dubbed the *PowerWall*) at Supercomputing '94.[1]

Driven by the needs of the United States Department of Energy's Accelerated Strategic Computing Initiative (ASCI) program [19] and the recommendations of the Data and Visualization Corridors (DVC) Workshop [35], research into tiled displays surged during the late 1990's and early 2000's. During the middle part of this decade, interest in tiled displays waned. But with the advent of supercomputers capable of computation rates in excess of one petaflop, we are once again seeing an uptick in interest in large-format displays.

As a new generation of large-format display research begins, it is important to understand what previous research has taught. To that purpose, this paper provides the following.

- We review some of the most important lessons learned during the previous tiled-display research while describing the research that leads to these conclusions.
- At the end of each lesson we provide a "redirection." That is, we consider the ramifications of the lesson and how the visualization research community must change because of it.

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[1]http://www.lcse.umn.edu/research/powerwall/powerwall.html

Each one of these lessons represents an advance in visualization technology. And as with most scientific and engineering advances, they reshape our understanding of the field and force us to reevaluate our course for exploring the field.

Lesson 1: We Know How To Build Tiled Displays

But it is not as straightforward as we initially thought. In principle, we can build a display of arbitrarily high resolution by using multiple projectors arranged in an array. However, simply tiling a group of projectors inevitably looks like an array of images, not a single contiguous display. Subtle imperfections in projector alignment and color balance, both of which change over time, affords obvious and distracting artifacts in the display as shown in Figure 2. Unifying the projectors requires the proper registration of each tile's projection and the blending of colors over any overlap of images. Although not trivial, we now have methods for the automatic registration and blending of tiled-display projectors, even when projecting on uneven surfaces [30, 31].

Another approach is to construct tiled displays from LCD panels. These thin displays are now relatively cheap and easy to mount. Consequently, tiled displays of LCD panels are cheaper to build and maintain than their projector counterparts. They also take up less space and do not have to be color matched as closely. These features make them easier to scale and consequently all of the existing tiled displays containing more than 100 million pixels (listed in Table 1) are of this type. However, the critical problem with LCD tiles is that their bezels create a discontinuity of the display. Even LCD tiles without bezels leave an inevitable seam between the tiles.

Little is known about how these bezels and seams affect perception although their impact appears minimal. While studying multi-monitor desktops, Tan and Czerwinski [36] find no difference when comparing windows on the same monitor or adjacent monitors, and Grudin [17] reports that users found the bezels helpful in positioning windows. Ball et al. [3] observe that participants use bezels to their advantage to segregate the data into (somewhat arbitrary) portions. McNamara et al. [21] report that seams have little effect even in virtual reality

Table 1. The world's largest tiled displays.

Name	Location	Pixels
Stallion	Texas Advanced Computing Center	307 M
HIPerSpace	Calit2 UC San Diego	266.7 M
hyperwall-2	NASA Ames	256 M
HIPerWall	Calit2 UC Irvine	204.8 M
Varrier	Calit2 UC San Diego	124.8 M
LambdaVision	UIC Electronic Viz Lab	105.6 M

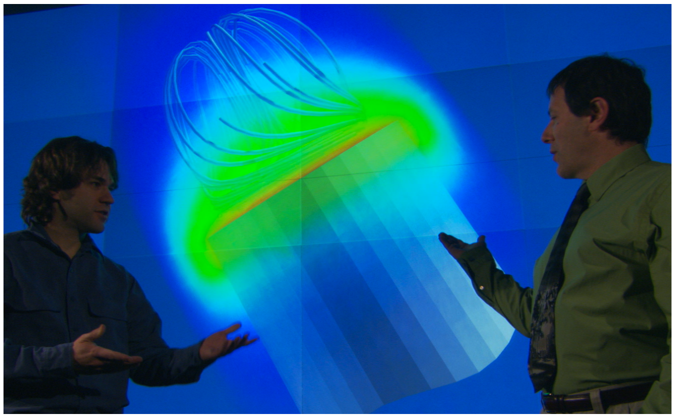

Fig. 2. A rear-projected tiled display at Sandia National Laboratories circa 2002. Despite regular manual tweaking of projector position and color, seams between tiles are still evident.

navigation.

Regardless of the technology composing each of the tiles, a large enough display will require a similar array of graphics hardware to create an image of sufficient resolution. The distributed nature of the graphics hardware presents challenges in driving these displays. Several solutions exist [24]. Some mimic a standard, albeit high resolution, single display whereas other allow applications to be modified to take advantage of the parallel distributed nature of the hardware.

Redirection: It is time for industry to take over.

The details of building, supporting, and driving tiled displays are well known but nontrivial. Repetitively tackling these challenges is an impediment to performing new research. A mutually beneficial approach is to requisition large-format displays from service providers specializing in them.

The improvements to be made in tiled display technology are incremental. Such advances have little impact on the broader field of visualization, but can provide a large competitive advantage to a service provider.

Thankfully, industry has already begun to engage in providing large-format tiled displays. Several commercial entities such as Cyviz, Visbox, HoloVis, Mechdyne, Barco, and Absolut Technologies are already providing turnkey tiled display solutions. Moreover, display components have significantly improved in the last fifteen years. For example, Sony and JVC sell "4K" projectors with a resolution similar to that of Woodward's original PowerWall.

Lesson 2: A Pixel is Not the Same Thing as a Datum

A common, and invalid, assumption is that every discernible pixel is an independent datum for your cognitive reasoning. This rationale presupposes that the human visual system reads light stimulus as a regular grid of color values, which is nonsense as demonstrated in Figure 3. Indeed, there is a great amount of *eccentricity* in the visual field that makes target processing better at the focal point than in the periphery [11]. When looking at a display, particularly a large-format display, a user can focus only on a small part of the screen. The details around this focal point are not assimilated [5].

In essence, a large-format display really behaves as a focus+context presentation to the human observer. Cluttering the display with detail will simply force the observer to narrow his or her focus. In fact, increasing the mental workload reduces the effective visual field [27] and can cause observers to miss highly salient visual stimuli that they are *directly* looking at if not properly aware [33]. Large-format displays aggravate the problem if not used carefully.

Visual acuity, the pixel spacing beyond which humans cannot discern details, is a poor goal for displays with respect to information. A detail at visual acuity is one which a user must struggle to see and which is almost assuredly missed. A desktop display is often viewed with a pixel spacing about twice that of visual acuity. Although denser pixel arrangements may provide a more refined image, it will not appreciably increase the visual information.

Although visual acuity is a useful target for specifications in physical device engineering [40], visual acuity is also sometimes used to infer (inappropriately) the maximum useful resolution of a display. The argument assumes that the user is unable to move his or her head to view more pixels because either the user's head will be clamped in place or, more realistically, the display is mounted directly on the user's head. Exploration and externalization are key components in learning and understanding; large-format displays can help provide both, if used correctly [42].

Redirection: Focus on how to *use* displays.

Compared to the amount of work spent on designing, building, and driving large-format displays, surprisingly little effort is spent in learning how to use them. How a user interacts with a large-format display makes a substantial difference in how effective the display is.

Yost et al. [41, 42] investigate how a large-format display can be used to scale a visualization. They report that it is indeed possible to address larger scale visualization problems with larger displays, even when the pixel count exceeds what can be perceived from a given position. However, the scalability is not uniform among visualization tasks.

User studies of this nature are vital for effectively using tiled displays. Many questions remain unanswered. What classes of visualization problems are best solved using large-format displays, and what are the design principles for designing visualizations on large-format displays? How do these techniques compare to alternate visualizations on smaller displays? Could similar scalability be achieved through interaction techniques?

How the properties of large-format displays change the effectiveness of a visualization are also poorly understood. How do discontinuities in the display impact a visualization, and what techniques can be used to get around the problem? At what point does growing a large-format display cease to be useful? Can we really effectively use all 300 million pixels of TACC's Stallion tiled display (Figure 1)? Is there a "sweet spot" for the size of a display?

Lesson 3: Large-Format Displays Can Impede Interaction

The appeal of large-format displays is that they can potentially increase the data flow from the computer to the human. It is therefore ironic that they tend to simultaneously reduce the data flow from the human to the computer.

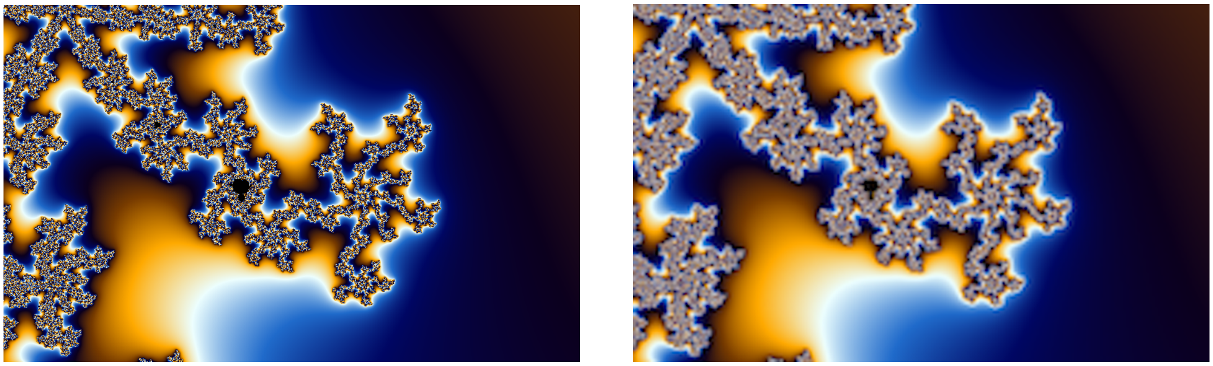

Fig. 3. These two images show the same view of the Mandelbrot data set. Although the image on the right contains only $1/16$ the pixel data as the image on the left, they convey about the same amount of information to a human observer. Although superstructures are easy to discern, details near visual acuity are difficult to distinguish even at the higher pixel density. Image courtesy of Michael Bradshaw.

The combination keyboard-mouse has been the de facto computer input device for decades because they are cheap and still one of the most effective means of controlling a desktop computer. However, using a keyboard and mouse is problematic on a large-format display. Even on a moderately sized display users have problems with the mouse including losing the cursor, accessing far away GUI elements, and managing windows [12, 28].

An even more obvious problem is that these devices generally require a fixed location, which stands in the way of any physical interaction directly with the display. A radio-controlled mouse, tablet computer, or other portable device can be used to untether the user, but these devices do not have as fine of controls as their tethered counterparts, which exacerbates the other interaction problems.

A common solution is to employ virtual-reality pointing mechanisms such as wands or gesture recognition. Although using such a device is effective for navigating 3D spaces and manipulating objects therein, it lacks the versatility for most other tasks. A 3D wand is inadequate for such tasks as selecting a file or writing oneself a note.

Redirection: Design better interaction modes and devices.

Even moderately sized displays necessitate improvements in our most basic computer interactions such as mouse support [4, 28] and window management [8]. However, interaction issues with large-format displays are likely much more systemic. Just as we have found that small-format displays of mobile and tablet devices introduces a paradigm shift in human-computer interaction [2], so should large-format displays induce their own interface paradigm shift.

Andrews et al. [1] give an overview of many interaction challenges facing large-format displays including navigating, linking, selecting, and controlling. Some of these challenges stem from the need to coordinate more data and multiple views. Other challenges are prompted by the physical distance between the user and the items to control.

Implementing any interaction technique is contingent on having the correct physical mechanisms, which is also an active area of research. One basic method is to use a separate device like a tablet, which is essentially the same control paradigm as using a separate laptop or desktop but more portable. Other more direct methods of interaction are being developed including wand-based methods [10, 23, 26] and direct touch or gesture based modes [7, 18, 22, 39].

All of these technologies are in their infancy. Not until we discover appropriate interaction paradigms will large-format displays become truly useful.

Lesson 4: Display Technology is a Means, Not an End

Large-format displays are often touted as solutions for things like collaboration and large-data visualization. Although the technology may be enabling, it is not itself a solution.

Several experiments suggest that a larger display can aid tasks that require a high cognitive load by reducing the cost of switching between contexts [6, 13]. Other experiments show that a wide-format display can improve the understanding of spatial relationships in a virtual 3D environment [37, 38]. It should be noted, however, that none of these experiments scale the display beyond three tiles and that some of the observed effects are attributed more to the user's field of view than the actual size or resolution of the display. It is not known if these improvements will continue to larger displays.

Using a large-format display effectively requires applications and workflows that consider how users will interact with the display and that play to the display's strengths. It is not sufficient to simply move an application from a desktop display to a large-format display. The usage model of the application is unlikely to fit well with the large-format display. For example, Yost et al. [41, 42] observe that "graphical encoding differences were more important on a smaller display with less data, while spatial grouping became more important on a large display with more data."

Redirection: Let the application drive the display, not the other way around.

What types of problems lend themselves well to large-format displays? What types of applications work well on a large-format display? How do each of these benefit from the display and work within the constraints that the display imposes? These questions remain unanswered.

We stumble over these problems because our approach is backwards. For pragmatic reasons we do not consider using a large-format display unless we have one available. Once we have one available, we look for ways in which we can apply it.

Instead, we should consider the problem first. What void exists in the current analysis applications, and how can it be filled? If the limitation is related to the amount of information that can be displayed, what is the best way to correct it? If a larger display is necessary, how does our interaction change and how do we direct the user's attention to salient features?

As we consider larger-format displays, we should also realize that a tiled-display is not the only large-format display; it is simply the largest and most expensive form. For example, a 30 inch LCD display containing four thousand pixels is moderately priced and easy to drive. A high end graphics card can then double the amount of pixels by adding a second 30 inch LCD display. Even larger displays can be prototyped by simply printing posters. Although this type of display is clearly static, it can serve as a helpful tool for prototyping an application that will eventually be dynamic. Simply observing how the display is used provides valuable information and provides a baseline on how the system can be improved.

One practical problem domain that appears to be well suited to large-format displays is that of searching and route finding in maps, which is often used for perceptual studies of large-format displays [3, 6, 32]. To be sure, the natural focus+context of the large-format display makes such queries faster and more accurate than pan+zoom in a traditional display. Of course, most analysis on static maps are just as well suited with the traditional and cheap approach of paper map, acetate overlays, and grease pencils. An electronic large-format display is better suited for map applications requiring much remote collaboration and dynamic landscapes such as that needed for situational awareness in military campaigns [15, 16, 25].

It is reasonable to hypothesize that the natural focus+context of a large-format display could also improve the visualization of more abstract data with similar hierarchies where detail is only significant in relation to its place in the hierarchy. For example, Hibbs et al. [20] find a large-format display useful in analyzing gene expression microarrays by clustering and then displaying heat maps arranged by dendrograms.

Cheap large-format displays in common areas can provide "ambient" information to a collaborating team. Russell et al. [29] describe using such a display to coordinate the work of a system administration team. Biehl et al. [9] have a similar display for the status of a collaborative software development project. In both cases, the large display serves to communicate important information among staff without requiring direct attention to dispatch or garner this information.

Large-format displays may also be used to enhance traditional collaboration workspaces. For example, Guimbretière et al. [18] seek to mimic and enhance how collaborative brainstorming sessions use the physical space (such as tables and walls) to post and organize information. In this environment, a large-format display is critical, and most of the work is in designing the interaction tools for the display.

Singh et al. [34] use a large-format display as part of an integrated system to help cyber security analysts study and organize unstructured documents. The extra size of the display provides focus+context that allows users to externalize their thought process by simultaneously displaying important document content and inter-document relationships, something that otherwise requires physical paper notes. In addition, the large-format display allows the visual interface to be integrated with underlying data foraging algorithms, provides feedback to the analysis algorithms through semantic interaction, and enables visualization researchers to study analysts work patterns to provide better interfaces [14].

CONCLUSION

Research in large-format displays has proceeded for almost two decades. During this time, these displays have become cheaper to construct and easier to drive making the technology of large-format displays accessible to most organizations. As such, research in visualization with large-format displays should switch to a mode where a problem domain drives the acquisition, development, and use with these large-format displays rather than driving problem domains where large-format displays happen to be.

To make an argument by analogy, consider the recent surge in the popularity and use of mobile devices with small-format displays. This surge has as much to do with the careful design of interaction modes and applications that are well suited to and specifically designed for these devices as it has to do with the technology that creates it, much of which has existed for many years.

Similarly, large-format displays necessitate their own natural interaction techniques and their own device-specific software that will look significantly different than those for desktop or mobile devices.

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