

Designing Large High-Resolution Display Workspaces

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ABSTRACT

Large, high-resolution displays have enormous potential to aid in scenarios beyond their current usage. Their current usages are primarily limited to presentations, visualization demonstrations, or conducting experiments. In this paper, we present a new usage for such systems: an everyday workspace. We discuss how seemingly small large-display design decisions can have significant impacts on users' perceptions of these workspaces, and thus the usage of the space. We describe the effects that various physical configurations have on the overall usability and perception of the display. We present conclusions on how to broaden the usage scenarios of large, high-resolution displays to enable frequent and effective usage as everyday workspaces while still allowing transformation to collaborative or presentation spaces.

Categories and Subject Descriptors

H.5.2. User Interfaces.

General Terms

Design, Human Factors.

Keywords

large high-resolution displays.

1. INTRODUCTION

Large, high-resolution displays come in a wide variety based on their physical configuration (i.e. form factor), technology used for construction, and usage [1]. In size, they range from small scale systems such as D-SHARP, which expands the conventional desktop [2] to much larger powerwalls capable of presenting large amounts of information at a high level of detail (Figure 2). Their form factors vary from tabletop displays, to immersive caves, to powerwalls. The computers driving these displays vary from clusters with distributed computational power to single nodes equipped with multiple video cards. The display technology ranges from projectors to LCDs, and usually tiled displays, but larger continuous displays are forthcoming.

Large, high-resolution displays have previously been defined in terms of exceeding traditional physical display size and resolution, increasing the amount of data capable of being displayed, and surpassing visual acuity [3]. Throughout this paper, we will use the definition of surpassing visual acuity, as this is the only definition that relies on a standard reference point. In the

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purest sense, large, high-resolution displays provide a large, continuous virtual space with a homogenous appearance and a high pixel count and density [3]. In practice, these displays may approximate continuity due to current technology constraints such as LCD bezels.

The design of a large, high-resolution display impacts the users' perception of how such a display can be used. The choices made when designing a space should carefully reflect the type of work a user will be able to accomplish. This work can range from presenting information to a large group, where limited interaction is required, to individual tasks where actively interacting with the information is critical to the success of the task.

Traditional CAVE and tabletop displays have reasonably clear, predefined usage scenarios based on their form-factor and design. The metaphors for use of these systems are based on real physical artifacts, making the transition more obvious. For other large, high-resolution displays, the metaphors for use are less obvious. Typically, the metaphors chosen are based on other display technologies: desktop monitors, televisions, and large-scale projections, ranging from conference room scale presentations to IMAX screens. The choice of metaphor ultimately determines how the user perceives the display and how they interact with it (Table 1).

In this paper, we discuss how large, high-resolution displays can be placed into a standard office environment and used by an individual for everyday office and analytic tasks (Figure 1). In this setting, the user can leverage large display benefits such as physical navigation to access information [4], spatial organization of information or tasks [5], etc. This shift from traditional large display usage (e.g. powerwalls, caves, etc.) can be achieved if designed correctly.

We present the scenario for such a display being used for everyday individual analytic work. Then, we discuss how changing seemingly small design decisions regarding the physical presence of the display impacts the users' perception and

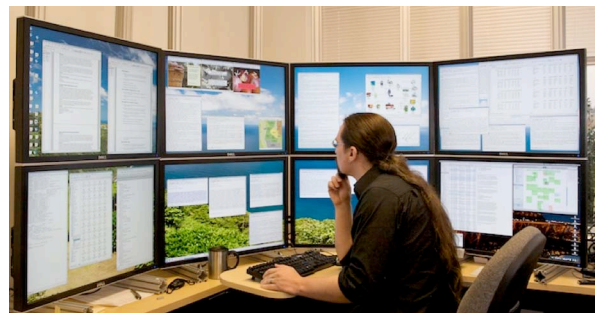


Figure 1 A large, high-resolution display designed for standard productivity tools used for everyday tasks.



Figure 2 The “Gigapixel” powerwall.

behavior. Finally, we discuss the various design implications this has for large, high-resolution displays and their usage.

2. LARGE DISPLAYS

There have been a number of previous studies that explored the role of display characteristics in shaping user perceptions and behavior. Ball et al. looked at how increasing the display size and resolution affected user performance for spatial tasks like route tracing and map comprehension. They found significant performance increases on larger displays as well as a decrease in *virtual navigation* (panning and zooming) with a corresponding increase in *physical navigation* (glancing, head turning, etc.) [6]. Further, the physical navigation of users is dependent on correctly designing the visual encodings of information in visualizations [7].

Shupp et al. demonstrated that the performance characteristics of large displays could be further altered by curving them in towards the user [8]. The curved display further improved performance by making physical navigation more efficient (transforming translations along the display to rotations in place) [9]. More importantly, they showed that curving the display changed the strategies adopted by users (removing bias for the left side of the display) as well as the kinds of insights generated by the users (flat display users tending towards more global insights and curved display users tending towards more localized details) [10].

Czerwinski et al. studied users navigating a virtual environment on large displays and found that there was a positive benefit of larger displays for women. The larger field of view afforded greater access to landmarks in the environment, which allowed women, who are primarily biased towards landmark based navigation, to perform as well as men, who tend to use more directionally based navigation [11].

In an effort to completely isolate the effect of size from resolution, Tan et al. performed a series of studies comparing a small display to a large one with exactly the same content. Users were positioned further away from the large display so that the size of the foveal image for the user was the same in both conditions. Despite this, they still found that users in the large condition were biased towards adopting an egocentric frame of reference with respect to the displayed information, in contrast to the exocentric frame of reference that was usually adopted in the small display condition [12].

These results are important because they show that large, high-resolution displays are not just about displaying additional information. Instead, they actually change users’ perception of tasks and thus their behavior and performance. The work presented in this paper builds on these results by showing that

even small, seemingly subtle changes can have a large impact on user perceptions and behavior.

There are many types of large displays. These range in physical size from wall-sized displays down to multiple monitor set-ups. This category of displays includes powerwalls, caves, and tabletops. There are several application areas associated with these displays: prototyping, simulations, visualizations, demonstrations [13]. We will not be addressing tabletop displays in this paper. Tabletops may be used for collaborative work [14], but their design is for a different set of tasks (i.e., not extended periods of individual work, such as document viewing or editing) [15]. We have classified user perception of large displays into two primary categories: presentation space and workspace (Table 1). Both display categories stem from workspaces with spatial affordances.

2.1 Powerwalls

Powerwalls are often constructed using tiled LCD displays. They are constructed primarily for collaborative visualizations and demonstrations. These displays are particularly effective at providing users with situated awareness, embodied cognition, and a large amount of data [1].

2.1.1 Construction

Powerwalls are typically constructed with a cluster of computers that use a specialized API to distribute rendered content across the display (e.g. Chromium [16]). While this scales up well beyond what a single machine can handle, it makes it difficult to use conventional document creation and office productivity tools.

Powerwalls can be constructed with either projectors or LCD panels. Projectors can be tiled seamlessly, but they require a fair amount of space in order to project the image, can have problems with occlusion, and cannot achieve the same clarity, uniformity, and pixel density of LCD panels. The high-pixel density of LCDs is of critical importance to enable the full range of physical navigation and all of the benefits of the increased space. While this tradeoff comes at the cost of having more prominent bezels, the size of bezels is continuously decreasing on LCDs.

2.1.2 Usage

Many large, high-resolution displays can be classified as powerwalls, such as “Gigapixel” (Figure 2). The typical usage for powerwalls is to present a uniform, highly detailed view. For example, one might use a powerwall to examine satellite imagery or scientific visualization of large and complex data sets. These uses are specialized and frequently custom and single-purposed [1, 17]. Designers of these systems envisioned them being used frequently and for a broad range of tasks. However, powerwalls are primarily used for experiments, presentations, and demonstrations, but not general multi-purpose use. Bi and Balakrishnan [18] studied the use of a large display for individual everyday tasks on a wall-sized projector-based display. They found that users placed main tasks in the center with others in the periphery. However, this display’s construction tethered the user to a position six feet from the display at a desk, which did not afford physical navigation. We believe that small (yet important) design decisions, such as the mobility and position of the keyboard and mouse, the curvature of the display, and the tools provided to the users can increase the benefit large displays provide for such tasks.

2.1.3 Limitations



Figure 3 A raised, flat large display used for presentation purposes.

There are several usability factors that contribute to current designs of powerwalls not being used much for everyday work. These factors include physical location of the machines and user unfamiliarity with the structure and maintenance of clustered displays.

Powerwalls tend to be located in large presentation, collaboration, or laboratory spaces. Users often are required to reserve timeslots and provide justification for use. They also need to consciously decide whether or not to travel to the display space's location and what data to bring with them. If any changes need to be made in this data, the analyst must return to their original workspace, process the data, then return. Because of this effort, powerwalls are seldom used to complete everyday work-related tasks.

Several technological issues concerning powerwalls compound the usability issues that prevent users from completing everyday tasks. A cluster of computers often powers these machines. Clustering provides the potential for very large tiled displays with more pixels than a single machine could support. However, they are often difficult to "boot", requiring a technician's assistance. A severe downside is the restrictions this architecture places on the applications that can be run on the display. For small powerwalls, a tool such as Xdmx can be used to distribute standard Linux desktop tools. However, no similar tools exist for other operating systems and the performance limitations quickly make this option insufficient as display size increases. SAGE can emulate some of this functionality by displaying views of other machines, but it doesn't provide a uniform interactive environment.

An alternative is to use one of the growing numbers of distributed rendering frameworks such as Chromium, VRJuggler, or CGLX, which distributed low-level graphics commands. To move beyond displaying an image, movie, or simple 3D model, custom software has to be developed. Since all of the support is for low-level graphics commands, this strongly favors scientific visualization applications over other kinds of applications that rely heavily on text and interaction controls

We believe that there is an opportunity for a new design space for large, high-resolution displays that focuses on the everyday workspace. These displays should be able to be located in a standard office to eliminate the issue of physical location. Also, we can allow users to use more familiar operating systems and tools by stressing the boundaries of what a single machine can handle, eliminating the issue of clustered machines.

2.2 Multi-Monitor Environments

Typical desktop users who want to add more display space add another monitor or two to their systems to create multi-monitor arrangements. Each display is frequently treated as a separate area, and in most cases, the area has a predefined role (e.g., viewing email), from which it rarely varies [19, 20]. Large, high-resolution powerwall displays, however, remove the partitioning bias, allowing for a more continuous use of space. These displays naturally provide whitespace between documents, a trait seldom found in multi-monitor arrangements, letting users spatially arrange tasks into separate areas of the screen.

Our interest is in a midpoint between these two methods of creating additional display space that shares attributes of each. From the multi-monitor set-up, we would like to support the heterogeneous mix of applications and documents. From the powerwall set-up, we would like the single contiguous environment and spatial affordances that surpasses visual acuity. In other words, the workspace should be more than a collection of monitors; the workspace should be a large spatial environment in which documents can have real spatial relationships, both between themselves and with respect to the user.

Table 1 Perceptions of large displays can enable either presentation spaces, or workspaces.

Presentation Space	Workspace
<ul style="list-style-type: none"> • Scenario: demonstrations, presentations • Metaphor: theatre, IMAX • Single presenter, large audience • Theatre seating • Special occasions • Watch animations • Wizard of Oz interaction, operator at head node • Medium density pixels • A separate room and system • Cluster computing technology and OS • Static construction • Technology driven 	<ul style="list-style-type: none"> • Scenario: individual, everyday work • Metaphor: office workspace • Individuals, few collaborators • Office chairs, standing • Normal, daily usage • Work on documents, analysis • Everyone interacts directly, wireless devices • High density pixels • Users' primary workspace • Standard OS and applications • Reconfigurable, flexible • Usability driven

3. THE CASE FOR SPACE

In daily life, humans make use of space in a myriad of ways, leveraging it to simplify perception, reduce decision fan-out, and save internal computation [21]. Many of the representations that are created in space are ultimately a form of external memory. Space is particularly effective at supporting external memory because artifacts that are created in it are visible and *persistent*. This creates a highly accessible, on-demand information source that is available through *physical navigation*. While the evidence for accurate spatial memory is not strong [22], it does not need to be exact if the information is persistent in space as the perception system provides many cues, allowing for the combination of recall and recognition to rapidly find targets. Human-sized space also encourages the adoption of egocentric frames of reference [12], which can provide valuable additional cues for understanding and using the space. All of these factors combine to reduce the need to internally store information about the environment – the environment becomes its own rapid access model.

Space can also be used as a semantic layer in which extra meaning is conveyed through spatial position. There are many ways that information can be encoded into space using ordering, proximity, and alignment to create structures like piles, clusters, lists, and even heterogeneous interrelated types [23]. This reduces the need for elaborate internal models and computation, replacing it with organization and the use of the perception system to *recognize* properties of a collection of artifacts. The other advantage of using space to encode meaning is the flexibility of the medium. In our studies of intelligence analysts, we found that they freely mixed multiple spatial metaphors into the same space [24]. It also provides the opportunity for what Shipman refers to as “incremental formalism”. When nothing is known about a body of information, any organizational strategy that is initially chosen is likely to be inappropriate or limited. Space can provide an unstructured environment in which it is easy to rapidly change structures as understanding evolves.

There are a variety of compelling ways that a spatial environment can be used when coupled with a document centric environment. On a conventional desktop computer, task is heavily coupled to applications or tools. Editing a text document, for example, may consume the entire display with only a portion of a single page of the document visible. Changing documents or tasks requires explicit interactions and potentially a complete swap of the visible content of the display. A spatial environment switches the emphasis to the documents. Task switching then can be a simple matter of physical navigation – switching attention from one area of the environment to another [9].

An area of interest is the use of such an environment for the cognitively demanding task of sensemaking. We are particularly interested in the synthesis process, which requires managing a large body of information, identifying connections and relationships, and building an overall understanding or identifying a binding story that makes sense of the whole. The flexibility and expressiveness combined with the visible persistence afforded by a spatial environment seem well suited to this task [25, 26].

4. THE EVERYDAY WORKSPACE

How can the capabilities of large displays be leveraged for everyday work?

The “everyday workspace” (Figure 1) is one that enables users to perform their productivity tasks on a daily basis. For example, our goal is a workspace for analysts to use for their information-intensive work. As such, it is important for us to base our design principles for such a workspace on the experiences of users who are familiar with large displays, and ideally those who have used them for a significant time.

The design decisions below are based on the experiences of 7 users who used a large display as an everyday workstation. The average amount of time each user worked on these workspaces is 31 months. The tasks being performed range based on the current focus of the user, but range from analyzing data, writing reports, corresponding via email, etc. Additionally, we present evidence to support these decisions from previous studies with intelligence analysts [25], cyber analysts [5], and other large display studies [7, 9]. In the following sections, we share some of the experiences and best practices adopted by these users, critical to shaping the perception and functionality of these displays.

4.1 Perception of the Display

In previous studies, we have seen an unexpected phenomenon occur when users are presented with an flat, large, high-resolution display [5]. Users feel the need to stand or sit back at a distance

that allows them to view the entire display at once. At this distance, they lose the ability to view the level of detail provided by a pixel-dense screen. This “see it all” phenomenon seems to have been driven by expectations and experiences gained from other displays such as large televisions, movie screens, projectors, and even perhaps powerwalls. The general sense was that the primary reason to use a large display was to see a lot of information.

While we agree that a lot of information can be shown, we maintain that the ability to *see all of it all the time* is not needed. This reaction is problematic because at the distance required to fit the entire display into the field of view, the users were not able to take advantage of the high pixel density of the display. They could view the big picture, but lost details. When completing text-based tasks, users had difficulty reading the documents that are displayed using conventional font sizes, which lead to eye straining or font size increases. The use of larger fonts is not only a waste of pixels, but it also alters the ratio between the document size and the space available on the display. Increasing the font size reduces the amount of space available on the display, which decreases the utility of the display, which ultimately undermines the purpose of the display.

Some users were concerned that they may forget or ignore areas of the display that are out of sight if they move closer to the display. This concern is not without merit. A common usability issue with the display is windows or dialog boxes that appear silently in unattended areas of the display. However, the combination of cognitive resources, spatial persistence, and space with meaning do help users to keep track of the space. An important tenant of physical navigation is that it is entirely reasonable for some portion of the display to be outside of the user’s view sometimes, in much the same way that portions of an office workspace may be occasionally out of view as when people put some work “aside” on their desk while working on other tasks.

The “see it all” issue is ultimately one of display perception. Ultimately, our goal is to enable the user to engage with the display by staying in their “cognitive zone” [27], using physical navigation to exploit the large space. In order to achieve this, we must look at the different components that compose a large, high-resolution display and how they can be adjusted to change user perception from a presentation space to a space to work.

4.2 Display Configuration

The display uses (8) 30-inch displays to provide a large, pixel-rich area. While there are still bezels present with such a setup, the amount of continuous virtual space afforded by a single monitor enables users to move past the multi-monitor paradigm of one maximized window per monitor. The stacked monitors are intended to contribute to the sense of a single uniform display while remaining within the bounds of a comfortable range of motion. Each column is freestanding to allow exploration of various configurations. Using a curved configuration, the footprint of the display is one that can easily fit into a standard size cubicle.

The resulting system is a 108.5 in. x 35 in. display with an overall resolution of 10,240 x 3200 pixels (~33 megapixels) that can fit comfortably in an office. The entire display runs off a single computer, which can dual boot both Windows and OSX, allowing a wide range of conventional productivity tools to be used.

In order to change the perception of a large display from a presentation space to an everyday workspace, the following design characteristics can be changed. These changes in

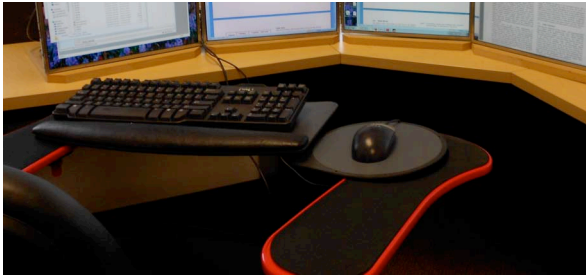


Figure 4 A keyboard and mouse tray attached to the armrests of an office chair enable accessibility to these when moving the chair to access information on various locations on the display.

perception can lead to a change in user behavior. In addition, this perception is caused not by one single characteristic, but a combination of all of them that make up the complete environment.

Height of the display. Adjusting the height of the flat display greatly affects the perception of the large display. With the display height level with a standing user's eyes (Figure 3), the display closely resembled a powerwall. This display height can cause users to stand back from the display at a distance of at least 6 feet. At this distance, users can see the entire display at all times. Standard productivity tools can be difficult to use at this distance due to small menu font sizes, a small cursor, etc. However, presentation-oriented tools can may perform well.

Conversely, a display at a lower height (near an average user's eye line while seated) creates an environment more inviting, where users can sit and perform longer tasks. Simply, lowering the display to desktop-height enables users to treat it like a standard desktop computer. In contrast, taller display configurations lead to the perception that this is a "lab machine" rather than a "personal computer".

Curvature of the display. In terms of aiming to produce a workspace rather than a presentation space, curving the display produced the greatest impact. Flat displays imply a display on which presentations and demonstrations will be shown. This is evidenced by the preference of users who prefer to stand further back when shown a flat, large display. In contrast, a curved display invites users to come closer, and become more engaged with the information shown.

When shown a curved display, users of previous studies [5] behaved considerably different when presented with a curved display. They immediately moved in to work much closer to the display. Fonts and window sizes remained at their standard settings (usually 10 or 12 point). This allowed users to take advantage of not only the size of the display, but also the resolution. Additionally, the need to "see it all" was diminished. Users used subtle physical navigation (turning their head versus moving laterally) to focus on the current task.

Display Stands. Changing the manner in which the large display is supported alters user perception by mimicking a traditional office environment. Display stands (Figure 3) hinder users from integrating physical artifacts common in office environments, such as coffee mugs and notebooks. However, when the display was placed in the normal desk-like office context, users felt more encouraged to complete daily tasks. The stands are also problematic from a usability standpoint. While having a small

footprint, the stands did not allow seated users to place their feet underneath the display, as permitted by a standard desk. When sitting close to the stands, any movement (feet, chair or keyboard tray) knocked into the base of one of the stands. This caused users to be reluctant to move or push themselves back away from the display, hindering physical navigation.

Placing the display on a pair of standard office desks created a different perception of the workspace. Users can sit and slide their chair closer to the desk by grabbing on to the edge of the desks. The desks gave a much more stable appearance than the display stands. The keyboard and mouse could be placed on the desk or a separate keyboard tray based on the user's preference. In addition, there was space to place notepads, drinks, and other materials important in office environments. In essence, this change altered the context of use to be closer to the office desktop computing metaphor, thus encouraging a different behavior.

4.3 Keyboard Placement

There are four possible choices for (wireless) keyboard position for large display workspaces: on the desks, on a mobile keyboard tray, multiple keyboards at varying positions in front of the display, and attaching the keyboard to the desk chair.

Keyboard placed on desks. With the displays placed on desks, there is enough space for the keyboard as well. This works well when applications requiring keyboard interaction are located on the screen immediately in front of the keyboard. However, when the focus application was located in other areas, users are reluctant to move the keyboard closer to the application. Instead, users twist their upper body so their hands are able to type on the keyboard while their head is directed at the tool they are typing in. Users are accustomed to static keyboard positions from traditional computer workspace setups. However, it becomes important to position the keyboard relative to the task rather than relative to the display. Thus, fluid repositioning of the keyboard is important.

Keyboard on mobile tray. The use of a height-adjustable keyboard and mouse tray enables users to dynamically position their keyboard and mouse within the workspace. This gives users the freedom to move in the physical space in front of the display, easily navigating to different areas of the display when needed. However, depending on the user, he or she may be reluctant to move the keyboard tray [5]. The result is a "tethering effect", anchoring the users to the position of the keyboard tray. Users were observed (in [5]) to either use the tray as a static pillar, walking back and forth from the display to type, or as a barrier preventing closer movement. With this barrier, users leaned over the keyboard tray and squint to read text that is illegible from farther distances, which resulted in increasing font sizes. As a result, while the tray *can* be moved, it was not.

Multiple keyboards placed at various locations on the desk. Another option for keyboard placement was having multiple keyboards placed on a stationary desk. By attaching three keyboards and placing them at three equidistant locations on the display, a keyboard was always "nearby" given the location on the display requiring text input.

Keyboard attached to armrest. Another configuration option for keyboards is to attach the keyboard itself to a detachable platform that can rest on the chair armrests (Figure 4) [9]. This allows users to rotate their chair to different areas of the display while keeping their keyboard centered in front of them. This eliminated the issue of users being reluctant to move their keyboard from the initial

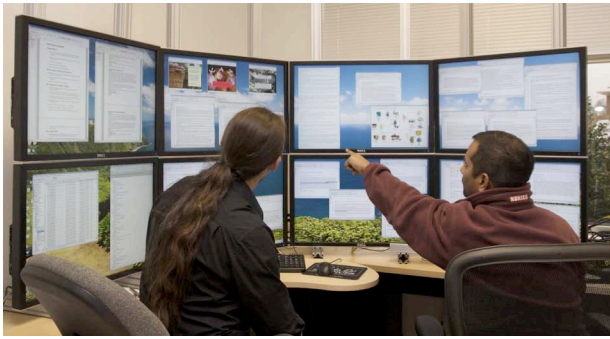


Figure 5 Two users collaborating on a large display workstation. By reducing the amount of curvature, two users can easily collaborate on a task.

central position on a standard desk, creating a more spatially focused task.

4.4 Mouse Placement

There are several possible variations of mouse type and placement. With each of these variations, we acknowledge a common issue and open research area: the problem of losing track of the mouse cursor while navigating such a display. The various technologies that have addressed this issue are outside of the scope of this paper, thus we will not address them. Fundamentally, when switching to a different area of the display, users expect the cursor to be nearby instead of having to wiggle and row the mouse to reacquire the cursor location and move it into their current focus.

Wireless mouse on keyboard tray. Although the surface area of the keyboard tray was large enough to comfortably use a mouse, the same issues mentioned with the keyboard tray are present.

Handheld Gyro-mouse. These mice are designed to allow users the freedom of moving the mouse cursor without requiring a surface (i.e., a mouse pad) to move it. Users can gesture towards a direction, and the cursor follows. However, our experiences with these mice for longer, full-day work are poor. For example, when standing back to use the display, one may expect the Gyro-mouse to perform as though it were a wand. As a result, we have observed users pointing to absolute positions on the display, becoming confused and frustrated when the cursor would not follow. Also, the mouse became an inconvenience when it was not necessary to perform actions with the cursor. This results in having to find a place to leave the mouse while typing, etc.

Mouse placed on armrest. An additional option for mouse placement is directly attached to the armrest of the chair. This allows users to continue to move their chair freely to interact with all areas of the display. As a result, one can place a mouse pad and keyboard on the armrest of the chair (Figure 4). This method enables users to position themselves with respect to their current focus area on the display, while always having the mouse available.

4.5 User Stance

Many of the factors that we have discussed have the potential to bias the user to either sit or stand when performing work on the display. In this section we will discuss tradeoffs associated solely with each of these two user stances.

User standing. Standing for an 8-hour workday could be tiring. Aside from fatigue, a user who is standing has the ability to move

freely in the physical space. They are not limited by any movements of the chair. However, the mouse and keyboard can still tether the user to a particular location.

User seated. When choosing a seated position, the height of the desk chair has a sizable impact on the usability of the display, as well as the perception of the task. Users on a raised drafting chair (taller than standard desk chair) have the advantage of positioning themselves to where they are at a comfortable eye level with the vertical dimensions of the display. However, even with the displays at a height of a standard desk, most users find the chair too high for them to firmly touch the ground with their feet. This makes user movement difficult, requiring users to find other means to move physically navigate (e.g., using the table on which the display rests to push and pull themselves).

A lower chair allows users to perceive the large display as their personal work area instead of an awkward environment with little freedom of movement. The higher chair affords more accessibility to the top portion of the display because the user's eye-level is vertically central, but makes physical navigation more difficult.

5. DESIGN CONSIDERATIONS FOR LARGE DISPLAYS

Through the discussion of the tradeoffs each of these design decisions have on the perception and usability of such a display, we describe a setup that has been successful in creating the perception of an everyday workstation.

A curved, "horseshoe" configuration for the display allows a single user easy access to all areas of the display. The degree of the curvature is somewhat up to personal preference, but we suggest that curving the display to a configuration where the user is equidistant from all areas of the display. Placing the displays on a pair of regular office desks successfully changes the perception of the display from that of a powerwall (i.e. presentation, demonstration, and collaborative work) to a workspace equipped to handle everyday work. Ideally, these desks should have as little support on the bottom of them as possible to minimize the interference with the user's feet when rotating in their chair.

We recommend allowing the display curvature to be easily changed by the user. When needed, slight curvature changes can be made to support collaboration [28]. Slightly flattening the display from their curved setup allows two or three users to easily access the display at a comfortable distance (Figure 5). Aside from planned collaborations such as demonstrations, this is useful for ad hoc collaborations such as when asking a co-worker for help on a task. The user can expand the curvature, pull up another chair, and share the space with a colleague.

We recommend a seated position in a regular office chair at a height allowing their feet to touch the ground. This is critical for the type of physical navigation needed to utilize such workspaces, ranging from rolling their chair to a new location to rotating in-place to access a different area of the curved display. Attaching the keyboard and the mouse pad to the armrest allows easy access from all positions. Alternatively, in situations where more flexibility is required, they can be placed on a rolling stand.

Placing these displays in an environment where they are accessible for users on a daily basis allows users to integrate their usage into their everyday tasks. Placing these displays in offices as the individual's workspace allows them to avoid transitioning files and materials to separate locations. This benefit is amplified in exploratory analytics tasks, where users may frequently return

to their office to re-process data to modify visualizations on a large display located elsewhere.

The concept of using such large displays for common everyday work tasks is a usage scenario not frequently considered by large, high-resolution display designers. In part this can be attributed to the difficulty of justifying the large outlay of financial resources involved in building the display as well as the space required for it merely for the use of a single individual. Building displays like the everyday workspace is a step towards bridging the gap between the potential of the powerwall and the utility of the desktop. The conference room of the future may someday be structured around large-scale powerwalls, but only if users have methods to usefully work at large scales in individual settings and can seamlessly transition their work from private to public spaces.

Our call to action is to carefully consider and measure the usability of various large display designs. Thus, we are *not* advocating that large display systems should not be built. On the contrary, large displays have proven very beneficial when designed appropriately for different usage scenarios. Thus, it is critical that everyday large display workspaces be designed so that users will perceive these benefits and exploit them. This is a fertile area for usability research.

6. CONCLUSION

Slight changes in the design of large displays can impact the type of tasks that can be performed. In this paper we described how seemingly unimportant design characteristics, such as the physical configuration of the display, have a meaningful impact on users' perceptions and usage of the display. We have shown that such changes can bring a powerwall display into an everyday workspace scenario (e.g. an office or cubicle). By doing so, users can capitalize on the added display space without sacrificing the convenience of their office environment.

The resulting large display workspace design that we chose affords individual users the usability to perform common office or analytic tasks as well as the flexibility to collaborate and give presentations. We describe how slight variations in that design can allow for local, small-scale collaboration. In future work, we plan to explore how these spaces can transition seamlessly from personal workspaces to large-scale, collaborative spaces. A central tenet of this work is that many factors including the technological design decisions, form factor, interaction techniques and context of use all come together to shape the user's perceptions of large, high-resolution displays. These perceptions shape how users interact with the display and ultimately determine the display's utility.

These experiences provide designers with insight into the impacts of their design decisions on users, and an opportunity to carefully consider their design goals and predict outcomes. Armed with these guidelines, our hope is that designers will be able to create rich, usable workspaces using large, high-resolution displays.

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