Interaction with Large Displays: A Survey

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Large interactive displays are increasingly placed in public (or semipublic) locations, including museums, shops, various city settings, and offices. This article discusses the evolution of such displays by looking at their use and analyzing how they are changing the concept of human-computer interaction through new modalities. By surveying the literature on systems using these displays, relevant features were identified and used as classification dimensions. The analysis provided may inform the design and development of future installations. A discussion on research challenges concludes the article.

Categories and Subject Descriptors: H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*Interaction styles*

General Terms: Design, Human Factors

Additional Key Words and Phrases: Public installations, multitouch displays, touchless interaction

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1. INTRODUCTION

The first prototypes of touch screens were already presented in the 1960s, but significant installations of large touch screens and other large interactive displays appeared only in the new millennium. Thanks to the great advances in technology, these displays are now available at affordable prices, so they have moved from laboratories to public (or semipublic) settings, like museums, tourist information centers, offices, shopping malls, and various urban locations. People are stimulated to interact with such displays through new and engaging modalities to retrieve information and/or to perform useful tasks, possibly collaborating with other people. These new uses are creating many challenges for both designers and users, especially because public displays attract people who are very diverse in age, skills, and experience with technology. As we will see in this article, many features of such installations affect users' experience.

Since 2000, several workshops have been organized to discuss topics related to large interactive displays. Special issues in journals have been published: one appeared as early as 2000 and addressed research and experience in building large display systems, which were very innovative at that time [Li et al. 2000]. A second considered

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the applications of large displays [Kurtenbach and Fitzmaurice 2005], and a third one, published in 2006, looked at digital tabletops [Scott and Carpendale 2006]. More recently, Hinrichs et al. [2013] edited a special issue on interactive public displays, which actually range from large-scale media façades, requiring user interaction from a distance through some kind of device to large interactive displays that can be directly touched by users. In this article, we do not consider façade displays (i.e., displays integrated into architectural structures like buildings and usually of very large scale) because they have different requirements.

Because of the large number of papers published on this topic, a comprehensive overview of the research on systems using large interactive displays is very challenging. Only surveys limited to specific aspects have been presented so far. The one reported in Greimel [2011] addresses interaction techniques for public displays, but it only considers interaction based on input devices and interaction based on direct-touch technology and haptics, analyzing a small number of papers. Some interactive tabletop exhibits in museums and galleries are discussed in Geller [2006]. A review of the state of the art of tabletop computing is presented in Bellucci et al. [2014].

This article surveys 206 papers that describe systems using large interactive displays developed over recent years, which were selected after an accurate search of the literature. The aim, rather than to give a comprehensive survey, is to show how the use of these systems has been evolving, how they are changing the concept of human-computer interaction (HCI), also stimulating collaborative interaction of colocated groups. Specific features of these systems are identified and used as dimensions for classifying the surveyed papers. We believe that the analysis presented in this article could provide hints for the design and development of new installations in many contexts.

This article is organized as follows. Section 2 briefly reports the history of interactive displays before the current millennium. Section 3 summarizes the literature search performed. Section 4 describes the five dimensions used by the classification framework. These dimensions are illustrated in more details in Section 5, together with examples of some representative systems; each dimension is reported in a separate subsection. Section 6 discusses research challenges, and Section 7 concludes the article.

2. ORIGINS OF INTERACTIVE DISPLAYS

The interaction with many large displays is still touch-based. The first prototypes of touch-screen devices appeared in the 1960s and used cathode-ray tube technology. One of the pioneers was Eric Arthur Johnson, an engineer at the Royal Radar Establishment in Malvern, England. He proposed a display with very novel input/output capabilities, thanks to wires, sensitive to the touch of a finger, that were put on the surface of a cathode-ray tube [Johnson 1965]. This approach is still used today in several common devices. At that time, such touch displays were experimented primarily for air traffic control [Orr and Hopkins 1968].

A prototype of a flat plasma display, called *PLATO IV*, was built as early as 1972 at the University of Illinois at Urbana-Champain [McWilliams 1972; Sherwood 1972]. It was an 8.5-inch display with a tactile surface based on an infrared emitter matrix of 16×16 sensors. The prototype was used to allow a student to answer multiple-choice test questions by touching the screen.

In the late 1970s, several researchers worked to improve the touch-screen technology, for example by taking into account touch pressure and the angle of the finger touching the screen [Herot and Weinzapfel 1978; Minsky 1984]. Various technological solutions were proposed in the 1980s, creating the first multitouch displays capable of detecting the touch of multiple fingers [Mehta 1982]. Other researchers investigated how to interact with the display not only through several fingers of one hand but also through the use of both hands by multiple users. For example, Krueger et al. [1985] implemented many of the hand gestures for zooming and rotating objects that are still very popular today.

Almost all prototypes developed up to the end of the 1980s were monitors that used either cathode-ray tube or plasma technology. Because of the limited size of such monitors, several researchers worked to develop solutions for much larger displays. The early 1990s were influenced by the famous papers of Mark Weiser [1991], in which he clearly says that ubiquitous computers have to be of different sizes, each suited to a particular task, as real power emerges from the interaction of all the different devices. This pushed researchers toward the construction of very large displays, which could be set up vertically, and thus used as an interactive wall, or horizontally as a tabletop. One of the first examples of a tabletop display was *Digital Desk* [Wellner 1991], which used both optical and acoustic finger detection on the display and also introduced the possibility of tactile manipulation of physical objects on the display. A "graspable" user interface on a tabletop display was presented in Fitzmaurice et al. [1995]: some physical artifacts, called *bricks*, were the input devices operating on the display. They could be attached (i.e., tightly coupled) to virtual objects for manipulation or for expressing actions. *Portfolio Wall* was a system that used a vertical touch-screen display developed at the end of the1990s [Buxton et al. 2000]. It was proposed as a digital corkboard for sharing work within a design team. The users could sort and annotate images shown on the display, which was about 2 meters wide.

As shown in this article, the new millennium brought a considerable proliferation of large interactive displays, thanks also to their capacity to promote activity and social awareness [Huang and Mynatt 2003]. Moreover, the first large interactive displays appeared on the market. One of the first products is *Lemur*, released by Jazz Mutant in 2004, which is still on the market; it is a multitouch display used by deejays as a music controller [JazzMutant 2014]. *DiamondTouch* is a multitouch table produced by Mitsubishi and is well known because it is one of the few products capable of identifying users during the interaction [Dietz and Leigh 2001]. This is possible because users are sitting on chairs around DiamondTouch and there is a microelectric contact to each chair. Up to four users at a time can touch the screen; the system recognizes each user by detecting the electrical frequency going through the user's body to the fingers touching the display. In 2007, Microsoft commercialized *Surface 1.0*, another multitouch table that allows multiple users to interact through either gestures or some real-world objects. However, it does not identify the touch of a specific user. Many other products are now on the market. The *Paravision* multitouch table can reach a width of 200 inches [Paravision 2014]. *Microsoft Perceptive Pixel* is an 82-inch display [Microsoft 2014]. Some products (e.g., *Multitaction* [MultiTaction 2014] or *Planar Clarity Matrix* [Planar 2014]) can be arranged side by side in a 2D array in order to build much larger displays (a few meters in width and height).

3. LITERATURE SEARCH

The goal of this article is to show the evolution of large interactive displays by looking primarily at their use, rather than at the technology that made them possible. A careful literature search was carried out. Positive and negative aspects of different academic search engines were considered. Eventually, the chosen search engines were (1) the search engine of the ACM Digital Library [ACM 2014] and (2) Google Scholar [Google 2014]. The ACM Digital Library includes important scientific papers in computer science, that is, those published by the ACM. Google Scholar is considered one of the top search engines on the Web thanks to several factors. From our point of view, its main advantage is that it searches in the largest databases of scientific papers.

The string used to query the two search engines was *interactive public display*. We started by examining 400 papers, which were the first 200 results retrieved by

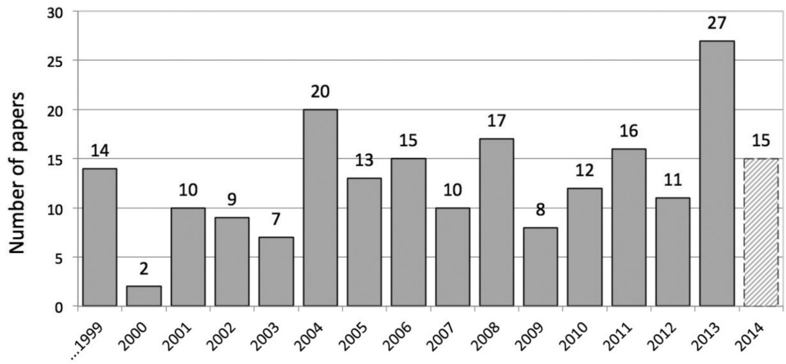


Fig. 1. Distribution over the years of the surveyed papers.

each search engine. At first glance, we noticed that, after the first 150 papers, the results did not appear very relevant. Nevertheless, we decided to examine the first 200 results. This search was performed in January 2013. We started with Google Scholar, and by reading the title and abstract, we selected 114 relevant publications. Of the 200 publications retrieved by the ACM search engine, we first removed those already considered by Google Scholar and we read the title and abstract of the remaining ones to identify those of interest. As a result of this first screening, a total of 180 publications were selected. After reading the full papers, we reduced the selection to 94 papers. This automatic search was complemented with a manual search, based on the analysis of the references of the papers we read. If a referred paper appeared relevant, we retrieved it and read the abstract first and, in most cases, the full paper, to decide if it should be in our selection. While working on our survey, we kept the set of papers up to date by examining the proceedings of very relevant conferences (e.g., CHI 2013, CHI 2014, INTERACT 2013, ITS 2013, UIST 2013) and the latest issues of journals that usually contain articles on large displays (e.g., IEEE Computer Graphics and Applications), published from January 2013 to June 2014.

The final set consists of 206 papers. Their references are in the Online Appendix because only those explicitly mentioned in this article are reported in the References. A paper was selected if it described one (or more) system(s) implementing an interactive large display, in public or semipublic settings. A paper was excluded if it met at least one of the following criteria: (1) it presented façade large displays; (2) it was an introductory paper of a special issue, a book, or workshop; (3) it referred to the same installation of an interactive large display system, published in a different venue; d) it was a paper in the grey literature (i.e., PhD theses, industrial and technical reports, patents, reports, working papers, white papers, unpublished results, and preprints); (4) it was not written in English.

The distribution of the selected 206 papers, according to the publication year, is shown in Figure 1. The 14 papers in the first column were published in the years up to 1999 (this is indicated by the symbol "..."). The last column is dashed to indicate that only papers published in the first 6 months of 2014 were analyzed.

4. THE CLASSIFICATION DIMENSIONS

The selected papers have been surveyed in order to detect relevant features of the systems described and to use them as dimensions in a classification framework able to provide an overview of the field's state of the art. As previously mentioned, the main goal of this article is to analyze how large interactive displays have been used and how they are changing HCI by introducing new interaction modalities. Thus, we focused on

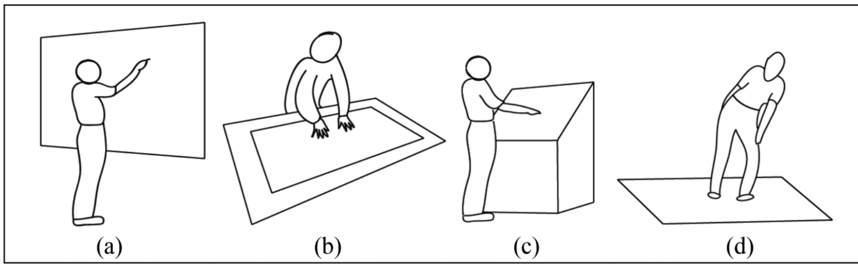


Fig. 2. Display setups: (a) vertical, (b) horizontal, (c) diagonal, (d) floor.

how, *why,* and *where* large displays are used, rather than on the various aspects of the technology at the base of such devices.

The selected dimensions are briefly illustrated in the following, while more details are reported in Section 5, where examples of systems belonging to the specific categories are described.

1. **Visualization technology**. This is the only technological dimension we considered because, even if it does not specifically focus on *how*, *why,* and *where* large displays are used, it affects the cost of both the display and the overall system. Thus, it influences the selection of the display to be used. It addresses the solutions for visualizing the computer output on very large displays. The two main technologies are based on projection (*front* or *rear projection*) and *monitors* (LCD or Plasma).
2. **Display setup**. Setup refers to the physical installation and orientation of the display [Pedersen and Hornbæk 2012]. Together with *interaction modality* (next dimension), it determines *how* the display is used. Most displays are installed with a *vertical* orientation, like the traditional PC. Wall displays have this position (Figure 2(a)). Many systems also adopt a *horizontal* setup, for example, tabletops (Figure 2(b)). A few systems propose a *diagonal* setup (Figure 2(c)), a *floor* display (Figure 2(d)), while some project the computer output on any surface.
3. **Interaction modality**. The adoption of new post-WIMP interaction modalities is the most characteristic aspect of the use of large interactive displays. We distinguish the following ways of interaction: (1) by touching and/or manipulating objects visualized on the display (*Touch* in Table I), (2) through *external devices*, (3) through *tangible objects,* and (4) through *body* movements (including movements of arms, shift of gaze, etc.).
4. **Application purpose**. This dimension refers to *why* the display is used by considering the purpose of the applications implemented. The first uses of large interactive displays were aimed at entertainment or performing specific tasks, which were usually very simple. More recently, the implemented applications allow more complex tasks. For this reason, one of the categories that was identified is *productivity*, along with *entertainment*, *social interaction*, *gaming,* and *advertising* (see Table I). Even if the purpose of a game is entertainment and fun, we considered *gaming* a separate category because of the considerable number of game-based applications. The same application may have more than one purpose (e.g., it can be a serious game designed for both education and fun). In this case, the paper describing the application appears in both the *productivity* and the *gaming* categories.
5. **Location**. Another important feature that affects the use of a large display is the location *where* it is installed, namely, *city*, *office*, *university/school*, *conference*, the so-called *third place*, that is, a location where people get together to socialize (like a café), any *cultural site* (such as a museum), and *shop*.

Table I. Paper Classification

Frequency (f) and percentage (%) of papers in each category of the five dimensions are indicated. A single paper may describe one or more systems with different features and thus may be classified into more than one category per dimension.

Visualization technology			Display setup			Interaction modality			Application purpose			Location		
Category	f	%	Category	f	%	Category	f	%	Category	f	%	Category	f	%
Rear Projection	70	34	*Vertical*	*138*	67	*Touch*	118	57	*Productivity*	112	54	*City*	34	17
Front Projection	64	31	*Horizontal*	63	31	*External device*	70	34	*Entertainment*	80	39	*Office*	33	16
Projection (unspecified)	5	3	*Diagonal*	3	2	*Tangible object*	44	21	*Social interaction*	52	25	*University / School*	23	9
Monitor	73	35	*Floor*	5	3	*Body*	43	21	*Gaming*	31	15	*Conference*	10	5
Unspecified	7	3	*Other*	17	8				*Advertising*	13	6	*Third place*	10	5
												Cultural site	9	4
												Shop	6	3
												Lab prototype	89	43

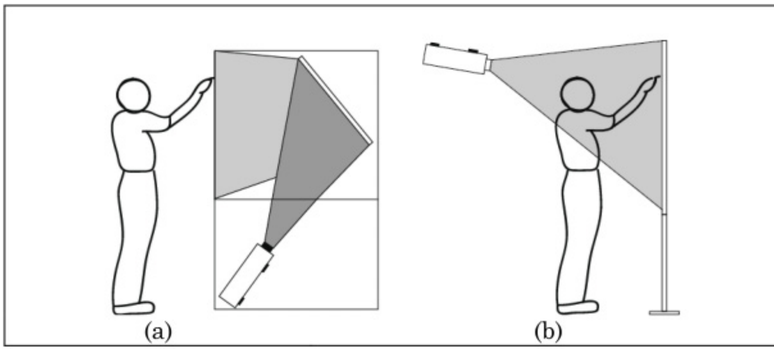


Fig. 3. Two different projection solutions: (a) the projector is behind the visualization surface, (b) the projector is in front of the visualization surface.

Table I summarizes the paper classification by reporting frequency (f) and percentage (%) of papers in each category of the five dimensions. The sum of frequencies may exceed the number of surveyed papers and the sum of percentages may exceed 100% because a single paper may describe one or more systems that have different features, and thus it can be classified into more than one category per dimension. The label *Projection (unspecified)* in the first column indicates that some papers describe systems whose visualization technology is *Projection*, but it is not specified whether it is *Rear* or *Front*. The label *Unspecified* is used in the same column because the visualization technology is not specified in some papers. The label *Other* in the second column refers to papers whose systems do not belong to any of the listed categories. The label *Lab prototype* in the fifth column is used for papers describing prototype systems experimented only in the laboratory. Table I provides an overview of the paper classification useful to understand the overall distribution of the papers along the different dimensions. The reader interested in knowing the 206 selected papers and how each of them has been classified may consult the Online Appendix.

5. LARGE INTERACTIVE DISPLAYS ALONG THE CLASSIFICATION DIMENSIONS

This section analyzes the surveyed papers according to the five classification dimensions, providing insight into the different categories and reporting examples of relevant systems. Each subsection refers to a dimension and concludes by showing a graph of the temporal trend in order to highlight the evolution of large interactive displays over the years.

5.1. Visualization Technology

Visualization technology refers to the technological solutions adopted to create very large displays. The two main technologies are denoted as *projection (rear/front)* and *monitor*. The first column of Table I shows the percentage of papers classified within each visualization technology category.

5.1.1. Projection (Rear/Front). Projection technologyis based on the use of one (or more) projector(s) and a surface, such as a wall, a canvas, or a special material, on which the output of the computer is projected. If the projector is behind the surface, it is called *rear projection* (34% of papers); if it is in front, it is called *front projection* (31% of papers, see Figure 3). In 3% of the papers, it is not specified whether the adopted projection technology is rear or front. An advantage of front projection is the absence of the box, behind the screen, containing the projector(s). However, the user's shadow on the surface does not allow him/her to see the occluded area. Recently, short-throw

Fig. 4. A matrix of 15 projectors (a) is used for a display of 5 × 2.5 meters (b). Source Schikore et al. [2000], © IEEE.

projectors have reduced this problem. In the case of *rear projection*, a disadvantage is that the box with the projector(s) might be very big.

Projection technology is very popular because it is usually economical and quite effective, as discussed in Hereld et al. [2000] and Schöning et al. [2010]. However, a significant limitation with respect to LCD and plasma monitors is the low image resolution, making it difficult for users to perceive image details. Very large interactive displays may be easily built because several projectors can be combined, projecting the output image on a surface of tens of meters, like the interactive wall installed at the Hard Rock Café in Las Vegas. Thus, several individuals or groups of people can interact in parallel. In Schikore et al. [2000], 15 projectors were arranged in a 5 × 3 array (Figure 4(a)), producing a display of 6,400 × 3,072 pixels across 5 × 2.5 meters (Figure 4(b)). A key goal was to edge-match the output image of each projector to its neighbors without either overlap or separation lines. Other similar displays were presented in Ojala et al. [2012], Peltonen et al. [2008], and Shinohara et al. [2007]. Such wall displays require a complex structure for the projectors and a specific technology has to be used in order to properly align the outputs of all the projectors. Therefore, the overall cost of such displays is still very high.

An unusual projection technique is described in Rakkolainen and Lugmayr [2007], where the authors present experiments with a kind of immaterial display, called *FogScreen*, in order to provide visually compelling advertisements. FogScreen forms a projected image on a midair immaterial image plane. Thus, the viewer can even walk through the display because it is actually made of air (Figure 5). This kind of projection is visually intriguing and can also be made two-sided, so that the opposite viewers on each side see their side of the screen and each other through it. Interaction with immaterial 2D or 3D graphical objects occurs by virtually "touching" them with either hand(s) or a stylus. The application is able to track the position of the viewer who has "touched" the screen, thanks to a commercial laser scanner, which emulates the functionality of a mouse device. The reported experiments revealed some affordance problems: the concept of an immaterial, midair display was unusual for viewers and they would have needed hints for using it (e.g., a projected text saying "touch me").

5.1.2. Monitor. Another popular visualization technology adopts an LCD or plasma *monitor*. Such monitors are largely used today because they are ultra-thin and provide very high resolutions, greatly improving the quality of the displayed image. However, their high cost severely restricted their diffusion until a few years ago; costs are now quickly decreasing. The size of current monitors reaches 110 inches. *C Seed 201* is a recent product that reaches the size of 201 inches after unfolding 7 LCD panels

Fig. 5. An example of *FogScreen* [Rakkolainen and Lugmayr 2007]. Image courtesy of A. Darlington, Business development manager of Fogscreen.

[C Seed 2014]. Indeed, the size limitation of LCD displays may be overcome by combining several monitors side by side. This solution is often called “tiled panel”: it consists of a set of monitors arranged in a 2D array. The array can be organized like a wall display, like a table or in other configurations. An example is *Lambda display*, a 100MPixel wall display. It was developed at the Electronic Visualization Laboratory, University of Illinois [Krumbholz et al. 2005]. This large display can be used both in a vertical and in a horizontal setup (see Section 5.2).

A wall display conceived by NASA is called *Hyperwall*, a very large display built with 49 LCD panels tiled in a 7 × 7 array. Each flat panel display is 18 inches long and the entire array is driven by 49 rack-mounted dual-CPU nodes, each with its own high-end graphics card [Sandstrom et al. 2003]. Hyperwall helps researchers to display, analyze, and study high-dimensional datasets in meaningful ways, allowing the use of different tools, viewpoints, and parameters to look at the datasets from different perspectives. In recent years, NASA updated this display by developing a larger version called *Hyperwall-2*: it consists of 128 LCD panels tiled in an 8 × 16 array, which is 10 meters wide and 3 meters high [Bo-Wen et al. 2011; NASA 2014].

Tiled LCD panels have the advantage of being easier to align into the array and to adjust the colors, compared with projectors, which require a complex structure in order to be composed in a single large display. Thus, tiled LCD panels might even be cheaper than projection-based tiled displays. However, the resulting image has a visible border between adjacent monitors [Koppel et al. 2012], even if recent commercial solutions, such as the *MultiTaction with ultra-thin bezel* [MultiTaction 2014], are reducing this problem.

5.1.3. Temporal Trend of Visualization Technology. To highlight the evolution of large interactive displays over the years according to the visualization technology, Figure 6 shows the graph of the distribution of the surveyed papers. Before 2004, both technologies were used, while in the successive years, projection has been more frequent than monitor. This might be due to the fact that large displays are still more economical with projection technology.

5.2. Display Setup

The display of traditional PCs has a *vertical* setup. For large interactive displays, besides the vertical one, *horizontal* and *diagonal* setups have also been used. More recently, *floor* installations have been presented, primarily for entertainment. Furthermore, there are systems that project the computer output over any surface: spherical, cylindrical, or even irregular.

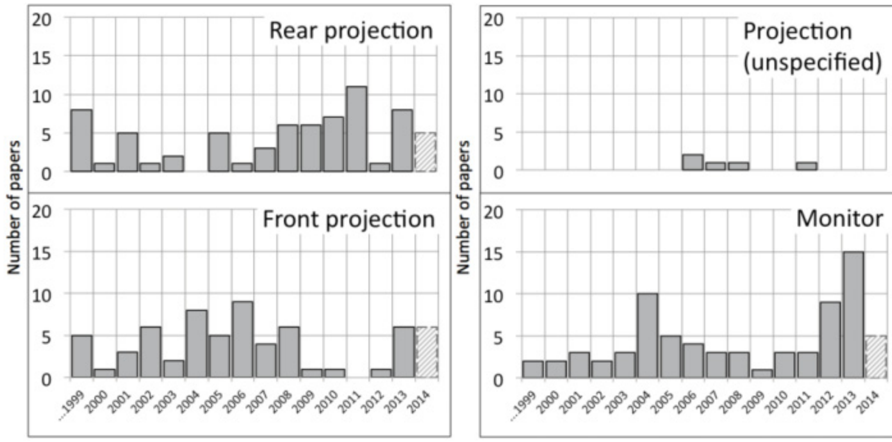


Fig. 6. Distribution over the years of the surveyed papers according to the *visualization technology* dimension.

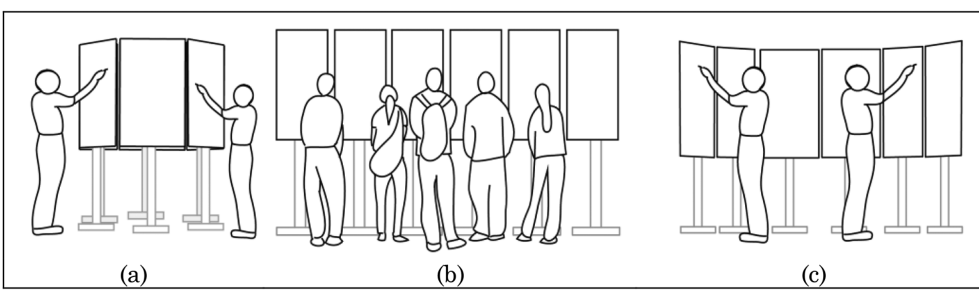


Fig. 7. Chained Displays: (a) hexagonal, (b) flat, and (c) concave.

5.2.1. Vertical. As shown in Table I, most papers in our survey (67%) describe displays that are vertically installed (Figure 2(a)). This setup is often used in a city context because it is suitable for passers-by who remain only a short time in front of the display, and also in a shop window [Perry et al. 2010], or at a university [Hardy et al. 2011]. A vertical setup is convenient for easily reaching a very big size, such as the aforementioned wall displays [Guimbretière et al. 2001; Li et al. 2000]. Koppel et al. [2012] presented *Chained Displays,* a flexible combination of vertical LCD displays, which have been evaluated in a university setting, in order to see how the shapes influence people's behaviors. The displays can be combined to create different shapes: hexagonal, flat, and concave (Figure 7). The experiments performed showed that a hexagonal shape prevents users in front of the display from seeing what other users are doing on the other portions of the display, resulting in low collaboration and sociability. A flat arrangement triggers the strongest honey-pot effect, attracting other people to interact even in collaboration, while the concave arrangement does not stimulate collaborative interaction.

5.2.2. Horizontal. In several cases, it is useful to set the display horizontally, like the top of a desk (Figure 2(b)), so that users can interact even for a long time while sitting around it. This setup is presented in 31% of the papers, and after the vertical setup, it is the most used, especially in locations like offices [Bi et al. 2006], museums [Hinrichs et al. 2008], schools [Piper et al. 2006], and in general when the activities require some time, so user comfort becomes important. It appears to be appropriate for collaborative

Fig. 8. Using iFloor a group of users can discuss and interact, by using personal mobile phones to write SMSs that are visualized on the floor [Krogh et al. 2004]. Image courtesy of P.G. Krogh.

tasks because multiple users can discuss and share the display while comfortably sitting around it [Shen et al. 2003]. Unlike the vertical setup, which allows users to easily look at other areas of the display, two users sitting on opposite sides of a tabletop display see contents reversed with respect to each other. Some design solutions try to overcome this problem (see, e.g., Dragicevic and Shi [2009] and Shen et al. [2004]).

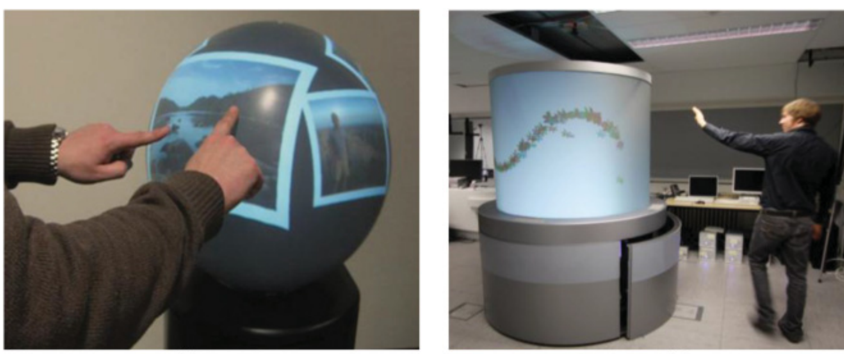
The study reported in Pedersen and Hornbæk [2012] compared vertical and horizontal setups to analyze their influence on users' performance, satisfaction, and general behavior. For example, it showed that a tapping task was performed 5% faster on the vertical display, whereas a dragging task was performed 5% faster and with fewer errors on the horizontal display. In general, many users preferred the horizontal setup because they felt less tired when using that surface. The few users that preferred the vertical surface explained that it offered a better overview and hands were less likely to occlude objects on the screen.

5.2.3. Diagonal. A few papers (2%) present displays with a *diagonal* setup (see Figure 2(c)). The display is installed with the lowest side at a height similar to a horizontal setup. It has been shown that this solution improves the interaction of the user(s) located at the lowest side, while it greatly limits collaboration with the users standing at the other sides, even if they have a common task to perform [Shen et al. 2003]. Other studies show that the angle of the display has a strong impact on user interaction and collaboration (e.g., see Inkpen et al. [2005]), confirming that a diagonal display provides some users with a better viewing angle, but does not afford people gathering around it [Buxton et al. 2000]. Thus, collaboration is better supported by both horizontal and vertical displays. The former allows several possibilities for user arrangement, also providing a flat surface for placing objects. The latter gives all viewers the same perspective of the task and provides a holistic view of the data.

5.2.4. Floor. New fascinating setups have been implemented, especially when the system's main purpose is entertainment. Specifically, in a few systems, the display is the *floor*. In *iFloor*, a projector is mounted on the ceiling, together with a camera that tracks users' movements [Krogh et al. 2004]. People may use their mobile phones to post messages on the floor that they want to discuss with others (Figure 8).

Another interactive floor is able to show, in front of each user walking on it, the forecasted trajectories that presumably a user will follow [Ozturk et al. 2012]. Recent technological solutions have investigated how to build a more accurate floor display by mounting tracking cameras inside the floor, like in *Multitoe*, a high-precision

Fig. 9. Projecting the image on different surfaces, including uneven surfaces such as the interior of an umbrella or a fan. Source Lee et al. [2008], © ACM.



(a) (b)

Fig. 10. Example of (a) a spherical display (Source Benko et al. [2008], © ACM) and (b) a cylindrical display (Source Beyer et al. [2011], © ACM).

interactive floor display able to sense per-pixel pressure of users [Augsten et al. 2010]. This technology allows the floor to locate and analyze users' soles, to recognize foot postures, and thus to identify users.

5.2.5. Other. Of the papers examined, 8% present special setups not classifiable within those previously described. Indeed, some projection technologies permit the visualization of the computer output on a surface that has not been chosen a priori so that it is adaptable to different situations. Thus, the output can be projected on a wall, a floor, or any surface, such as the interior of an umbrella or a fan (see, e.g., Figure 9) [Lee et al. 2008]. These types of setups are used in conjunction with special touch-sensing technologies that can detect the gestures of the users on the projected surfaces [Lee et al. 2005; Pinhanez 2001].

Other systems present spherical (e.g., Bolton et al. [2012]) or cylindrical displays (e.g., Beyer et al. [2011] and Lin et al. [2009]), as shown in Figure 10. A comparison between spherical, cylindrical, vertical, and horizontal displays is made in Benko et al. [2008]. With both spherical and cylindrical displays, each user can see at most one half of the display. Thus, these displays, rather than fostering collaboration, allow different users to interact without disturbing each other and with more privacy, as each user sees only the portion of the display in front of him/her.

5.2.6. Temporal Trend of Display Setup. Figure 11 shows the graph of the distribution over the years of the papers surveyed, according to the display setup dimension. The

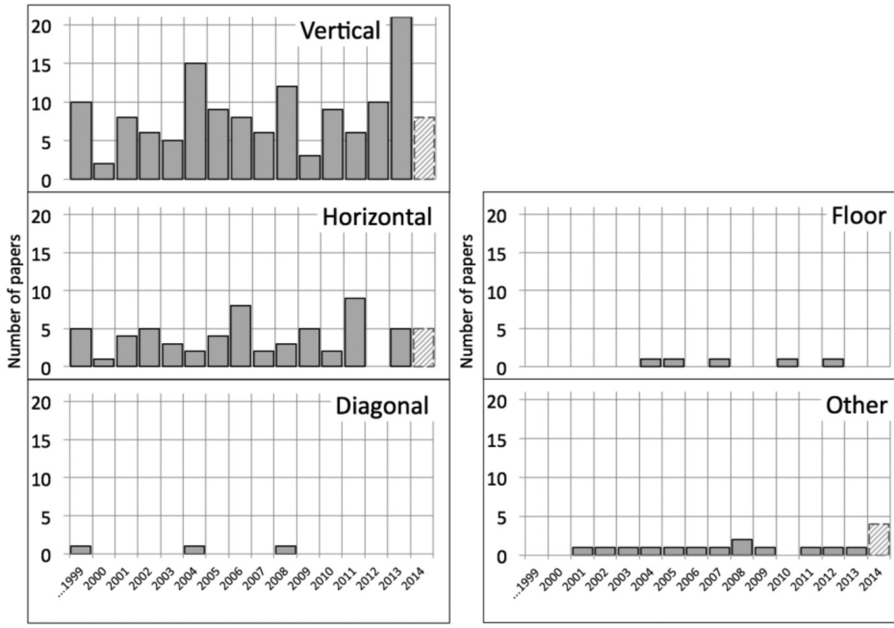


Fig. 11. Distribution over the years of the surveyed papers according to the *display setup* dimension.

first systems used the vertical setup, which is still the most popular. The horizontal setup (i.e., the one for tabletop displays) is the second most used. There are commercial solutions available on the market for both vertical and horizontal setups (e.g., FlatFrog [2014], JazzMutant [2014], and ZaagTech Inc. [2014]). The remaining setups are still in an experimental phase.

5.3. Interaction Modality

Systems equipped with large displays adopt several innovative interaction modalities to engage people as much as possible. Most installations have the potential to support different interaction modalities, but usually only one primary interaction modality is provided to users. We distinguish four main categories, denoted as *touch*, *external device*, *tangible object,* and *body* (see Table I).

5.3.1. Touch. Of the surveyed papers, 57% refer to systems whose interaction modality is based on the touch of users' fingers and/or users' hands on the display surface to move, zoom, rotate, annotate objects, or provide other types of input. For a few systems, touch is limited to one finger at a time (e.g., Vogel and Balakrishnan [2004]), while most systems allow users to interact using many fingers simultaneously (e.g., Kim et al. [2010]). Various technical solutions are adopted to make the surface interactive; a detailed description of such technologies is out of our scope. We only mention that for detecting the touch of users' hands and fingers (and also tangible objects), some solutions are based on (1) infrared emitters and an infrared camera [Schöning et al. 2008]; (2) ultrathin overlay placed on the visualization surface [FlatFrog 2014; PQ Labs 2014]; and (3) ultrasound emitters and sensors [Ashdown and Robinson 2004].

Besides detecting more fingers at a time, the system described in Peltonen et al. [2008] is also capable of recognizing hand touch. This is useful, for example, to rotate a sheet of paper shown on the display. The user touches the sheet with his/her hand oriented in a certain direction, and the system is able to recognize this orientation and rotate the sheet to align it with the hand. Finally, there are systems that are able to disambiguate users' hands over the display when many users interact simultaneously with it. The first product that appeared on the market capable of distinguishing the touch of each user was DiamondTouch, described in Section 2 [Dietz and Leigh 2001]. Today, other systems do the same, but they use other approaches. One is proposed in Wang et al. [2009], which analyzes the orientations of the fingertips to identify the user. Another one, described in Dohse et al. [2008], combines a multitouch tabletop with a camera mounted above the table that tracks the hands in order to distinguish users. This approach works well when users stand on opposite sides of the tabletop.

5.3.2. External Device. A considerable number of papers (34%) describe systems that allow users to interact by using an external device, which is not in direct contact with the display surface, but communicates with the surface through wireless technologies (e.g., Bluetooth, Wi-Fi, SMS). As stated in Bellucci et al. [2010], there are not standards, paradigms, or design principles yet for remote interaction with large, pervasive displays. Interaction through external devices is useful when the display is very big; thus, it is impossible for users to touch the highest parts of the display. The device could be a smartphone or a tablet, provided it is equipped with specific software. For example, the 3D motion sensors of the Nokia 5500 are used in Vajk et al. [2008] as a "Wii-like" controller for playing games on a large public display. However, it is difficult to actually use personal devices, due to the requirements of their specific configurations, so this approach is only applicable to private or semipublic settings. Boring and Baur [2013] created a conceptual framework and implemented techniques that leverage cell phone cameras to enable from-a-distance interaction with any public-display technology Boring and Baur [2013]. Other remote devices are purpose built, for example, *uPen*, a device composed of a laser pointer combined with a contact-pushed switch, three press buttons (as on a mouse), and a wireless communication module. Users may interact with a large display either from a distance or directly by touching the surface (i.e., using uPen as a mouse). Interestingly, each user may hold a uPen; thus, more users can interact together, possibly collaborating, and the system is able to identify them and provide personalized services [Bi et al. 2006]. She et al. [2014] discuss how the integration of mobile devices with interactive displays allows useful information to be instantly delivered to audiences for effective and informative advertising. It is worth noting that the use of external devices helps to solve some privacy problems: people can input personal data, passwords, and so forth through the device, without worrying about others looking at the display (see, e.g., Magerkurth and Tandler [2002]).

5.3.3. Tangible Object. Of the surveyed papers, 21% describe systems that allow users to interact by manipulating real objects on the display (e.g., Lucchi et al. [2010] and Tuddenham et al. [2010]). This modality is used, for example, to implement workspaces that support collaborative tasks. The system presented in Rogers et al. [2006] recognizes miniature models of street furniture (e.g., flowers, trees, shrubs, benches, chairs, statues) placed on an interactive table, thanks to an RFID tag attached under each object. During a collaborative activity to design a layout plan of a public garden for a new university building, users select objects and decide their best position. Recent systems are more sophisticated and capable of recognizing complex objects. In *BlueTable,* a combination of computer vision and Bluetooth technologies is used to connect a mobile device to a tabletop display in order to exchange specific data. The user establishes the connection by simply placing the device on the display and the system is able to retrieve the contents stored in the mobile device, like photos or a calendar, and show them on the tabletop (Figure 12). Any change the user makes on the tabletop (e.g., editing the calendar) is automatically reported in the mobile device.

Fig. 12. User interface of a calendar application that spills out of a mobile device onto *BlueTable.* Source Wilson and Sarin [2007]. Image courtesy of A.D. Wilson.

Fig. 13. Interactive mannequins in a shop window. Source Reitberger et al. [2009], © ACM.

A photo is transferred by simply dragging it from one device to another. Removing the device breaks the connection [Wilson and Sarin 2007].

5.3.4. Body. Papers describing systems that enable interaction through the user's body, not only the whole body but even just a part of it, like arms or facial expressions, are increasing. In Table I, we indicate *body* as the only category. However, there are already various body interaction modalities (see also Müller et al. [2010]). They are a clear indication of how HCI is changing, so we describe them in more detail.

Body presence. Different types of sensors (e.g., cameras, microphones, Bluetooth and RFID scanners, pressure sensors, Microsoft Kinect) are used to detect body presence in the proximity of a display. The system reacts to the user's presence by activating an implicit interaction. One of the first examples of presence sensing is provided by *GossipWall* [Streitz 2003]. The users' presence in the proximity of the display is identified because users carry RFID-based *ViewPorts*, which triggers the visualization of information on the display. In Reitberger et al. [2009], a 3D virtual mannequin is described, located in an interactive shop window, that reacts to the presence of a person by changing its body posture and looking at the person (Figure 13). The goal is to capture the attention of potential customers and increase the time they spend in front of the shop window.

Body position. Cameras installed in the environment or pressure sensors in the floor are often used to detect the exact position of a user with respect to the display. This information provides hints on how to adapt the displayed content to the user. An example is *EDs Urban Carpet,* which uses a grid of LEDs embedded in a carpet to make it interactive; the carpet can be located in an urban context [Briones et al. 2007]. When users walk on the carpet, different patterns of lights are generated depending on the users' movements on the carpet. A recent paper describes a prototype of a very long display located along a corridor and a model of the perception area in front of the display. Thanks to cameras installed in the environment, the system is capable of sensing human position and predicting from where that person can read the content on the display. Based on this model, a technique called *Screenfinity* has been implemented to automatically rotate, move, and zoom content. It actually follows people while they are walking in front of the display, making it possible for them to comfortably read it [Schmidt et al. 2013]. One of the uses of this system could be to show advertisements and commercials to people while they are walking along a path (e.g., in an airport or a metro station).

Body posture. More recent interaction modalities exploit users' body orientation and movements; thus, the system may assess how a user approaches a display, whether he/she faces it, or whether he/she simply passes by. It also interprets users' postures. Müller et al. [2012] described a study on an interactive shop window aimed at comparing different visual feedbacks that communicate shop window interactivity to passers-by. In particular, the shop window grabs the user's attention by reproducing an image of the user in front of it. The field study compared four different user representations: mirror image (interactive colored image of the user on a black background), silhouette (a white-filled silhouette of the user), avatar (a 2D avatar including head, torso, and hands), and abstract representation (just the head of the user, with abstract eyes and mouth). The study showed that mirror and silhouette representations are equally effective in attracting people and both more effective than the avatar and the abstract representations. Other systems enable people to interact with advertisements on a large display through body and touch gestures (e.g., see Fukasawa et al. [2006]).

Hand gestures. These refer to familiar, conventional *hand* movements used to perform some tasks. Several gesture classifications are proposed in the literature of interactive displays. For example, Bellucci et al. [2014] distinguish (1) *surface gestures*, which imply touching the display surface; (2) *remote gestures*, performed by the user without any contact with the display; (3) *motion gestures*, performed while the user is carrying a device (e.g., holding a mobile phone or wearing an ad-hoc device). Systems exploiting surface gestures and motion gestures have been classified in the *Touch* and *Remote Device* categories, respectively (see Table I). Thus, in hand gestures, we classified systems whose interaction modality is through remote gestures. They are also called *midair* or simply *air gestures*.

Facial expression. Software and hardware components are available today to recognize facial expressions. The *eMir* is a display that shows the face of a human character. A camera installed on top of the display observes and classifies the facial expressions of the passer-by and detects whether someone watches the display so that the system can react to the audience's emotions. This information is used to let a human character on the screen react accordingly and encourage interaction with the face [Exeler et al. 2009].

Gaze. Sophisticated technologies, such as eye-tracking, permit the precise detection of users' gaze paths. This information may be used in various ways for user-display

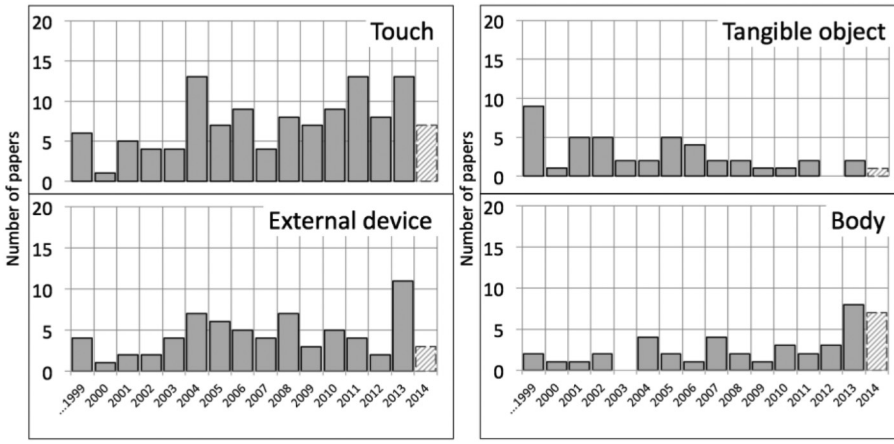


Fig. 14. Distribution over the years of the surveyed papers according to the *interaction modality* dimension.

interaction. Zhai et al. [1999' proposed an approach called *MAGIC* (Manual And Gaze Input Cascaded) *pointing*, since it exploits the user's gaze for fine manipulation of widgets on the display. This work considers that overloading the vision perceptual channel with a motor control task is unnatural. Thus, gaze is used to set the cursor position on a target (i.e., on what the user is looking at). Once the cursor position is set, the user has only to make small movements to the target with a usual manual input device and click on it. This approach reduces the cursor movement to select targets. *ReflectiveSigns* uses gaze detection to learn which content the user is looking at in order to display the next contents according to his/her preferences [Müller et al. 2009].

5.3.5. Temporal Trend of Interaction Modalities. The temporal trend of interaction modalities is shown in Figure 14. Touch-based interaction is the oldest and still most used modality. However, thanks to advanced sensor technology, several other modalities have been proposed more recently and the interest in recognizing a user's body positions, postures, movements, and so forth keeps increasing to meet the desire for a more intuitive and still effective interaction.

5.4. Application Purpose

The fourth classification dimension refers to the main *purpose* of the application(s) implemented on a large display system. The first applications were quite simple because researchers focused primarily on technological aspects, as well as on defining new interaction modalities. With the consolidation of technology, applications of increasing complexity and for different purposes were developed, as reported in the following.

5.4.1. Productivity. Of the papers, 54% refer to applications that, besides being attractive and engaging, have a specific utility for their users (i.e., support them in performing tasks that go beyond mere entertainment). Examples of such tasks are manipulating content in a particular browser [Johanson et al. 2001], mixing and manipulating multiple video streams in real-time with multitouch gestures [Hawkey et al. 2005], creating and mixing music tracks [Taylor et al. 2009], and searching for information about cultural heritage and defining touristic itineraries [Ardito et al. 2010]. Some papers describe applications that have an explicit learning purpose. For example, *Tree of Life* is an application implemented on a tabletop display, which supports learning during a visit to the Berlin Museum of Natural History by asking visitors to answer questions about the museum contents [Hornecker 2008].

5.4.2. Entertainment. A significant number of papers (39%) describe applications designed to entertain people and let them enjoy themselves. Such applications permit simple tasks like browsing the pages of a newspaper [Denoue et al. 2003], recording personal messages on an interactive bulletin board installed in a café [Churchill and Nelson 2007], and walking on an interactive floor that shows glow shapes when people walk on it [Briones et al. 2007]. In several cases, entertaining applications are designed to be performed in collaboration with other people. As an example, *MobiLenin* is a system that allows a group of people to interact simultaneously with a multitrack music video, shown on a large public display installed in a pub or other public spaces, by using their personal mobile phones [Scheible and Ojala 2005]. Interaction is stimulated by a lottery mechanism that rewards the winners with a coupon for a free beer or pizza, sent to their mobile phones.

5.4.3. Social Interaction. Twenty-five percent of the papers report applications that, by allowing multiuser interaction, trigger social interaction and the creation of virtual communities through the use of the display. One of the most recent examples is in Hosio et al. [2012]. The system enables young people to give personalized feedback on municipal issues to local workers. It also facilitates discussion through modern social networking services. Another example is the aforementioned *iFloor* [Krogh et al. 2004] (see Section 5.2.4). Morris et al. [2006] discuss motivating scenarios for the use of cooperative gesturing and describe some initial experiences with *CollabDraw*, a system for collaborative art and photo manipulation. Another system allows people to post information on a public display, to acquire information from it, and to modify and annotate previously posted contents in order to create publicly observable threads [Carter et al. 2004]. For example, by using a personal mobile device, a user may post a photo and later other people may annotate it with their own comments.

5.4.4. Gaming. Games are often for mere entertainment and fun, but sometimes they are for other purposes, such as learning and/or training. All papers that describe game-based applications (15%) are in this category, regardless of their purpose. *Polar Defense* is a game for shared entertainment, inviting a large audience to play in a public space [Finke et al. 2008]. Users send SMSs using their own cell phones to indicate the coordinates where to play six towers on a virtual field visualized on the display. The towers defend the field by firing bullets against the enemies. The Poker game was implemented on a multitouch tabletop: each player holds a mobile phone displaying his/her own cards, while other cards and coins are on the tabletop and each player can interact with them [Shirazi et al. 2009]. An implementation of Sudoku, available through a multitouch display, is presented in Echtler et al. [2009]; of course, more people can play together.

5.4.5. Advertising. Large displays have been installed in several contexts to show advertisements. Only a few papers (6%) describe systems whose display is interactive. One of the most appealing examples is the interactive mannequin already described in Section 5.3.4 [Reitberger et al. 2009]. Authors carried out a 3-day field study to assess the persuasive effect of this solution. The results gave useful insights to make the system more engaging. Payne et al. [2006] described *BluScreen* and showed that the efficiency of an advertising system improves if the display is aware of the identity and interests of the audience. The system identifies users by detecting any Bluetooth-enabled device they are carrying (e.g., phones, PDAs) and adapts the visualized content to them on the basis of their advertisement history.

5.4.6. Temporal Trend of Application Purpose. Figure 15 shows the distribution over the years of the surveyed papers according to the *application purpose.* Most applications

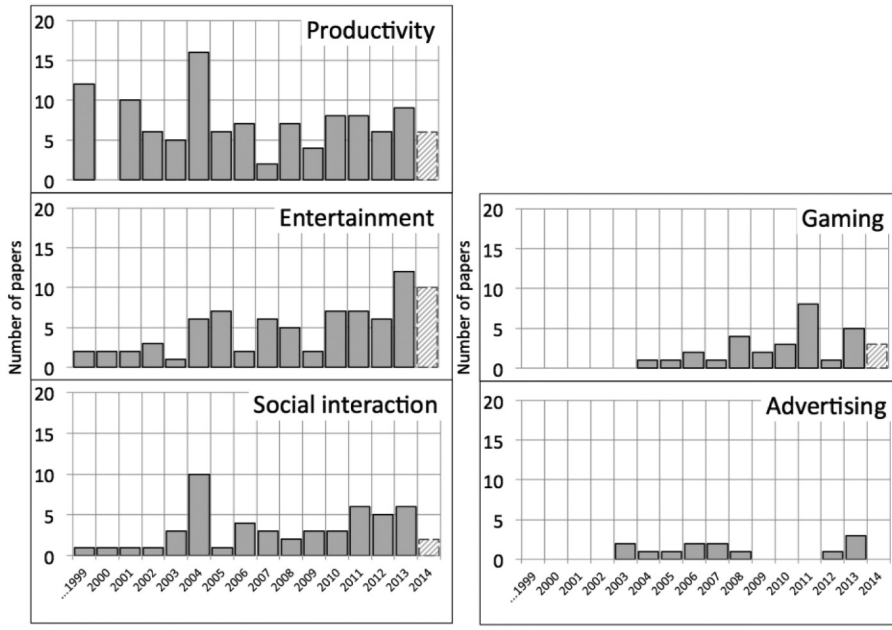


Fig. 15. Distribution over the years of the surveyed papers according to the *application purpose* dimension.

are designed to provide a specific utility to their users. However, applications for entertainment and social interaction are also well represented.

5.5. Location

Location refers to the place where a large display is installed. It affects the behavior of people in the environment around the display, depending very much on whether the location is public (a city street) and thus accessible to unknown people, or semipublic (an office), where most people know each other and could thus be less inhibited working together. Large interactive displays modify the traditional HCI paradigm, not only because different people may interact at the same time, but also because the display may attract the attention of other people who are standing nearby.

From the analysis of the surveyed papers, the following locations are identified: *city* (referring to streets and other urban locations), *office, university/school*, *conference*, *third plac*e, *cultural site*, and *shop*.

5.5.1. City. This category refers to displays installed in urban locations like streets, squares or other specific points of a city, depending on the type of application that, in several cases, is implemented to satisfy the needs of citizens and/or tourists. This category includes 17% of the surveyed papers. One of the earlier examples is in Grasso et al. [2000], where the display, called *CommunityWall,* is the back-rest of a bench, where users can write their own messages with a special pen or manipulate virtual objects by hand touch.

Peltonen et al. [2008] presented *CityWall*, a system whose large multitouch display was installed in a shop window next to a café in the center of Helsinki, Finland, during the summer of 2007. It allowed citizens to browse photos and videos downloaded from social networks, such as FlickR and YouTube; thus, anyone could provide interesting contents. The performed studies (see also Peltonen et al. [2007]) revealed that the large display tended to encourage collaborative activities of different groups (up to seven) who used the system in parallel (i.e., at the same time), possibly for different tasks. In several cases, groups of strangers had fun together even if they started out interacting separately.

Still in Finland, at Oulu, several studies have been carried out to analyze the impact of a network of 12 multitouch displays (6 indoor and 6 outdoor), available in the city streets and squares. These displays allow citizens and tourists to find information, socialize with other people, and play games [Hosio et al. 2010; Ojala et al. 2010; Valkama and Ojala 2011]. Such studies provided interesting results about the importance of the location: it emerged that displays in places like swimming baths are used more than those in "businesslike" locations, like municipal halls. The reason is that users prefer to interact when they are in a relaxed mood with some spare time. Another interesting finding regards the type of application: fun applications and games were the most used because the most frequent users were children and adolescents who appeared much less inhibited than the adults when trying out the hotspots.

5.5.2. Office. This location is indicated in 16% of the papers. In most cases, an office is indicated as a semipublic environment [Huang and Mynatt 2003; Peltonen et al. 2008]. In an office, a large display can be installed in different workplace contexts. For example, in McCarthy et al. [2001], three contexts are considered: (1) within an individual office, where the display is used by the person in that office (the office "owner"); (2) immediately outside the office in order to display information that the owner intends to show to others (e.g., project information, favorite URLs); and (3) in a common area to provide interaction opportunities to people passing in front of the display. The aim of the display in the common area, rather than supporting the performance of primary work activities, as in Streitz et al. [1999], is to create greater awareness among people who gather together in the same physical space. The displayed information should encourage them to initiate a conversation with someone, leading to an increasing sense of community spirit.

Don't Touch Me is an interesting system that supports the operators of a crisis management unit, who can collaboratively coordinate the activities of the forces in the field by analyzing geo-referenced information displayed through a large interactive display [Bellucci et al. 2010]. Each operator interacts with the display by hand gestures performed with a personal Wiimote device held in one hand. The Wiimote also permits the system to distinguish the actions performed by different users.

5.5.3. University/School. A considerable number of surveyed papers report that large public displays have been situated in universities or in schools (9%), in halls, corridors, and so forth. In this case, researchers are facilitated in accessing real users in a safe, public location (displays in a city could be vandalized), which offers a controlled context for conducting studies. For example, *BlueInfo* was installed and evaluated at a bus stop on a university campus and later in a city. Its interactive display delivers information to users' mobile devices through Bluetooth [Kukka et al. 2011]. *History-Puzzle* is an educational game designed to be played by children interacting with a multitouch vertical display installed in their school laboratory [Ardito et al. 2013]. It is called History-Puzzle because pupils reassemble puzzles to discover historical elements of interest. The game requires the users to answer specific questions about history or to associate concepts. It is part of an educational format inspired by the Discovery Learning technique defined by Bruner [1990] in his Constructivism theory. A field study was conducted involving 107 children between the ages of 10 and 12 years. It showed that the game was very engaging and able to stimulate pupils to work together and to collaborate on learning tasks. Teachers appreciated that even students who were usually timid in class were very much involved and actively collaborated with their companions.

USIAlumni Faces is a vertical display used during a university alumni event, organized to reconnect old friends and colleagues [Rubegni et al. 2011]. It visualizes a virtual yearbook (i.e., photos of the alumni organized according to year and faculty), whose pages can be browsed by means of a “page flip” gesture performed using a custom-built input device (i.e., a Wii remote control and an infrared pen hidden inside a toy torch casing). This interactive installation acted as an “ice breaker” and stimulated people to interact in groups. Moreover, researchers observed a spontaneous way of propagating gesture patterns (i.e., users learn/understand how to interact through an observe-and-learn model). This is in accordance with the psychological theory of observation and learning, which characterizes human development and learning, especially in children [Schacter et al. 2011].

5.5.4. Conference. Another public location for large displays is a conference venue. In fact, 5% of surveyed papers have been classified in this category. An example is *MobiToss*, a system installed at a social event of an international conference [Scheible et al. 2008]. It allowed users to create and share multimedia contents, interacting with the system through a mobile phone equipped with built-in accelerometer sensors, allowing gesture control. People took photos or captured videos using the phone and, using a “throwing” gesture, transferred them onto the large public display where they could be manipulated by tilting the phone in different directions. The evaluation study revealed that MobiToss worked reasonably well in terms of engaging users and stimulating their creativity. The users also declared that they would have liked the possibility of manipulating photos and videos together with other people.

A system using a 46-inch-wide LCD multitouch display was installed during a 4-day international conference in the transit zone from the conference hall to the foyer where coffee breaks were held. Therefore, people could comfortably interact with it while they were not busy in the conference sessions [Ardito et al. 2012]. Three applications offered different services to conference participants: (1) *Taxi Sharing* to book a taxi/shuttle or share it with other people; (2) *Conference Photos* to visualize photos of the conference available in FlickR; (3) *Interactive Program* to interact with the conference program to gather various information about the sessions and the presented papers. An observational study was performed during the 4 days, revealing that these applications were very much appreciated by the conference participants. Even if the limited display size did not allow simultaneous interaction of a large group of people, the study showed that social interaction was very much fostered, that is, people often discussed their interaction experience with others standing by them or passing nearby.

5.5.5. Third Place. Third place refers to a location where citizens gather together to socialize and spend time [Oldenburg 1989]. Typical examples are cafes and pubs. *eyeCanvas* is a system implementing an interactive bulletin board on a large vertical display installed in a café [Churchill and Nelson 2007]. This system was running for over a year and showed interactive contents related to the café, including menus, nightly events, and artists’ work. Users could also write comments or sign up for the café newsletter. Another example is *Jukola*, an interactive display used like a jukebox [O’Hara et al. 2004]. It is an interactive MP3 Jukebox device designed to allow a group of people in a public space to democratically choose the music being played and to nominate songs that are subsequently voted on by people in the bar using networked handheld devices.

5.5.6. Cultural Site. This category refers to displays installed in locations of cultural interest, like museums, cultural heritage sites, art galleries, exhibitions, and aquariums. *EMDialog* is a diagonal interactive display installed at the Glenbow Museum in Calgary during the Emily Carr (a Canadian artist) exhibition, with the goal to both give

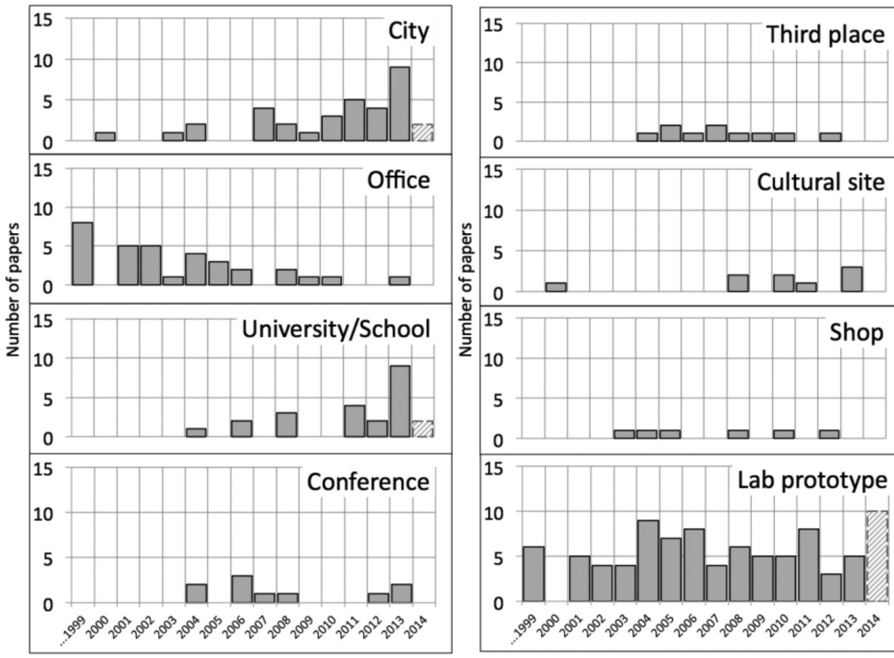


Fig. 16. Distribution over the years of the surveyed papers according to the *location* dimension.

information and stimulate discussions [Hinrichs et al. 2008]. Visitors were observed over 15 days to study how they approached and interacted with the system. A close connection between the age of visitors and their motivation to interact with EMDialog was found: children were very keen on touching the interactive display, while adults were hesitant and careful in approaching it. From the returned questionnaires, it emerged that the characteristics of EMDialog that motivated people to approach the system were display technology, appealing visualizations, and seeing other people interacting with it (the "honey pot" effect in [Brignull and Rogers 2003]).

Collection Viewer is a system installed at the Vancouver Aquarium to provide information about the Arctic environment on a tabletop display [Hinrichs and Carpendale 2011]. A field study involving 20 children and 20 adults focused on the gestures used for interacting with the system. It revealed that the choice of gestures was influenced by social factors, such as the number of visitors around the display and social relationships among them. Age also had an effect: differences were observed between the interaction of adults and children with the digital table.

5.5.7. Shop. Shops are chosen to assess the impact of large interactive displays in commercial contexts (e.g., to evaluate the benefits for merchandising, advertising, and communication among a community of people). *Nnub* is a noticeboard consisting of a 40-inch-wide multitouch LCD panel that was installed in a general store [Redhead and Brereton 2009]. It aimed at creating a digital community, collecting and displaying local information and communication provided by people living near the store. An innovative installation uses a virtual mannequin in a shop window [Reitberger et al. 2009], as described in Section 5.3.4.

5.5.8. Temporal Trend of Location. Figure 16 shows the distribution over the years of the surveyed papers according to *location*. In the earlier years, installations in offices prevailed, possibly because they offered a more controlled environment. In more recent years, systems are increasingly installed in cities, universities, schools, and sites of cultural interest. However, 43% of the papers describe prototypes that were experimented only in laboratories. This category is labeled *lab prototype* in Table I. Since the number of papers is considerable, their distribution is reported in Figure 16. With respect to Figures 6, 11, 14, and 15, the scale on the Y-axis is the same, but it is drawn up to the value 15 rather than 20.

6. FUTURE CHALLENGES

Large interactive displays are among the most promising technologies that will become ubiquitous over the next 20 years [Schmidt et al. 2012]. Since such devices can augment everyday pieces of furniture, such as tables or panels, they can be used in public spaces, indoor as well as outdoor, where many people may be exposed to them. The design of new installations poses many challenges; some of the most significant ones are addressed in the following. They reveal potential areas for future research in the field.

6.1. Blended Interaction in Ubiquitous Environments

The design and placement of large displays have to be conceived according to user tasks and context. The latter includes the physical space augmented by heterogeneous networked devices. There are already several examples of systems designed to blend the power of digital computing with work practices. These systems are usually set in the typical pervasive scenario of supporting collaborative human work in a meeting room, as in the case of *Augmented Surfaces*, one of the first ubiquitous systems for exchanging information among laptop computers, tabletops, wall-projected displays, and physical objects [Rekimoto and Saitoh 1999]. As early as 1999, the *i-LAND* project provided a vision of offices of the future by describing an environment to support the cooperative work of dynamic teams with changing needs. This included an interactive wall, an interactive table and computer-enhanced chairs, on which data and applications could easily migrate [Streitz et al. 1999]. More recently, Wigdor et al. [2009] presented *WeSpace*, a ubiquitous system that integrates a tabletop display, a large vertical display, and users' laptops to support collaborative scientific discussions. The *NiCE Discussion Room* integrates a large wall display, personal laptops, and traditional sheets of paper to support colocated group meetings with an intuitive pen-based interface [Haller et al. 2010]. Public displays are sometimes used in large-scale pervasive games like *Manhattan Story Mashup* [Tuulos et al. 2007], which combines the Web, cell phones, and a large display installed in Time Square.

As pointed out by Oulasvirta [2008], the device ecologies in which large interactive displays are integrated are characterized by an infrastructure that is not homogenous or seamless. A potential problem is that users might feel frustrated by the wide variety of interactive options offered by cross-device and multiuser interfaces. The goal is to achieve natural and unobtrusive computational support by providing interactive systems that are powerfully blended with the real context and the activities carried out. Recent proposals go in this direction. Specifically, to support designers of ubiquitous computing environments, Jetter et al. [2010] presented the *Blended Interaction* conceptual framework. This aims at supporting designers in creating spaces that tie together users' familiar concepts with the power of digital computing. In his Ph.D. thesis, Bellucci [2013] proposes another conceptual framework and its software implementation that facilitates the rapid prototyping of ubiquitous systems by allowing designers to abstract from the specific hardware.

6.2. Gesture Interaction

One of the goals of HCI is to enable more natural and intuitive communication between people and devices, more closely resembling human-human communication. According to Kurtenbach and Hulteen [1990], a gesture is a motion of the body that contains information. Gestures appear intuitive and powerful, as they exploit features such as naturalness, adaptability, and dexterity. Interacting through gestures, users do not think in terms of manipulating an input device, but move parts of their body to execute the task. However, enabling people to use typical, everyday gestures does not necessarily result in an optimal interaction modality. This was also pointed out by Norman [2010], who criticizes the naturalness of gestural interfaces in terms of their claimed intuitiveness, usability, learnability, and ergonomics. Several other issues have to be addressed to achieve successful gesture interaction. In particular, no single method for automatic gesture recognition is suitable for every application. Gesture recognition algorithms depend on the application domain, the user's cultural background and the specific context [Wachs et al. 2011]. For displays in a public space, it is also an issue to communicate to users which gesture is the initial gesture to start interacting. This was investigated in a recent paper that describes *StrikeAPose*, an interactive public display that allows users to play a game using air-gestures [Walter et al. 2013]. The authors explored three different approaches to reveal the initial gesture: (1) *spatial division,* which permanently shows the gesture on a dedicated screen area; (2) *temporal division*, which interrupts the running application to show the gesture; and (3) *integration*, which embeds gesture hints directly in the application. They found that a large percentage of users prefer spatial division (56%). They also observed that users intuitively discover a gesture vocabulary by exploring variations of the initial gesture by themselves as well as by imitating and extending other users' variations.

Hand gestures have been studied for many years. Many designers and researchers have focused on creating and evaluating natural gesture sets for multitouch interaction and on improving the visual feedback and learnability of hand gestures (see, e.g., Freeman et al. [2009] and Nacenta et al. [2013]). Sets of *symbolic gestures* are primarily proposed. A semantic is associated to each symbolic gesture, through which the user communicates a command to the system. For example, gestures for "accept" or "reject" are performed by drawing with a finger a check (✓) or a cross-out (✗) symbol, respectively. It is worth noting that the users need to learn the gesture language is a real issue [Ardito et al. 2014], especially because the interaction with public displays is often occasional. Gestural interfaces are not self-revealing, forcing the user to know the set of allowed gestures beforehand. Some authors actually note that a gesture provides a command, as happens in command line interfaces; thus, gestures are a step backward into the era of learning a command language [Jetter et al. 2010]. Designers should also consider the dependence of gestures on the cultural and social environment in which the interactive display will be installed. Indeed, for applications in a specialized context, where tasks are performed frequently, it is worth the investment of learning a particular set of gestures, whereas in everyday life, users will not be interested in a device that requires them to learn specific gestures. Some authors suggest that interaction based on symbolic gestures may be better accepted if users are allowed to expand or create their own sets of gestures (e.g., Lü and Li [2012], Oh and Findlater [2013], and Wobbrock et al. [2009]). Symbolic gestures can be useful for supporting the collaboration of a colocated groupware. Such cooperative gestures can enrich the applications by increasing participation, drawing attention to important commands and enhancing the social aspects of an interactive experience [Morris et al. 2006].

Jetter et al. [2010] distinguish *manipulations* from symbolic gestures and question the naturalness and the cognitive aspects of the latter. They say that "symbolic gestures are close to the keyboard shortcuts of WIMP systems. They are not continuous but they are executed by the user at a certain point of time to trigger an automated system procedure." On the other hand, "manipulations are continuous between manipulation initiation (e.g., user fingers down) and completion (e.g., user fingers up). During this time span, user actions lead to smooth continuous changes of the system state with immediate output. Typical examples of manipulations are the dragging, resizing and rotating of images." In their view, manipulations are more natural than symbolic gestures because the former are closer to direct manipulation and the latter are indirect and require learning an artificial sign language to interact with the system.

In short, for natural user interfaces, it is not enough to create and evaluate natural gesture sets. We agree with Jetter et al. [2010] that gestural input requires fundamental changes to the structure and visualization of content and functionality; thus, appropriate visual metaphors and consistent conceptual models in which users can act naturally should be proposed.

6.3. Collaboration

Although early discussions on the affordances of media spaces for collaboration dates back to the early 1990s, we are still far from a deep understanding of the physical, social, and cultural influence of technology on human behavior. Large interactive displays open new interesting issues in this discussion, and more empirical evidence is needed to better understand their potential to foster people collaboration.

The literature survey reported in this article shows that several features of large displays favor people collaboration. First, the technology adopted in large displays generally supports simultaneous use actions. According to Scott et al. [2003], who analyzed colocated collaboration around a tabletop display, this is a primary requirement because people collaborating in a task want to interact simultaneously with the visualized artifacts. In most displays, it is not possible to identify the touch of a specific user. This is not seen as an obstacle because, in many collaborative situations, what really matters is allowing more people to contribute to the task without needing to know who is doing what.

Another collaboration facilitator is the wide-screen real estate, which supports colocated multiuser interaction, as shown by several studies performed in the field [Ardito et al. 2013; Coutrix et al. 2011; Peltonen et al. 2008; Rogers and Lindley 2004]. For example, *Worlds of Information* is a system that visualizes information in the form of images, videos, and texts; it was evaluated during an exhibition of advanced technological products [Jacucci et al. 2010]. During 3 days, 101 people were observed. Data collected through survey and video analysis confirmed that the large display allowed people to use the system in parallel, often collaborating in pairs or in larger groups.

The display setup considerably influences people's collaboration. It has been shown that while a diagonal display provides a better viewing angle for the users placed at the lowest side, it does not facilitate people gathering around it, thus limiting collaboration possibilities [Buxton et al. 2000; Inkpen et al. 2005]. Vertical and horizontal setups are the most suited to people's collaboration for different reasons. In the horizontal setup, people stay comfortably seated around the display even for a long time. However, an inconvenience is that users on opposite sides of the display see contents reversed with respect to each other. The *Permulin* system presents an interesting proposal to overcome this problem [Lissermann et al. 2013]. By wearing active shutter glasses, each user can see her or his private view, which includes all content of interest, while the shared view is visible to everybody. This facilitates users' collaboration in manipulating the shared information. Other studies focused on how to enhance people's collaboration by using a horizontal setup [Morris et al. 2006; Shen et al. 2003]. Rogers and Lindley [2004] analyzed collaboration around vertical and horizontal large interactive displays. The results show that horizontal surfaces better support collaborative activities that closely couple the resources used and/or created during the various activities, while vertical displays are better at providing a shared surface that allows a group of people to view and annotate information to be talked about and referred to.

It appears that the location does not have a direct effect on people's collaboration. If the display is installed in a location where people do not know each other, they are initially a bit reluctant to approach the display [Brignull and Rogers 2003]. However, once they start interacting, in most cases, they soon socialize and collaborate with others, if required. On the other hand, the purpose of the application, and thus the tasks to be performed, actually affects collaboration, as is evident in the field study reported in Marshall et al. [2011]. They investigated the use of *Tourist Planner*, an application on a tabletop display installed in the tourist information center in Cambridge (UK). The study, conducted for 32 days, showed that the system changed people's behavior in the physical environment. Rather than being dispersed in the environment, as usually occurs, the system acted as an aggregator for a group of people coming together to the information center. It fostered their collaboration in interacting with Tourist Planner to define their itinerary. Contrary to what was observed in Jacucci et al. [2010] and Peltonen et al. [2008], collaboration and social interaction were focused toward preexisting groups, whose members actually felt discomfort when strangers came to the tabletop.

From the surveyed papers, it emerges that even though large interactive displays are increasingly used in public or semipublic spaces, it is still a challenge to model people's behavior when faced with such displays. What are the main triggers for starting interaction? Are people intimidated by the social context? Are they willing to collaborate with others? People's collaboration is actually important in several contexts. It increases people creativity; indeed, in Csikszentmihalyi [1997] and Norman [2006], it has been discussed that much creativity results from interacting with artifacts and collaborating with other individuals. Shneiderman [2007] says that tools for supporting creativity are needed (i.e., tools that extend users' capabilities to make discoveries or inventions). We see a large interactive display as such a tool. We look forward to the increasing use of these displays to provide interactive creative workspaces that let groups of individuals work collaboratively, express their creativity, and share their ideas and solutions.

6.4. Privacy

In the information society, privacy is a major concern. Managing how to display partly private information is an issue for the success of interactive public display installations. Some solutions use passwords to preserve the user's privacy during the input of confidential data. In the early approaches, the password was provided through a personal device, such as a mobile phone or a tablet (e.g., see Magerkurth and Tandler [2002]). More recently, techniques have been introduced that permit password input based on the combination of gestures and typing on a virtual keyboard [Kim et al. 2010].

In some situations (e.g., defining a travel itinerary or booking a hotel through a tourism application), some people do not like to have strangers looking at their preferences, cultural interests, accommodation possibilities, and so forth. To avoid this, it could be useful to distinguish between private and shared contents. In *Ubitable*, this distinction is physically implemented because the private data is visualized on a personal device (e.g., a tablet or a laptop) and possibly shared with others by transferring them onto a tabletop device [Shen et al. 2003]. The *Permulin* solution mentioned in Section 6.3 is very promising when there are two users interacting on the opposite sides of a tabletop display because it permits the coexistence of visible output and simultaneous input, which is partly shared and partly private [Lissermann et al. 2013]. Chan et al. [2008] suggested the adoption of a virtual panel, visualized in front of each user around a tabletop display, which reproduces the optical properties of a convex lens to avoid others looking at the private information displayed. The virtual panel is used for both visualizing and inputting private data. It could also be a way to support collaborative tasks, even if the authors did not consider this possibility in their paper.

6.5. Accessibility

Making interactive public displays accessible to disabled people is an issue that has been sparsely investigated. The technology most commonly used in current installations is not able to provide a tactile feedback when touching the display, and this causes interaction errors even with unimpaired users, as demonstrated by Hoggan et al. [2008], Koskinen et al. [2008], and Lee and Zhai [2009]. A tactile feedback is useful, for example, to give the feel of a button on the keyboard, which could represent a first rough interaction aid for visually impaired users. Harrison and Hudson [2009] proposed a visual display that contains deformable areas, able to produce physical buttons and other interface elements. Another hardware-based proposal for interfaces that allow the user to feel virtual elements through touch is *TeslaTouch* [Bau et al. 2010], which provides a wide range of tactile feedback sensations to fingers moving across a touch surface by means of electro-vibrations. Hardware-based approaches are successful, but present problems related to cost, scalability, and support for multiuser interaction. In the literature, some software-based approaches are reported; for example, *Slide Rule* is a set of audio-based multitouch interaction techniques that enable blind users to access touch screen applications [Kane et al. 2008]. *Access overlays* presents three software-based techniques that enable blind people to explore and interact with applications on tabletops [Kane et al. 2011].

Accessibility is a challenging aspect of designing both the hardware and the software of public displays because each kind of disability requires a different solution. Most research is focused on supporting visually impaired users, but other disabilities should be considered. For instance, people in a wheelchair cannot interact with vertical displays; interaction modalities based on remote devices or gaze control might provide a support for this type of disability.

6.6. Evaluation

Interaction with large displays in public spaces presents specific challenges related to the social dynamics elicited by the copresence of different users. The first studies explored the use of such displays in controlled settings, such as laboratories or offices. In the last few years, field studies have become the most popular for investigating spontaneous social dynamics that are difficult to assess in laboratories, that is,how people approach the display, what their overall behavior is, if and how they socialize and possibly collaborate. Indeed, the actual impact on users can be evaluated only in the field because environmental factors, for example, the physical space where the display is located (*location* dimension in our classification framework) as well as other specific factors, like *display setup* and *purpose* of the supported applications, influence people's interaction with such systems [Marshall et al. 2011; Ojala et al. 2010]. It is also difficult to simulate the environment in which the display is located because behavioral models are still lacking. In addition, it is worth considering that the evaluation should not only address the actual interaction with the display, but also take into account the behavior of those people standing nearby, who are attracted by the display. There are different zones of interest around a large display (see, e.g., Streitz [2003], and Vogel and Balakrishnan [2004]). The model of the physical space around the display described in Ott and Koch [2012] addresses users' behavior in four zones: (1) the Active Zone, immediately in front of the display, where people interact with the system; (2) the Communication Zone, in which users actively monitor other people and might talk to them while they are interacting with the system; (3) the Notification Zone, where people are not directly involved in the interaction, but their attention is attracted by the users interacting with the display and/or by what is visualized; and (4) the Ambient Zone, where users start to be aware of the interactivity of the display.

A work to provide guidelines for evaluating public displays is presented in Alt et al. [2012]. Its main motivation is that there are many different objectives when evaluating public displays and to pick out the most suitable evaluation method becomes a challenging task. The work is based on the analysis of many papers concerned with the evaluation of public displays. Actually, the authors ended up with very general guidelines, rather than indications for specific guidance. They indicated five types of methods, two more appropriate for informing the design of a prototype, namely methods based on ethnography and those asking users questions (interviews, questionnaires, focus groups), and three for evaluating a prototype, namely lab studies, field studies, and deployment-based research. The latter refers to a kind of action research, which consists of introducing a public display in the envisioned location for a certain time, during which users are observed. The findings are discussed with them in order to involve users in an iterative process to improve the deployment. The most popular research questions to be answered during an evaluation study were also identified and summarized with the following terms: Audience Behavior, User Experience, User Acceptance, User Performance, Display Effectiveness, Privacy, Social Impact.

We suggest moving toward some more systematic frameworks to guide the evaluation of large display systems, taking into account all their particular aspects. The paper by Ardito et al. [2012] provides some insights into an evaluation framework, whose aim is both to highlight factors of interest at the design time and to organize a systematic approach to the evaluation of large display installations in public settings. The framework indicates three types of factors that mainly influence the overall behavior of users:

—*Environmental* factors: They consider the location where the display is installed (e.g., city street, museum hall, school) and include how the display is positioned in the environment (e.g., whether it is in a visible location, in a crowded place).
—*Hardware* factors: They directly address the type of technology adopted, and its configuration. Among other important variables there are the display size and setup.
—*Software* factors: They include interface features as well as other software features, such as software functionality and performance.

The framework specifies a number of behavioral and psychological variables that are influenced by these factors and should, therefore, be addressed to analyze and understand the behavior of users with interactive displays. Each variable can actually be influenced by more than one primary factor. For example, a variable influenced by all three factors is *motivation to initiate interaction* (i.e., how people are motivated to interact and how they approach the display). A variable influenced primarily by software and hardware factors is *screen sharing* (i.e., how people share portions of the screen and physical space during the interaction). This evaluation framework was used to guide the design of a field study to analyze users' behavior and their experience with a large display, installed at an international conference [Ardito et al. 2012]. Analysis of the results provided support to the evaluation framework. It confirmed the influence of environmental factors on the user behavior with the display and further stressed the need to take into account psychological variables elicited by the physical context. Frameworks like this might indeed be useful when designing studies to evaluate public displays. However, a number of experiments should be performed to assess the actual validity of such frameworks in providing proper guidance.

6.7. Cutting-Edge Displays

Even if this survey does not focus on technology, it is worth mentioning some innovative proposals that envision new interaction possibilities. Displays that go beyond the familiar rigid surfaces and can be deformed by users (or by the computer) are being introduced. Users can actually pull, push, bend, or flex the display to show on-screen content better [Alexander et al. 2013]. Such displays support new modes of interaction. The term *Organic User Interfaces* was introduced by Vertegaal and Poupyrev [2008] to refer to "User interfaces with nonplanar displays, that may actively or passively change shape via analog physical inputs." The word "organic" was inspired by the millions of organic shapes that can be observed in nature, which are naturally adaptable and evolvable. A stretchable screen that allows users to interact by deforming the elastic membrane of the display was presented in Watanabe et al. [2008]. Due to its force of restoration, the elastic screen gives users a feedback of their manipulation actions, which could be meaningful in some specific applications. For example, the elastic display permits navigation in a temporal dataset. If a user presses deeper, he or she accesses older data. Another possible usage is 3D scene navigation, particularly to explore the human body.

Public displays are currently spread over the environment, but they are installed in fixed places. A very recent proposal that promises usage potentialities in public spaces is represented by midair displays (i.e., displays that can autonomously float in the air) [Schneegass et al. 2014]. Only some small-scale prototypes have been created by hanging an e-ink display under a copter drone. A possible application could be providing information to large crowds in emergency situations or to athletes during sporting events. At the current stage, midair displays are used to deliver information only, but they could easily become interactive by adding sensors that capture users' gestures and/or speech commands. Bubble-based systems are being proposed to provide a multimodal experience with a midair display. In *SensaBubble*, the external surface of the soap bubble is exploited as a projection screen, on which a couple of icons or digits can be effectively visualized [Seah et al. 2014]. Other parameters like bubble size, longevity, and frequency are manipulated to communicate different information. The scented fog inside the bubble represents a further communication channel. The authors envisage some possible, engaging applications. As an ambient clock, SensaBubble releases a number of scented bubbles corresponding to the current time. Furthermore, the bubble scent varies to communicate morning coffee break, lunchtime, and so forth. In a workstation setting, SensaBubble can be used as an alerting system to notify the user of a new email or social network service update, the system releases a bubble with the corresponding icon. By bursting the bubble, the user can see details of the notification on the computer display.

Thus far, 3D displays have not been used in public spaces. However, they are already available in specific contexts, for example, in research laboratories for visualizing scientific data, as well as in design studios for supporting the creation of high-fidelity virtual models of cars, buildings, and so forth (e.g., see Buxton et al. [2000]). The cost of such 3D displays keeps decreasing; however, there are other challenges that have to be addressed for their widespread adoption in public or semipublic settings. Such displays should allow an interactive 3D experience without the use of special devices (e.g., shutter glasses), which could hardly be made available in a public setting. A further challenge in this direction is represented by volumetric displays, which project a holographic 3D image into a physical space, such as the FogScreen example in Section 5.1.1 [Rakkolainen and Lugmayr 2007]. They allow users to manipulate the 3D object in a more direct way than flat displays, where such manipulations are mediated by unnatural gestures performed on a 2D surface. Another approach that aims at a more intuitive manipulation of digital content in 3D is presented in Hilliges et al. [2009]. The user is allowed to “pick up” virtual objects off the 2D table surface in order to manipulate them in the 3D space above the surface. A shadow-based feedback metaphor is exploited, which allows coupling the interactions occurring above the surface with the content being visualized on the tabletop.

7. CONCLUSION

This article has provided an overview of the use of large interactive displays installed in public or semipublic contexts. Such displays emerge as media to create new spaces for interactive experiences, enabling new forms of engagement with digital content. The analysis has shown that they provide interaction possibilities that go beyond the traditional desktop, which was based on the use of the mouse and the keyboard and limited the dialogue to a user and his or her own computer. Large displays allow more people to interact at the same time, fostering socialization and collaboration. Moreover, various interaction modalities are emerging, in particular those based on movements of different parts of the human body, not only hand gestures but also movements of the head, arms, legs, and feet.

All new technologies have great potential for more creative uses of computing than ever before; large interactive displays play a major role on this, as shown in this article. They can provide creative workspaces that stimulate the collaboration of groups of individuals, supporting them in sharing their ideas to reach a common goal. They can be used to visualize and reason about complex problems and information in new ways. Most of all, they are able to captivate the interest of people, enabling new forms of creative engagement in various contexts.

We see the value of a large display not only as a single device, but also as a part of an ecology of different devices in pervasive scenarios. This follows Marc Weiser’s [1991] vision of Ubiquitous Computing, which stresses that the real power does not come from any single device but emerges from the interaction of all of them. We have highlighted some significant challenges that have to be addressed to fully exploit the potentialities offered by large interactive displays and to give people the possibility of a seamless interaction with real-world objects and with other people.

ELECTRONIC APPENDIX

The Online Appendix can be accessed in the ACM Digital Library. It includes five tables, each reporting the papers classified according to a specific dimension. It also provides the list of references of all surveyed papers.

REFERENCES

ACM. 2014. ACM Digital Library. Retrieved from http://dl.acm.org/.

J. Alexander, R. Brotman, D. Holman, A. Younkin, R. Vertegaal, J. Kildal, A. A. Lucero, A. Roudaut, and S. Subramanian. 2013. Organic experiences: (Re)shaping interactions with deformable displays. In *Extended Abstracts on Human Factors in Computing Systems (CHI’13 EA)*. ACM, New York, NY, 3171–3174.

F. Alt, S. Schneegaß, A. Schmidt, J. Müller, and N. Memarovic. 2012. How to evaluate public displays. In *Proceedings of the International Symposium on Pervasive Displays (ISPD’12)*. ACM, New York, NY, 1–6.

C. Ardito, M. F. Costabile, and H.-C. Jetter. 2014. Gestures that people can understand and use. *Journal of Visual Languages & Computing* 25, 5 (2014), 572–576.

C. Ardito, M. F. Costabile, R. Lanzilotti, A. D. Angeli, and G. Desolda. 2012. A field study of a multi-touch display at a conference. In *Proceedings of the International Conference on Advanced Visual Interfaces (AVI’12)*. ACM, New York, NY, 580–587.

C. Ardito, M. F. Costabile, R. Lanzilotti, and A. L. Simeone. 2010. Sharable multitouch screens in cultural heritage and tourism applications. In *Proceedings of the IEEE Symposium on Visual Languages and Human-Centric Computing (VL/HCC’10)*. IEEE Computer Society, Los Alamitos, CA, 271–272.

C. Ardito, R. Lanzilotti, M. F. Costabile, and G. Desolda. 2013. Integrating traditional learning and games on large displays: An experimental study. *Educational Technology & Society* 16, 1 (2013), 44–53.

M. Ashdown and P. Robinson. 2004. A personal projected display. In *Proceedings of the ACM International Conference on Multimedia (MM'04).* ACM, New York, NY, 932–933.

T. Augsten, K. Kaefer, R. Meusel, C. Fetzer, D. Kanitz, T. Stoff, T. Becker, C. Holz, and P. Baudisch. 2010. Multitoe: High-precision interaction with back-projected floors based on high-resolution multi-touch input. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'10).* ACM, New York, NY, 209–218.

O. Bau, I. Poupyrev, A. Israr, and C. Harrison. 2010. TeslaTouch: Electrovibration for touch surfaces. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'10).* ACM, New York, NY, 283–292.

A. Bellucci. 2013. *A Comprehensive Framework for the Rapid Prototyping of Ubiquitous Interaction*. Ph.D. Dissertation, Universidad Carlos III de Madrid, Madrid, Spain.

A. Bellucci, A. Malizia, and I. Aedo. 2014. Light on horizontal interactive surfaces: Input space for tabletop computing. *ACM Computing Survey* 46, 3 (2014), 1–42.

A. Bellucci, A. Malizia, P. Diaz, and I. Aedo. 2010. Don't touch me: Multi-user annotations on a map in large display environments. In *Proceedings of the International Conference on Advanced Visual Interfaces (AVI'10).* ACM, New York, NY, 391–392.

A. Bellucci, A. Malizia, P. Diaz, and I. Aedo. 2010. Human-display interaction technology: Emerging remote interfaces for pervasive display environments. *IEEE Pervasive Computing* 9, 2 (2010), 72–76.

H. Benko, A. D. Wilson, and R. Balakrishnan. 2008. Sphere: Multi-touch interactions on a spherical display. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'08).* ACM, New York, NY, 77–86.

G. Beyer, F. Alt, J. Müller, A. Schmidt, K. Isakovic, S. Klose, M. Schiewe, and I. Haulsen. 2011. Audience behavior around large interactive cylindrical screens. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'11).* ACM, New York, NY, 1021–1030.

X. Bi, Y. Shi, and X. Chen. 2006. uPen: A smart pen-liked device for facilitating interaction on large displays. In *Proceedings of the IEEE International Workshop on Horizontal Interactive Human-Computer Systems (TABLETOP'06).* IEEE Computer Society, Washington, DC, 160–168.

S. Bo-Wen, T. Wei-Kuo, and B. Green. 2011. Coupling advanced modeling and visualization to improve high-impact tropical weather prediction. *Computing in Science & Engineering* 13, 5 (2011), 56–67.

J. Bolton, K. Kim, and R. Vertegaal. 2012. A comparison of competitive and cooperative task performance using spherical and flat displays. In *Proceedings of the ACM Conference on Computer Supported Cooperative Work (CSCW'12).* ACM, New York, NY, 529–538.

S. Boring and D. Baur. 2013. Making public displays interactive everywhere. *IEEE Computer Graphics and Applications* 33, 2 (2013), 28–36.

H. Brignull and Y. Rogers. 2003. Enticing people to interact with large public displays in public spaces. In *Proceedings of the IFIP TC 13 International Conference on Human-Computer Interaction (INTERACT'03).* IOS Press, IFIP, Zurich, CH, 17–24.

C. Briones, A. Fatah Gen. Schieck, and C. Mottram. 2007. A socializing interactive installation for the urban environments. In *Proceedings of the IADIS International Conference Applied Computing (AC'07).*

J. Bruner. 1990. *Acts of Meaning*. Harvard University Press, Cambridge, MA.

W. Buxton, G. Fitzmaurice, R. Balakrishnan, and G. Kurtenbach. 2000. Large displays in automotive design. *IEEE Comput. Graph. Appl.* 20, 4 (2000), 68–75.

C Seed. 2014. C Seed 201 Giant Outdoor LED TV. Retrieved from http://www.cseed.tv/.

S. Carter, E. Churchill, L. Denoue, J. Helfman, and L. Nelson. 2004. Digital graffiti: Public annotation of multimedia content. In *Extended Abstracts on Human Factors in Computing Systems (CHI'04 EA).* ACM, New York, NY, 1207–1210.

L.-W. Chan, H. Ting-Ting, L. Jin-Yao, H. Yi-Ping, and H. Jane. 2008. On top of tabletop: A virtual touch panel display. In *Proceedings of the IEEE International Workshop on Horizontal Interactive Human Computer Systems (TABLETOP'08).* IEEE Computer Society, Washington, DC, 169–176.

E. F. Churchill and L. Nelson. 2007. Interactive community bulletin boards as conversational hubs and sites for playful visual repartee. In *Proceedings of the Hawaii International Conference on System Sciences (HICSS'07).* IEEE Computer Society, Washington, DC, 76.

C. Coutrix, K. Kuikkaniemi, E. Kurvinen, G. Jacucci, I. Avdouevski, and R. Mäkelä. 2011. FizzyVis: Designing for playful information browsing on a multitouch public display. In *Proceedings of the Conference on Designing Pleasurable Products and Interfaces (DPPI'11)*. ACM, New York, NY, 1–8.

M. Csikszentmihalyi. 1997. *Creativity: Flow and the Psychology of Discovery and Invention*. Harper Perennial, New York, NY.

L. Denoue, L. Nelson, and E. Churchill. 2003. A fast, interactive 3D paper-flier metaphor for digital bulletin boards. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'03).* ACM, New York, NY, 169–172.

P. Dietz and D. Leigh. 2001. DiamondTouch: A multi-user touch technology. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'01).* ACM, New York, NY, 219–226.

K. C. Dohse, T. Dohse, J. D. Still, and D. J. Parkhurst. 2008. Enhancing multi-user interaction with multi-touch tabletop displays using hand tracking. In *Proceedings of the International Conference on Advances in Computer-Human Interaction (ACHI'08).* IEEE Computer Society, Washington, DC, 297–302.

P. Dragicevic and Y. Shi. 2009. Visualizing and manipulating automatic document orientation methods using vector fields. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS'09).* ACM, New York, NY, 65–68.

F. Echtler, S. Nestler, A. Dippon, and G. Klinker. 2009. Supporting casual interactions between board games on public tabletop displays and mobile devices. *Personal Ubiquitous Comput.* 13, 8 (2009), 609–617.

J. Exeler, M. Buzeck, and J. Müller. 2009. eMir: Digital signs that react to audience emotion. In *GI Jahrestagung (Annual Meeting of the German Society for Computer Science) (Informatik'09)*, S. Fischer, E. Maehle and R. Reischuk (Eds.). GI-Edition, Bonner Köllen Verlag, Germany, 3904–3910.

M. Finke, A. Tang, R. Leung, and M. Blackstock. 2008. Lessons learned: Game design for large public displays. In *Proceedings of the International Conference on Digital Interactive Media in Entertainment and Arts (DIMEA'08).* ACM, New York, NY, 26–33.

G. W. Fitzmaurice, H. Ishii, and W. A. S. Buxton. 1995. Bricks: Laying the foundations for graspable user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'95).* ACM, New York, NY, 442–449.

FlatFrog. 2014. FlatFrog Touch Technology. Retrieved from http://flatfrog.com/.

D. Freeman, H. Benko, M. R. Morris, and D. Wigdor. 2009. ShadowGuides: Visualizations for in-situ learning of multi-touch and whole-hand gestures. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS'09).* ACM, New York, NY, 165–172.

T. Fukasawa, K. Fukuchi, and H. Koike. 2006. A vision-based non-contact interactive advertisement with a display wall. In *Entertainment Computing (ICEC'06)*, R. Harper, M. Rauterberg and M. Combetto (Eds.). Lecture Notes in Computer Science, Vol. 4161. Springer, Berlin, 394–397.

T. Geller. 2006. Interactive tabletop exhibits in museums and galleries. *IEEE Computer Graphics and Applications* 26, 5 (2006), 6–11.

Google. 2014. Google Scholar. Retrieved from http://scholar.google.com/.

A. Grasso, A. Karsenty, and D. Snowdon. 2000. A bench for all moods. In *Extended Abstracts on Human Factors in Computing Systems (CHI'00 EA).* ACM, New York, NY, 197–198.

F. Greimel. 2011. A survey of interaction techniques for public displays. *Advances in Media Technology* (2011), 69–76.

F. Guimbretière, M. Stone, and T. Winograd. 2001. Fluid interaction with high-resolution wall-size displays. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'01).* ACM, New York, NY, 21–30.

M. Haller, J. Leitner, T. Seifried, J. R. Wallace, S. D. Scott, C. Richter, P. Brandl, A. Gokcezade, and S. Hunter. 2010. The NiCE Discussion Room: Integrating paper and digital media to support co-located group meetings. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'10).* ACM, New York, NY, USA, 609–618.

J. Hardy, E. Rukzio, and N. Davies. 2011. Real world responses to interactive gesture based public displays. In *Proceedings of the International Conference on Mobile and Ubiquitous Multimedia (MUM'11).* ACM, New York, NY, USA, 33–39.

C. Harrison and S. E. Hudson. 2009. Providing dynamically changeable physical buttons on a visual display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'09).* ACM, New York, NY, 299–308.

K. Hawkey, M. Kellar, D. Reilly, T. Whalen, and K. M. Inkpen. 2005. The proximity factor: Impact of distance on co-located collaboration. In *Proceedings of the International ACM SIGGROUP Conference on Supporting Group Work (GROUP'05).* ACM, New York, NY, 31–40.

M. Hereld, I. R. Judson, and R. L. Stevens. 2000. Introduction to building projection-based tiled display systems. *IEEE Computer Graphics and Applications* 20, 4 (2000), 22–28.

C. F. Herot and G. Weinzapfel. 1978. One-point touch input of vector information for computer displays. In *Proceedings of the Conference on Computer Graphics and Interactive Techniques (SIGGRAPH'78).* ACM, New York, NY, 210–216.

O. Hilliges, S. Izadi, A. D. Wilson, S. Hodges, A. Garcia-Mendoza, and A. Butz. 2009. Interactions in the air: Adding further depth to interactive tabletops. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'09)*. ACM, New York, NY, 139–148.

U. Hinrichs and S. Carpendale. 2011. Gestures in the wild: Studying multi-touch gesture sequences on interactive tabletop exhibits. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'11)*. ACM, New York, NY, 3023–3032.

U. Hinrichs, S. Carpendale, N. Valkanova, K. Kuikkaniemi, G. Jacucci, and A. Vande Moere. 2013. Interactive Public Displays. *IEEE Computer Graphics and Applications* 33, 2 (2013), 25–27.

U. Hinrichs, H. Schmidt, and S. Carpendale. 2008. EMDialog: Bringing information visualization into the museum. *IEEE Transactions on Visualization and Computer Graphics* 14, 6 (2008), 1181–1188.

E. Hoggan, S. A. Brewster, and J. Johnston. 2008. Investigating the effectiveness of tactile feedback for mobile touchscreens. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'08)*. ACM, New York, NY, 1573–1582.

E. Hornecker. 2008. "I don't understand it either, but it is cool"—visitor interactions with a multi-touch table in a museum. In *Proceedings of the IEEE International Workshop on Horizontal Interactive Human Computer Systems (TABLETOP'08)*. IEEE Computer Society, Washington, DC, 113–120.

S. Hosio, M. Jurmu, H. Kukka, J. Riekki, and T. Ojala. 2010. Supporting distributed private and public user interfaces in urban environments. In *Proceedings of the Workshop on Mobile Computing Systems & Applications (HotMobile'10)*. ACM, New York, NY, 25–30.

S. Hosio, V. Kostakos, H. Kukka, M. Jurmu, J. Riekki, and T. Ojala. 2012. From school food to skate parks in a few clicks: Using public displays to bootstrap civic engagement of the young. In *Pervasive Computing*, J. Kay, P. Lukowicz, H. Tokuda, P. Olivier and A. Krüger (Eds.). Lecture Notes in Computer Science, Vol. 7319. Springer, Berlin, 425–442.

E. M. Huang and E. D. Mynatt. 2003. Semi-public displays for small, co-located groups. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'03)*. ACM, New York, NY, 49–56.

K. Inkpen, K. Hawkey, M. Kellar, R. Mandryk, K. Parker, D. Reilly, S. Scott, and T. Whalen. 2005. Exploring display factors that influence co-located collaboration: Angle, size, number, and user arrangement. In *Proceedings of the International Conference on Human-Computer Interaction (HCII'05)*. Lawrence Erlbaum, Mahwah, NJ.

G. Jacucci, A. Morrison, G. T. Richard, J. Kleimola, P. Peltonen, L. Parisi, and T. Laitinen. 2010. Worlds of information: Designing for engagement at a public multi-touch display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'10)*. ACM, New York, NY, 2267–2276.

JazzMutant. 2014. Lemur. Retrieved from http://www.jazzmutant.com/.

H.-C. Jetter, J. Gerken, and H. Reiterer. 2010. Natural user interfaces: Why we need better model-worlds, not better gestures. In *Extended Abstracts on Human Factors in Computing Systems (CHI'10 EA)*.

H.-C. Jetter, H. Reiterer, and F. Geyer. 2013. Blended Interaction: Understanding natural human–computer interaction in post-WIMP interactive spaces. *Personal and Ubiquitous Computing* 8, 5 (2013), 1–20.

B. Johanson, S. Ponnekanti, C. Sengupta, and A. Fox. 2001. Multibrowsing: Moving web content across multiple displays. In *Ubiquitous Computing (Ubicomp'01)*, G. Abowd, B. Brumitt and S. Shafer (Eds.). Lecture Notes in Computer Science, Vol. 2201. Springer, Berlin, 346–353.

E. A. Johnson. 1965. Touch display—a novel input/output device for computers. *Electronics Letters* 1, 8 (1965), 219–220.

S. K. Kane, J. P. Bigham, and J. O. Wobbrock. 2008. Slide rule: Making mobile touch screens accessible to blind people using multi-touch interaction techniques. In *Proceedings of the ACM SIGACCESS Conference on Computers and Accessibility (ASSETS'08)*. ACM, New York, NY, 73–80.

S. K. Kane, M. R. Morris, A. Z. Perkins, D. Wigdor, R. E. Ladner, and J. O. Wobbrock. 2011. Access overlays: Improving non-visual access to large touch screens for blind users. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'11)*. ACM, New York, NY, 273–282.

D. Kim, P. Dunphy, P. Briggs, J. Hook, J. W. Nicholson, J. Nicholson, and P. Olivier. 2010. Multi-touch authentication on tabletops. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'10)*. ACM, New York, NY, 1093–1102.

M. T. Koppel, G. Bailly, J. Müller, and R. Walter. 2012. Chained displays: Configurations of public displays can be used to influence actor-, audience-, and passer-by behavior. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'12)*. ACM, New York, NY, 317–326.

E. Koskinen, T. Kaaresoja, and P. Laitinen. 2008. Feel-good touch: Finding the most pleasant tactile feedback for a mobile touch screen button. In *Proceedings of the ACM International Conference on Multimodal interfaces (ICMI'08)*. ACM, New York, NY, 297–304.

P. Krogh, M. Ludvigsen, and A. Lykke-Olesen. 2004. “Help me pull that cursor” a collaborative interactive floor enhancing community interaction. *Australasian Journal of Information Systems* 11, 2 (2004), 75–87.

M. W. Krueger, T. Gionfriddo, and K. Hinrichsen. 1985. VIDEOPLACE: An artificial reality. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'85)*. ACM, New York, NY, 35–40.

C. Krumbholz, J. Leigh, A. Johnson, L. Renambot, and R. Kooima. 2005. Lambda table: High resolution tiled display table for interacting with large visualizations. In *Proceedings of the Workshop for Advanced Collaborative Environments (WACE'05)*.

H. Kukka, F. Kruger, V. Kostakos, T. Ojala, and M. Jurmu. 2011. Information to go: Exploring in-situ information pick-up “in the wild.” In *Human-Computer Interaction (INTERACT'11)*, P. Campos, N. Graham, J. Jorge, N. Nunes, P. Palanque and M. Winckler (Eds.). Lecture Notes in Computer Science, Vol. 6947. Springer, Berlin, 487–504.

G. Kurtenbach and G. W. Fitzmaurice. 2005. Guest editors' introduction: Applications of large displays. *IEEE Computer Graphics and Applications* 25, 4 (2005), 22–23.

G. Kurtenbach and E. A. Hulteen. 1990. *Gestures in Human-Computer Communication*. Addison-Wesley, Boston, Massachusetts, USA.

J. C. Lee, S. E. Hudson, J. W. Summet, and P. H. Dietz. 2005. Moveable interactive projected displays using projector based tracking. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'05)*. ACM, New York, NY, 63–72.

J. C. Lee, S. E. Hudson, and E. Tse. 2008. Foldable interactive displays. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'08)*. ACM, New York, NY, 287–290.

S. Lee and S. Zhai. 2009. The performance of touch screen soft buttons. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'09)*. ACM, New York, NY, 309–318.

K. Li, H. Chen, Y. Chen, D. W. Clark, P. Cook, S. Damianakis, G. Essl, A. Finkelstein, T. Funkhouser, T. Housel, A. Klein, Z. Liu, E. Praun, J. P. Singh, B. Shedd, J. Pal, G. Tzanetakis, and J. Zheng. 2000. Building and using a scalable display wall system. *IEEE Computer Graphics and Applications* 20, 4 (2000), 29–37.

J.-Y. Lin, Y.-Y. Chen, J.-C. Ko, H. Kao, W.-H. Chen, T.-H. Tsai, S.-C. Hsu, and Y.-P. Hung. 2009. i-m-Tube: An interactive multi-resolution tubular display. In *Proceedings of the ACM International Conference on Multimedia (MM'09)*. ACM, New York, NY, 253–260.

R. Lissermann, J. Huber, J. Steimle, and M. Mühlhäuser. 2013. Permulin: Personal in- and output on interactive surfaces. In *Extended Abstracts on Human Factors in Computing Systems (CHI'13 EA)*. ACM, New York, NY, 3083–3086.

H. Lü and Y. Li. 2012. Gesture coder: A tool for programming multi-touch gestures by demonstration. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'12)*. ACM, New York, NY, USA, 2875–2884.

A. Lucchi, P. Jermann, G. Zufferey, and P. Dillenbourg. 2010. An empirical evaluation of touch and tangible interfaces for tabletop displays. In *Proceedings of the International Conference on Tangible, Embedded, and Embodied Interaction (TEI'10)*. ACM, New York, NY, 177–184.

C. Magerkurth and P. Tandler. 2002. Interactive walls and handheld devices – applications for a smart environment. In *UbiComp'02 Workshop on Interactive Walls and Tables (Interactive walls and handheld devices – applications for a smart environment)*.

P. Marshall, R. Morris, Y. Rogers, S. Kreitmayer, and M. Davies. 2011. Rethinking “multi-user”: An in-the-wild study of how groups approach a walk-up-and-use tabletop interface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'11)*. ACM, New York, NY, 3033–3042.

J. Mccarthy, T. Costa, and E. Liongosari. 2001. UniCast, OutCast & GroupCast: Three steps toward ubiquitous, peripheral displays. In *Ubiquitous Computing (Ubicomp'01)*, G. Abowd, B. Brumitt and S. Shafer (Eds.). Lecture Notes in Computer Science, Vol. 2201. Springer, Berlin, 332–345.

E. Mcwilliams. 1972. Large scale CAI: The NSF project. In *Proceedings of the ACM Annual Conference (ACM'72)*. ACM, New York, NY, 314–317.

N. Mehta. 1982. *A Flexible Machine Interface*. Master thesis, University of Toronto, Toronto, Canada.

Microsoft. 2014. Perceptive Pixel. Retrieved from http://perceptivepixel.azurewebsites.net/.

M. R. Minsky. 1984. Manipulating simulated objects with real-world gestures using a force and position sensitive screen. *SIGGRAPH Computer Graphics* 18, 3 (1984), 195–203.

M. R. Morris, A. Huang, A. Paepcke, and T. Winograd. 2006. Cooperative gestures: Multi-user gestural interactions for co-located groupware. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'06)*. ACM, New York, NY, 1201–1210.

J. Müller, F. Alt, D. Michelis, and A. Schmidt. 2010. Requirements and design space for interactive public displays. In *Proceedings of the ACM International Conference on Multimedia (MM'10)*. ACM, New York, NY, 1285–1294.

J. Müller, J. Exeler, M. Buzeck, and A. Krüger. 2009. ReflectiveSigns: Digital signs that adapt to audience attention. In *Pervasive Computing*, H. Tokuda, M. Beigl, A. Friday, A. J. B. Brush and Y. Tobe (Eds.). Lecture Notes in Computer Science, Vol. 5538. Springer, Berlin, 17–24.

J. Müller, R. Walter, G. Bailly, M. Nischt, and F. Alt. 2012. Looking glass: A field study on noticing interactivity of a shop window. In *Extended Abstracts on Human Factors in Computing Systems (CHI'12 EA)*. ACM, New York, NY, 1465–1466.

MultiTaction. 2014. Ultra Thin Bezel. Retrieved from http://www.multitaction.com/.

M. A. Nacenta, Y. Kamber, Y. Qiang, and P. O. Kristensson. 2013. Memorability of pre-designed and user-defined gesture sets. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'13)*. ACM, New York, NY, 1099–1108.

NASA. 2014. Visualization System: Hyperwall-2. Retrieved from http://www.nas.nasa.gov/hecc/resources/viz_systems.html.

D. A. Norman. 2006. Interaction design is still an art form: Ergonomics is real engineering. *Interactions* 13, 1 (2006), 45–60.

D. A. Norman. 2010. Natural user interfaces are not natural. *Interactions* 17, 3 (2010), 6–10.

K. O'hara, M. Lipson, M. Jansen, A. Unger, H. Jeffries, and P. Macer. 2004. Jukola: Democratic music choice in a public space. In *Proceedings of the Conference on Designing Interactive Systems (DIS'04)*. ACM, New York, NY, 145–154.

U. Oh and L. Findlater. 2013. The challenges and potential of end-user gesture customization. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'13)*. ACM, New York, NY, 1129–1138.

T. Ojala, V. Kostakos, H. Kukka, T. Heikkinen, T. Linden, M. Jurmu, S. Hosio, F. Kruger, and D. Zanni. 2012. Multipurpose interactive public displays in the wild: Three years laters. *Computer* 45, 5 (2012), 42–49.

T. Ojala, H. Kukka, T. Lindén, T. Heikkinen, M. Jurmu, S. Hosio, and F. Kruger. 2010. UBI-Hotspot 1.0: Large-scale long-term deployment of interactive public displays in a city center. In *Proceedings of the International Conference on Internet and Web Applications and Services (ICIW'10)*. IEEE Computer Society, Washington, DC, 285–294.

R. Oldenburg. 1989. *The Great Good Place: Cafes, Coffee Shops, Community Centers, Beauty Parlors, General Stores, Bars, Hangouts, and How They Get You Through the Day.* Paragon House, New York, NY.

N. W. Orr and V. D. Hopkins. 1968. The role of touch display in air traffic control. *The Controller* 7 (1968), 7–9.

F. Ott and M. Koch. 2012. Social software beyond the desktop—ambient awareness and ubiquitous activity streaming. *it - Information Technology* 54, 5 (2012), 243.

A. Oulasvirta. 2008. FEATURE: When users "do" the Ubicomp. *Interactions* 15, 2 (2008), 6–9.

O. Ozturk, T. Matsunami, Y. Suzuki, T. Yamasaki, and K. Aizawa. 2012. Real-time tracking of humans and visualization of their future footsteps in public indoor environments. *Multimedia Tools Appl.* 59, 1 (2012), 65–88.

Paravision. 2014. Multi-touch Table. Retrieved from http://www.paravision.org/multi-touch-table/multi-touch-table.php.

T. Payne, E. David, N. R. Jennings, and M. Sharifi. 2006. Auction mechanisms for efficient advertisement selection on public displays. In *Proceedings of the European Conference on Artificial Intelligence (ECAI'06)*. IOS Press, Amsterdam, The Netherlands, 285–289.

E. W. Pedersen and K. Hornbæk. 2012. An experimental comparison of touch interaction on vertical and horizontal surfaces. In *Proceedings of the Nordic Conference on Human-Computer Interaction (NordiCHI'12)*. ACM, New York, NY, 370–379.

P. Peltonen, E. Kurvinen, A. Salovaara, G. Jacucci, T. Ilmonen, J. Evans, A. Oulasvirta, and P. Saarikko. 2008. It's Mine, Don't Touch!: Interactions at a large multi-touch display in a city centre. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems (CHI'08)*. ACM, New York, NY, 1285–1294.

P. Peltonen, A. Salovaara, G. Jacucci, T. Ilmonen, C. Ardito, P. Saarikko, and V. Batra. 2007. Extending large-scale event participation with user-created mobile media on a public display. In *Proceedings of the International Conference on Mobile and Ubiquitous Multimedia (MUM'07)*. ACM, New York, NY, 131–138.

M. Perry, S. Beckett, K. O'hara, and S. Subramanian. 2010. WaveWindow: Public, performative gestural interaction. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS'10)*. ACM, New York, NY, 109–112.

C. Pinhanez. 2001. Using a steerable projector and a camera to transform surfaces into interactive displays. In *Extended Abstracts on Human Factors in Computing Systems (CHI'01 EA)*. ACM, New York, NY, 369–370.

A. M. Piper, E. O'Brien, M. R. Morris, and T. Winograd. 2006. SIDES: A cooperative tabletop computer game for social skills development. In *Proceedings of the ACM Conference on Computer Supported Cooperative Work (CSCW'06)*. ACM, New York, NY, 1–10.

PLANAR. 2014. Clarity Matrix. Retrieved from http://www.planar.com/.

PQ LABS. 2014. Mighty Glass. Retrieved from http://multitouch.com/.

I. K. Rakkolainen and A. K. Lugmayr. 2007. Immaterial display for interactive advertisements. In *Proceedings of the International Conference on Advances in Computer Entertainment Technology (ACE'07)*. ACM, New York, NY, 95–98.

F. Redhead and M. Brereton. 2009. Designing interaction for local communications: An urban screen study. In *Human-Computer Interaction – INTERACT 2009*, T. Gross, J. Gulliksen, P. Kotzé, L. Oestreicher, P. Palanque, R. Prates and M. Winckler (Eds.). Lecture Notes in Computer Science, Vol. 5727. Springer, Berlin, 457–460.

W. Reitberger, A. Meschtscherjakov, T. Mirlacher, T. Scherndl, H. Huber, and M. Tscheligi. 2009. A persuasive interactive mannequin for shop windows. In *Proceedings of the International Conference on Persuasive Technology (Persuasive'09)*. ACM, New York, NY, 1–8.

J. Rekimoto and M. Saitoh. 1999. Augmented surfaces: A spatially continuous work space for hybrid computing environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'99)*. ACM, New York, NY, 378–385.

Y. Rogers, Y.-K. Lim, and W. R. Hazlewood. 2006. Extending tabletops to support flexible collaborative interactions. In *Proceedings of the IEEE International Workshop on Horizontal Interactive Human-Computer Systems (TABLETOP'06)*. IEEE Computer Society, Washington, DC, 71–78.

Y. Rogers and S. Lindley. 2004. Collaborating around vertical and horizontal large interactive displays: Which way is best? *Interacting with Computers* 16, 6 (2004), 1133–1152.

E. Rubegni, N. Memarovic, and M. Langheinrich. 2011. Talking to strangers: Using large public displays to facilitate social interaction. In *Design, User Experience, and Usability. Theory, Methods, Tools and Practice (HCII'11)*, A. Marcus (Eds.). Lecture Notes in Computer Science, Vol. 6770. Springer, Berlin, 195–204.

T. A. Sandstrom, C. Henze, and C. Levit. 2003. The hyperwall. In *Proceedings of the Conference on Coordinated and Multiple Views In Exploratory Visualization (CMV'03)*. IEEE Computer Society, Washington, DC, 124.

D. L. Schacter, D. T. Gilbert, and D. M. Wegner. 2011. *Psychology* (2nd ed.), Worth, New York, NY.

J. Scheible and T. Ojala. 2005. MobiLenin combining a multi-track music video, personal mobile phones and a public display into multi-user interactive entertainment. In *Proceedings of the ACM international conference on Multimedia (MM'05)*. ACM, New York, NY, USA, 199–208.

J. Scheible, T. Ojala, and P. Coulton. 2008. MobiToss: A novel gesture based interface for creating and sharing mobile multimedia art on large public displays. In *Proceedings of the ACM International Conference on Multimedia (MM'08)*. ACM, New York, NY, 957–960.

D. R. Schikore, R. A. Fischer, R. Frank, R. Gaunt, J. Hobson, and B. Whitlock. 2000. High-resolution multiprojector display walls. *IEEE Computer Graphics and Applications* 20, 4 (2000), 38–44.

A. Schmidt, B. Pfleging, F. Alt, A. Sahami, and G. Fitzpatrick. 2012. Interacting with 21st-Century Computers. *IEEE Pervasive Computing* 11, 1 (2012), 22–31.

C. Schmidt, J. Müller, and G. Bailly. 2013. Screenfinity: Extending the perception area of content on very large public displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'13)*. ACM, New York, NY, 1719–1728.

S. Schneegass, F. Alt, J. Scheible, A. Schmidt, and H. Su. 2014. Midair displays: Exploring the concept of free-floating public displays. In *Extended Abstracts on Human Factors in Computing Systems (CHI'14 EA)*. ACM, New York, NY, 2035–2040.

J. Schöning, P. Brandl, F. Daiber, F. Echtler, O. Hilliges, J. Hook, M. Löchtefeld, N. Motamedi, L. Müller, P. Olivier, T. Roth, and U. Von Zadow. 2008. *Multi-Touch Surfaces: A Technical Guide.* Technical Report TUM-I0833, Technical University of Munich.

J. Schöning, J. Hook, T. Bartindale, D. Schmidt, P. Oliver, F. Echtler, N. Motamedi, P. Brandl, and U. Zadow. 2010. Building interactive multi-touch surfaces. In *Tabletops - Horizontal Interactive DISPLAYS*, C. Müller-Tomfelde (Eds.). Human-Computer Interaction Series. Springer, London, 27–49.

S. D. Scott and S. Carpendale. 2006. Guest editors' introduction: Interacting with digital tabletops. *IEEE Computer Graphics and Applications* 26, 5 (2006), 24–27.

S. D. Scott, K. D. Grant, and R. L. Mandryk. 2003. System guidelines for co-located, collaborative work on a tabletop display. In *Proceedings of the Conference on European Conference on Computer Supported Cooperative Work (ECSCW'03)*. Kluwer Academic Publishers, Norwell, MA, 159–178.

S. A. Seah, D. Martinez Plasencia, P. D. Bennett, A. Karnik, V. S. Otrocol, J. Knibbe, A. Cockburn, and S. Subramanian. 2014. SensaBubble: A chrono-sensory mid-air display of sight and smell. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'14)*. ACM, New York, NY, 2863–2872.

J. She, J. Crowcroft, H. Fu, and F. Li. 2014. Convergence of interactive displays with smart mobile devices for effective advertising: A survey. *ACM Transactions on Multimedia Computing Communication Applications* 10, 2 (2014), 1–16.

C. Shen, K. Everitt, and K. Ryall. 2003. UbiTable: Impromptu face-to-face collaboration on horizontal interactive surfaces. In *Ubiquitous Computing (UbiComp'03)*, A. Dey, A. Schmidt and J. McCarthy (Eds.). Lecture Notes in Computer Science, Vol. 2864. Springer, Berlin, 281–288.

C. Shen, F. D. Vernier, C. Forlines, and M. Ringel. 2004. DiamondSpin: An extensible toolkit for around-the-table interaction. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems (CHI'04)*. ACM, New York, NY, 167–174.

B. Sherwood. 1972. Status of PLATO IV. *SIGCUE Outlook* 6, 3 (1972), 3–6.

A. Shinohara, J. Tomita, T. Kihara, S. Nakajima, and K. Ogawa. 2007. A huge screen interactive public media system: Mirai-Tube. In *Human-Computer Interaction. Interaction Platforms and techniques*, J. Jacko (Eds.). Lecture Notes in Computer Science, Vol. 4551. Springer, Berlin, 936–945.

A. S. Shirazi, T. Döring, P. Parvahan, B. Ahrens, and A. Schmidt. 2009. Poker surface: Combining a multi-touch table and mobile phones in interactive card games. In *Proceedings of the International Conference on Human-Computer Interaction with Mobile Devices & Services (MobileHCI'09)*. ACM, New York, NY, 1–2.

B. Shneiderman. 2007. Creativity support tools: Accelerating discovery and innovation. *Commun. ACM* 50, 12 (2007), 20–32.

N. A. Streitz, J. Geißler, T. Holmer, S. I. Konomi, C. Müller-Tomfelde, W. Reischl, P. Rexroth, P. Seitz, and R. Steinmetz. 1999. i-LAND: An interactive landscape for creativity and innovation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'99)*. ACM, New York, NY, 120–127.

N. A. Streitz, C. Röcker, T. Prante, R. Stenzel, and D. Van Alphen. 2003. Situated interaction with ambient information: Facilitating awareness and communication in ubiquitous work environments. In *Proceedings of the International Conference on Human-Computer Interaction (HCII 2003)*. Lawrence Erlbaum Associates, Inc, Mahwah, NJ, 133–137.

S. Taylor, S. Izadi, D. Kirk, R. Harper, and A. Garcia-Mendoza. 2009. Turning the tables: An interactive surface for vjing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'09)*. ACM, New York, NY, 1251–1254.

P. Tuddenham, D. Kirk, and S. Izadi. 2010. Graspables revisited: Multi-touch vs. tangible input for tabletop displays in acquisition and manipulation tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'10)*. ACM, New York, NY, 2223–2232.

V. Tuulos, J. Scheible, and H. Nyholm. 2007. Combining web, mobile phones and public displays in large-scale: Manhattan Story Mashup. In *Pervasive COMPUTING*, A. LaMarca, M. Langheinrich and K. Truong (Eds.). Lecture Notes in Computer Science, Vol. 4480. Springer, Berlin, 37–54.

T. Vajk, P. Coulton, W. Bamford, and R. Edwards. 2008. Using a mobile phone as a "Wii-like" controller for playing games on a large public display. *International Journal on Computer Games Technology* 2008, 1–6.

V. Valkama and T. Ojala. 2011. Stakeholder value propositions on open community testbed of interactive public displays. In *Proceedings of the International Conference on Management of Emergent Digital EcoSystems (MEDES'11)*. ACM, New York, NY, 107–113.

R. Vertegaal and I. Poupyrev. 2008. Organic user interfaces. *Commun. ACM* 51, 6 (2008), 26–30.

D. Vogel and R. Balakrishnan. 2004. Interactive public ambient displays: Transitioning from implicit to explicit, public to personal, interaction with multiple users. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'04)*. ACM, New York, NY, 137–146.

J. P. Wachs, M. Kölsch, H. Stern, and Y. Edan. 2011. Vision-based hand-gesture applications. *Commun. ACM* 54, 2 (2011), 60–71.

R. Walter, G. Bailly, and J. Müller. 2013. StrikeAPose: Revealing mid-air gestures on public displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'13)*. ACM, New York, NY, 841–850.

F. Wang, X. Cao, X. Ren, and P. Irani. 2009. Detecting and leveraging finger orientation for interaction with direct-touch surfaces. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'09)*. ACM, New York, NY, 23–32.

Y. Watanabe, A. Cassinelli, T. Komuro, and M. Ishikawa. 2008. The deformable workspace: A membrane between real and virtual space. In *Proceedings of the IEEE International Workshop on Horizontal Interactive Human Computer Systems (TABLETOP'08)*. IEEE, Los Alamitos, CA, 145–152.

M. Weiser. 1991. The Computer for the 21st Century. *Scientific American* 265, 3 (1991), 94–104.

P. Wellner. 1991. The Digital Desk Calculator: Tactile manipulation on a desktop display. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'91)*. ACM, New York, NY, 27–33.

D. Wigdor, H. Jiang, C. Forlines, M. Borkin, and C. Shen. 2009. WeSpace: The design development and deployment of a walk-up and share multi-surface visual collaboration system. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'09)*. ACM, New York, NY, 1237–1246.

A. D. Wilson and R. Sarin. 2007. BlueTable: Connecting wireless mobile devices on interactive surfaces using vision-based handshaking. In *Proceedings of the Graphics Interface (GI'07)*. ACM, New York, NY, 119–125.

J. Wobbrock, M. Morris, and A. Wilson. 2009. User-defined gestures for surface computing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'09)*. ACM, New York, NY, 1083–1092.

ZaagTech Inc. 2014. ZaagTech Multi-Touch Products. Retrieved from http://www.zaagtech.com/.

S. Zhai, C. Morimoto, and S. Ihde. 1999. Manual and gaze input cascaded (MAGIC) pointing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'99)*. ACM, New York, NY, 246–253.

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