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Interaction with large displays: a survey

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Large interactive displays are increasingly placed in public (or semi-public) 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, Multi-touch displays, Touchless interaction

1. INTRODUCTION

The first prototypes of touch screens were already presented in the '60s, 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 semi-public) 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, in order 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 since 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]. Another considered 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. edited a special issue on interactive public displays, which actually range from large-scale media fa-

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çades, requiring user interaction from a distance through some kind of device, to large interactive displays that can be directly touched by users [Hinrichs et al. 2013]. In this article, we do not consider façade displays, i.e. displays integrated into architectural structures like buildings and usually of very large scale, since they have different requirements.

A comprehensive overview of the research on systems using large interactive displays is very challenging, due to large number of papers published on this topic. 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]. Very recently, 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 co-located 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.

The 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 sub-section. 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 '60s 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-Champaign [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 '70s, 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 '80s, creating the first multi-touch 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. implemented many of the hand gestures for zooming and rotating objects that are still very popular today [Krueger et al. 1985].

Almost all prototypes developed up to the end of the '80s were monitors that used either cathode-ray tube or plasma technology. Due to the limited size of such monitors, several researchers worked to develop solutions for much larger dis-

plays. The early '90s were influenced by the famous papers of Mark Weiser [Weiser 1991], in which he clearly says that ubiquitous computers have to be of different sizes, each suited to a particular task, since real power emerges from the interaction of all the different devices. This pushed researchers towards 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 the '90s [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 two meters wide.

As shown in this paper, 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 multi-touch display used by deejays as a music controller [JazzMutant 2014]. *DiamondTouch* is a multi-touch 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 micro-electric 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. Some years later, in 2007, Microsoft commercialized *Surface 1.0*, another multi-touch 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* multi-touch 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]. ACM Digital Library includes important scientific papers in computer science, i.e. those published by 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 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 Electronic 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 semi-public settings. A paper was excluded if it met at least one of the following criteria: a) it presented façade large displays; b) it was an introductory paper of a special issue, a book or workshop; c) 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; e) it was not written in English.

The distribution of the selected 206 papers, according to the publication year, is shown in Fig. 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 six months of 2014 were analyzed.

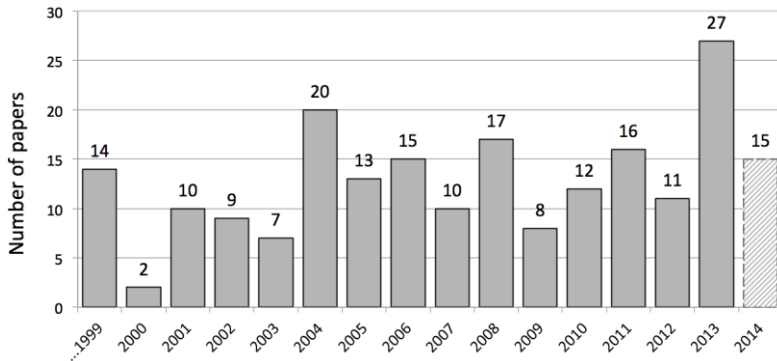


Fig. 1. Distribution over the years of the surveyed papers.

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 human-computer interaction by introducing new interaction modalities. Thus, we focused on *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 set-up.** Set-up 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 (Fig. 2a). Many systems also adopt a *horizontal* set-up, e.g. tabletops (Fig. 2b). A few systems propose a *diagonal* set-up (Fig. 2c), a *floor* display (Fig. 2d), while some project the computer output on any surface.

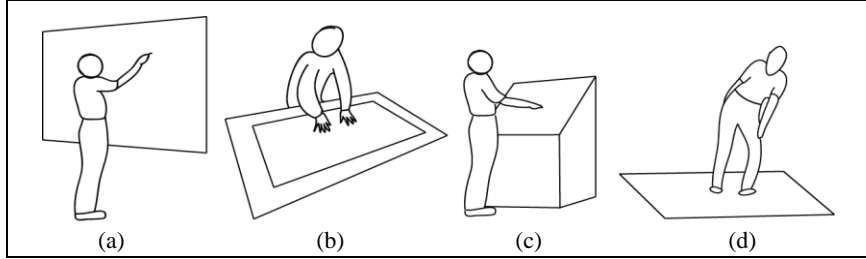


Fig. 2. Display set-ups: (a) vertical, (b) horizontal, (c) diagonal, (d) floor.

- 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: a) by touching and/or manipulating objects visualized on the display (*Touch* in Table I), b) through *external devices*, c) through *tangible objects* and d) 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 due to 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* category.
- 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*, i.e. 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 set-up			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

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%, since 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, since in some papers the visualization technology is not specified. 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 Electronic 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 sub-section 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 technology is 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 Fig. 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 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.

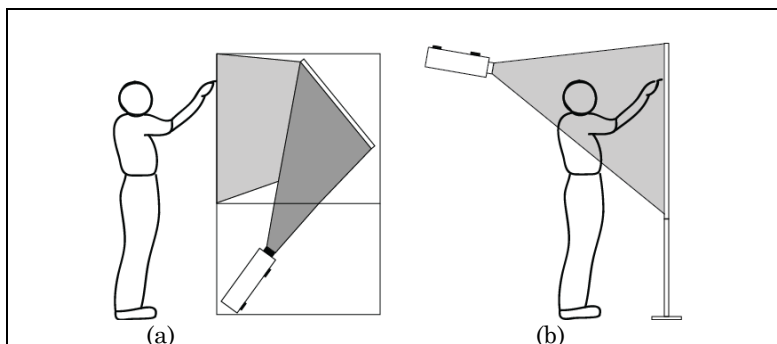


Fig. 3. Two different projection solutions: (a) the projector is behind the visualization surface, (b) the projector is in front of the visualization surface.

Projection technology is very popular, since it is usually economical and quite effective, as discussed in [Hereld et al. 2000; 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, since 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 (Fig. 4a), producing a display of $6,400 \times 3,072$ pixels across 5×2.5 meters (Fig. 4b). 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; 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.



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.

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 mid-air immaterial image plane. Thus, the viewer can even walk through the display, since it is actually made of air (Fig. 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, by using 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, mid-air display was unusual for viewers and they would have needed hints for using it, for example a projected text saying “touch me”.



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

5.1.2 Monitor

Another popular visualization technology adopts an LCD or plasma *monitor*. Such monitors are largely used today, since 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 [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 100 MPixel 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 set-up (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 [Bowen 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

In order to highlight the evolution of large interactive displays over the years according to the visualization technology, Fig. 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.

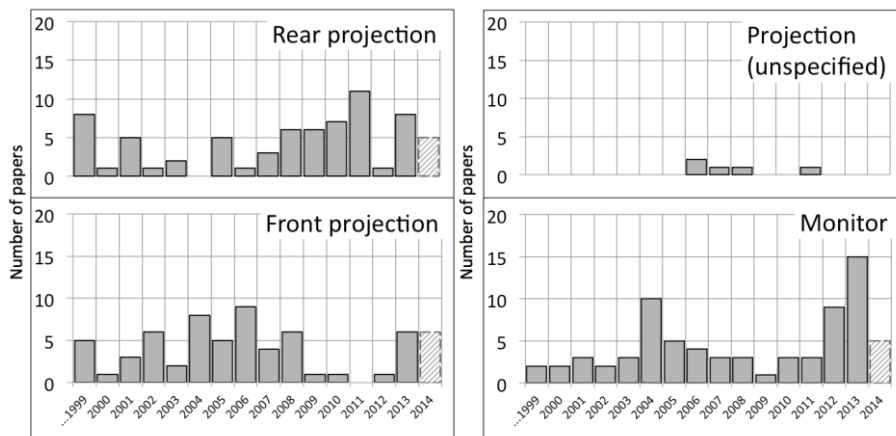


Fig. 6. Distribution over the years of the surveyed papers according to the *visualization technology* dimension.

5.2 Display Set-up

The display of traditional PCs has a *vertical* set-up. For large interactive displays, besides the vertical one, *horizontal* and *diagonal* set-ups have also been used. More recently, *floor* installations have been presented, primarily for entertain-

ment. Furthermore, there are systems that project the computer output over any surface: spherical, cylindrical or even irregular.

5.2.1 Vertical

As shown in Table I, most papers in our survey (67%) describe displays that are vertically installed (Fig. 2a). This set-up is often used in a city context, since 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 set-up 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. 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 [Koppel et al. 2012]. The displays can be combined to create different shapes: hexagonal, flat and concave (Fig. 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.

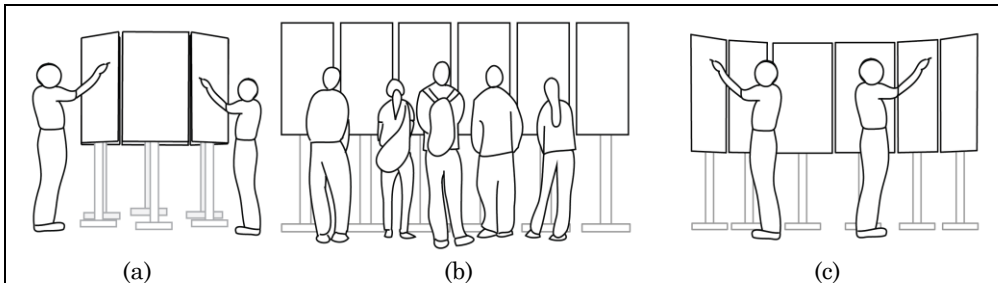


Fig. 7. Chained Displays: (a) hexagonal, (b) flat and (c) concave.

5.2.2 Horizontal

In several cases, it is useful to set the display horizontally, like the top of a desk (Fig. 2b), so that users can interact even for a long time while sitting around it. This set-up is presented in 31% of the papers and, after the vertical set-up, 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 tasks, because multiple users can discuss and share the display while comfortably sitting around it [Shen et al. 2003]. Unlike the vertical set-up, 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; Shen et al. 2004]).

The study reported in [Pedersen and Hornbæk 2012] compared vertical and horizontal set-ups 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 set-up 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* set-up (see Fig. 2c). The display is installed with the lowest side at a height similar to a horizontal set-up. 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 set-ups 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 (Fig. 8).



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.

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 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

8% of the papers examined present special set-ups not classifiable within those previously described. Indeed, some projection technologies permit the visualization of the computer output on a surface which 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 for example Fig. 9 [Lee et al. 2008]. These types of set-up 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; Lin et al. 2009]), as shown in Fig. 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, since each user sees only the portion of the display in front of him/her.



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.

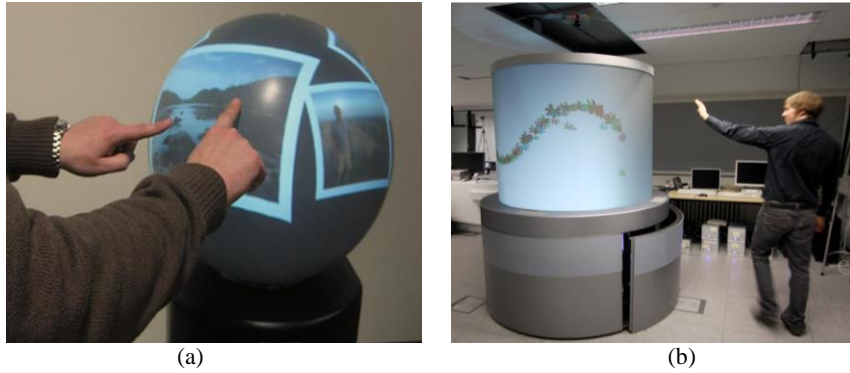


Fig. 10. Example of: (a) a spherical display (Source [Benko et al. 2008], © ACM); (b) a cylindrical display (Source [Beyer et al. 2011], © ACM).

5.2.6 Temporal trend of display set-up

Fig. 11 shows the graph of the distribution over the years of the papers surveyed, according to the display set-up dimension. The first systems used the vertical set-up, which is still the most popular. The horizontal set-up, 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 set-ups (e.g., [FlatFrog 2014; JazzMutant 2014; ZaagTech Inc 2014]). The remaining set-ups are still in an experimental phase.

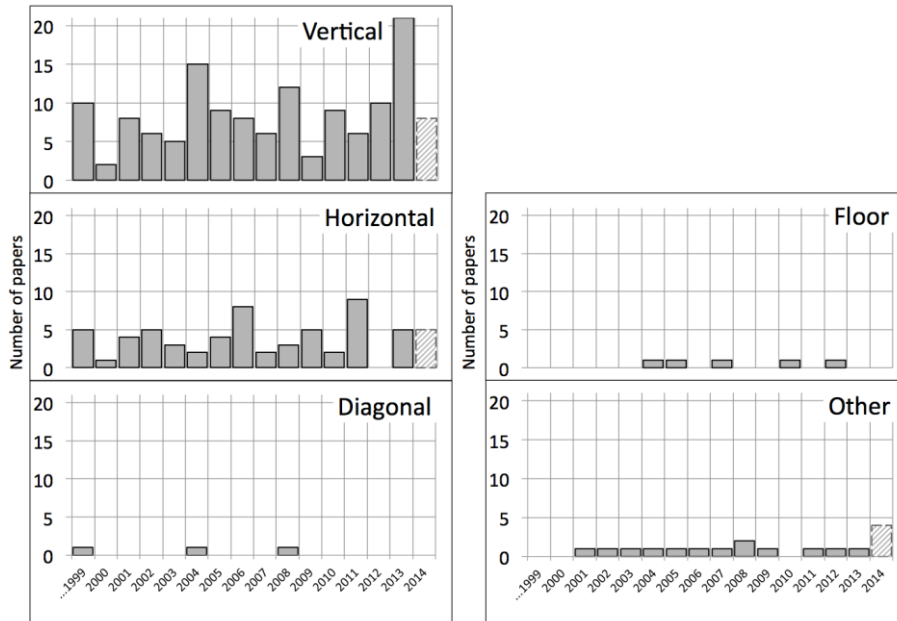


Fig. 11. Distribution over the years of the surveyed papers according to the *display set-up* dimension.

5.3 Interaction modality

Systems equipped with large displays adopt several innovative interaction modalities, in order 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

57% of the surveyed papers refer to systems whose interaction modality is based on the touch of users' fingers and/or users' hands on the display surface, in order 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]; 3) ultrasound emitters and sensors [Ashdown and Robinson 2004].

The system described in [Peltonen et al. 2008], besides detecting more fingers at a time, 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 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 multi-touch tabletop with a camera mounted above the table, which 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 smart-phone 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 semi-public settings. Boring and Baur 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. discuss how the integration of mobile devices with interactive displays allows useful information to be instantly delivered to audiences for effective and informative advertising [She et al. 2014]. It is worth noting that the use of external devices helps to solve some privacy problems: people can input personal data, passwords, etc. through the device, without worrying about others looking at the display (see for example [Magerkurth and Tandler 2002]).



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.

5.3.3 Tangible object

21% of the surveyed papers describe systems that allow users to interact by manipulating real objects on the display (e.g. [Lucchi et al. 2010; 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 (Fig. 12). Any change the user makes on the tabletop, e.g. editing the calendar, is automatically reported in the mobile device. 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 human-computer interaction 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 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 (Fig. 13). The goal is to capture the attention of potential customers and increase the time they spend in front of the shop window.



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

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 simply passes by. It also interprets user's postures. Müller et al. described a study on an interactive shop window aimed at comparing different visual feedbacks that communicate shop window interactivity to passers-by [Müller et al. 2012]. 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 4 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. distinguish: a) *surface gestures*, which imply touching the display surface; b) *remote gestures*, performed by the user without any contact with the display; c) *motion gestures*,

performed while the user is carrying a device, e.g. holding a mobile phone or wearing an ad-hoc device [Bellucci et al. 2014]. 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 mid-air 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 interaction. Already in 1999, Zhai et al. 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 [Zhai et al. 1999]. 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].

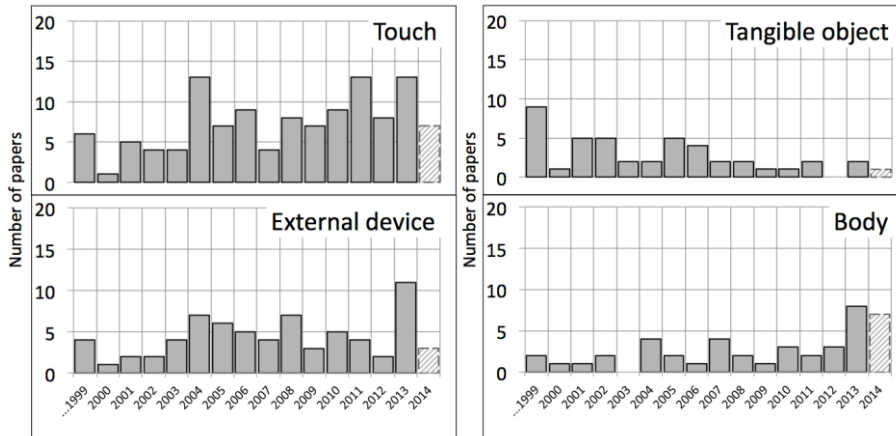


Fig. 14. Distribution over the years of the surveyed papers according to the *interaction modality* dimension.

5.3.5 Temporal trend of interaction modalities

The temporal trend of interaction modalities is shown in Fig. 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, etc. 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, ap-

plications of increasing complexity and for different purposes were developed, as reported in the following.

5.4.1 Productivity

54% of the papers 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 multi-touch gestures [Hawkey et al. 2005], creating and mixing music tracks [Taylor et al. 2009], 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 multi-track 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

25% of the papers report applications that, by allowing multi-user 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 afore-mentioned *iFloor* [Krogh et al. 2004] (see Section 5.2.4). Morris et al. discuss motivating scenarios for the use of cooperative gesturing and describe some initial experiences with *CollabDraw*, a system for collaborative art and photo manipulation [Morris et al. 2006]. 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 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 multi-touch tabletop: each player holds a mobile phone displaying his/her own cards, while other cards and coins are on the tab-

letop and each player can interact with them [Shirazi et al. 2009]. An implementation of Sudoku, available through a multi-touch 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, in order 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 three-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. 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 [Payne et al. 2006]. The system identifies users by detecting any Bluetooth-enabled device they are carrying (e.g. phones, PDAs, etc.) and adapts the visualized content to them on the basis of their advertisement history.

5.4.6 Temporal trend of application purpose

Fig. 15 shows the distribution over the years of the surveyed papers according to the *application purpose*. Most applications are designed to provide a specific utility to their users. However, applications for entertainment and social interaction are also well represented.

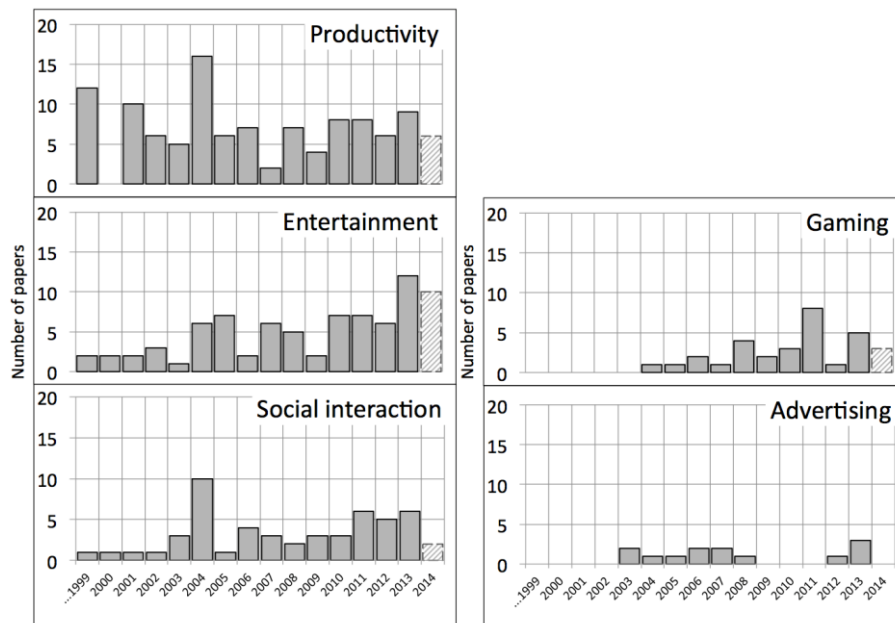


Fig. 15. Distribution over the years of the surveyed papers according to the *application purpose* dimension.

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 semi-public (an office), where most people know each other and could thus be less inhibited working together. Large interactive displays modify the traditional human-computer interaction 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 place*, *cultural site*, *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. presented *CityWall*, a system whose large multi-touch display was installed in a shop window next to a café in the center of Helsinki, Finland, during the summer of 2007 [Peltonen et al. 2008]. 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 multi-touch displays (six indoor and six 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 more used 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 semi-public 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: i) within an individual office, where the display is used by the person in that office (the office “owner”); ii) immediately outside the office, in order to display information that the owner intends to show to others (e.g. project information, favorite URLs, etc.); iii) in a common area, in order 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, etc. 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 con-

ducting 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 multi-touch 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 in his Constructivism theory [Bruner 1990]. A field study was conducted involving 107 pupils, aged 10-12 years old. It showed that the game was very engaging, able to stimulate pupils to work together and to collaborate on learning tasks. Teachers appreciated that even pupils who were usually timid in class were very much involved and actively collaborated with their companions.

USIAumni 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 multi-touch display was installed during a four-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 four 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, i.e. 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 juke-box [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, to nominate songs which 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 information and stimulate discussions [Hinrichs et al. 2008]. Visitors were observed over fifteen 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 in order 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 multi-touch LCD panel, which was installed in a general store [Redhead and Brereton 2009]. It aimed at creating a digital-community, collecting and displaying local information and communications 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*

Fig. 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 Fig. 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.

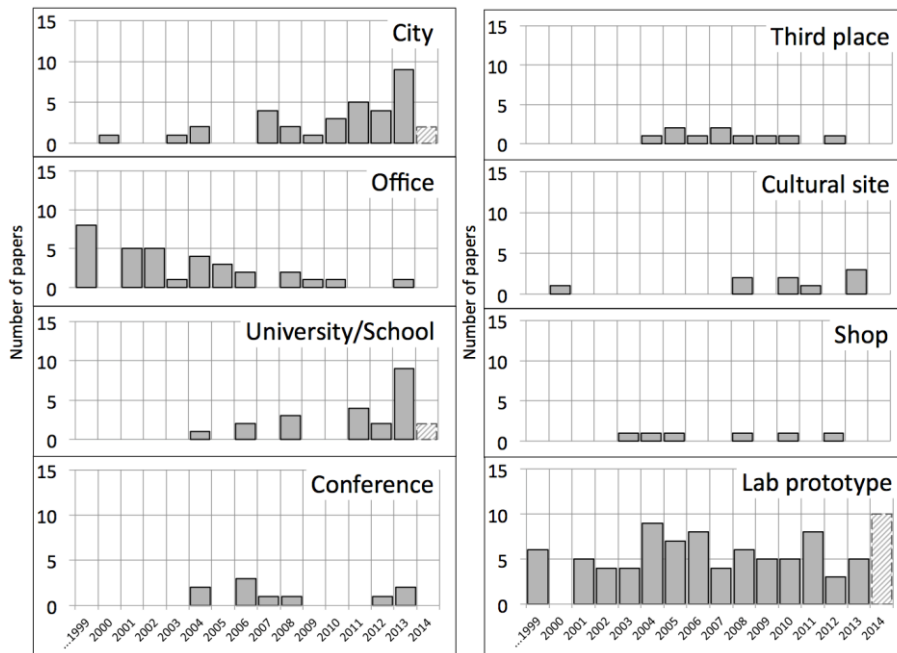


Fig. 16. Distribution over the years of the surveyed papers according to the *location* dimension.

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, tablets, 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. presented *WeSpace*, a ubiquitous system which integrates a tabletop display, a large vertical display and users' laptops to support collaborative scientific discussions [Wigdor et al. 2009]. The *NiCE Discussion Room* integrates a large wall display, personal laptops and traditional sheets of paper to support co-located 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, the device ecologies in which large interactive displays are integrated are characterized by an infrastructure which is not homogenous or seamless [Oulasvirta 2008]. A potential problem is that users might feel frustrated by the wide variety of interactive options offered by cross-device

and multi-user 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, in order to support designers of ubiquitous computing environments, Jetter et al. have 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 [Jetter et al. 2010]. In his Ph.D. thesis, Bellucci proposes another conceptual framework and its software implementation, which facilitates the rapid prototyping of ubiquitous systems, by allowing designers to abstract from the specific hardware [Bellucci 2013].

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 Hultheen 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, who criticizes the naturalness of gestural interfaces in terms of their claimed intuitiveness, usability, learnability and ergonomics [Norman 2010]. 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 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* that permanently shows the gesture on a dedicated screen area; 2) *temporal division* that interrupts the running application to show the gesture; 3) *integration* that 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 multi-touch interaction and on improving the visual feedback and learnability of hand gestures (see for example [Freeman et al. 2009; 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; Wobbrock et al. 2009]). Symbolic gestures can be useful for supporting the collaboration of a co-located 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. distinguish *manipulations* from symbolic gestures and question the naturalness and the cognitive aspects of the latter [Jetter et al. 2010]. 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, since the former are closer to direct manipulation, 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 ‘90s, 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 paper shows that several features of large displays favor people collaboration. First of all, the technology adopted in large displays generally supports simultaneous use actions. According to Scott et al., who analyzed co-located collaboration around a tabletop display, this is a primary requirement, since people collaborating in a task want to interact simultaneously with the visualized artifacts [Scott et al. 2003]. In most displays, it is not possible to identify the touch of a specific user. This is not seen as an obstacle since, 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 co-located multi-user 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 three 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 set-up 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 set-ups are the most suited to people’s collaboration for different reasons. In the horizontal set-up, 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/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 set-up [Morris et al. 2006; Shen et al. 2003]. The work in [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; Peltonen et al. 2008], collaboration and social interaction were focused towards pre-existing 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 semi-public 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; Norman 2006] it has been discussed that much creativity results from interacting with artifacts and collaborating with other individuals. Shneiderman says that tools for supporting creativity are needed, i.e. tools that extend users' capabilities to make discoveries or inventions [Shneiderman 2007]. 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, etc. To avoid this, it could be useful to distinguish between private and shared contents. In *Ubitable*, this distinction is physically implemented, since 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. 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 [Chan et al. 2008]. 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 in [Hoggan et al. 2008; Koskinen et al. 2008; 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 proposed a visual display that contains deformable areas, able to produce physical buttons and other interface elements [Harrison and Hudson 2009]. 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 multi-user interaction. In the literature, some software-based approaches are reported; for example, *Slide Rule* is a set of audio-based multi-touch 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 wheel-chair 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 co-presence of different users. The first studies explored the use of such displays in controlled settings, like 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, i.e. 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, e.g. the physical space where the display is located (*location* dimension in our classification framework) as well as other specific factors, like *display set-up* 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 ad-

dress 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 for example [Streitz 2003; 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; 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. 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 [Ardito et al. 2012]. 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, etc.).
- *Hardware* factors: they directly address the type of technology adopted, and its configuration. Among other important variables there are the display size and set-up.
- *Software* factors: they include interface features, as well as other software features, like software functionality and performance.

The framework specifies a number of behavioral and psychological variables, which 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, in order to show on-screen content better [Alexander et al. 2013]. Such displays support new modes of interaction. The term Organic User Interfaces was introduced in [Vertegaal and Poupyrev 2008], to refer to “User interfaces with non planar 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 has been 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/she accesses older data. Another possible usage is 3D scene navigation, in particular 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, etc. In a workstation setting, *SensaBubble* can be used as an alerting system: in order 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.

So far three dimensional (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, etc. (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 semi-public 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 semi-public 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/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 rather as a part of an ecology of different devices in pervasive scenarios. This follows Marc Weiser’s vision of Ubiquitous Computing, which stresses that the real power does not come from any single device, but it emerges from the interaction of all of them [Weiser 1991]. We have highlighted some significant challenges that have to be addressed, in order 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 Electronic 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.

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Online Appendix to: Interaction with large displays: a survey

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This Appendix provides more details on the classification of the 206 surveyed papers. It first shows five tables (Table II-VI), each reporting the papers classified according to a specific dimension. In each table, a paper is indicated by a number, which corresponds to the paper reference in the List of Surveyed Papers, shown afterwards.

Table II. Paper classification according to *Visualization technology*

Visualization technology	Papers
Rear Projection	3-5; 7-9; 13; 14; 16-19; 21; 30; 39; 44; 46; 48; 50; 53; 55; 56; 59; 63-65; 70; 73; 74; 76; 78; 80; 81; 83; 84; 87; 88; 92; 99; 103; 107; 110; 128; 131-134; 146; 150; 158; 161; 163; 165-172; 174; 179; 180; 185; 186; 189; 192; 197; 201; 206
Front Projection	19; 26-28; 32; 42; 43; 49; 61; 67; 71; 72; 75; 85; 86; 91; 97; 111; 112; 115-117; 129; 130; 135; 136; 138; 142; 143; 147; 148; 152; 153; 164; 168; 170; 171; 174-177; 187; 188; 193; 196; 198; 202; 204
Projection (unspecified)	33; 52; 98; 139; 183
Monitor	1; 2; 6; 11; 12; 20; 22; 24; 25; 29; 31; 32; 34-38; 41; 45; 51; 54; 57; 60; 62; 66; 68; 69; 75; 77; 79; 82; 89; 90; 93-95; 100; 101; 104-106; 108; 109; 113-115; 119; 120; 122-125; 130; 140; 141; 151; 154; 156; 157; 159; 162; 168; 171; 173; 178; 181; 182; 184; 190; 191; 194; 203; 205
Unspecified	10; 15; 40; 47; 102; 118; 127

Table III. Paper classification according to *Display set-up*

Display set-up	Papers
Vertical	1; 2; 5-8; 10-12; 14; 15; 19-21; 23; 24; 27-29; 31-39; 41; 43; 45-47; 49-62; 66; 68; 69; 71-73; 75-77; 79-82; 86; 88-90; 92; 94; 95; 98; 101; 102; 104-106; 108; 109; 111; 113-116; 118-125; 127; 129-134; 136; 139-142; 144-146; 150; 151; 154-159; 162; 166; 168; 171; 173; 174; 177; 178; 180-186; 189-192; 194; 195; 197; 201; 203-206
Horizontal	3; 4; 13; 19; 22; 26; 30; 40; 42; 44; 55; 63; 64; 67; 70; 71; 74; 76; 78; 83; 84; 87; 93; 96; 97; 100; 103; 107; 110; 112; 117; 128; 130; 135-138; 143; 144; 147; 148; 153; 161; 163; 165; 167-170; 172; 174-176; 179; 187; 188; 193; 195; 196; 198-200; 202
Diagonal	48; 65; 152
Floor	9; 25; 75; 91; 126
Other	16-18; 21; 26; 85; 96; 97; 99; 128; 135; 137; 149; 160; 164; 176; 200

Table IV. Paper classification according to *Interaction modality*

Interaction modality	Papers
Touch	1-8; 11-13; 16; 21; 22; 30; 31; 33-42; 44; 45; 48; 51; 52; 55; 59; 61-65; 67-70; 72-74; 76-78; 80; 83-87; 90; 93-96; 99-101; 103; 105; 107-112; 118-120; 122-125; 128; 129; 132-134; 136; 138-140; 143; 146-148; 151-153; 160; 161; 163; 165; 167; 169; 172-174; 176; 178-180; 184; 190; 192-199; 202; 203
External device	2; 10; 11; 15; 19; 23; 24; 26-29; 32; 40; 47; 51; 54; 55; 58; 61; 62; 66; 68; 71; 77; 79; 90; 91; 94; 97; 98; 101; 102; 109; 111; 115; 117; 120; 122-124; 127; 129; 133; 142; 144; 150; 154-157; 161-163; 165; 171; 173-177; 181-185; 187; 195; 197; 199; 206
Tangible object	14; 19; 38; 43; 44; 46; 48; 51; 53; 55; 56; 58; 62; 70-72; 76; 78; 81; 83; 88; 93; 96; 110; 116; 130; 131; 136; 142-144; 148; 161; 167; 169-171; 173; 175; 188; 196; 198; 201; 204
Body	1; 9; 11; 17; 18; 20; 25; 43; 49; 50; 57; 60; 63; 75; 80; 82; 89; 92; 104; 106; 113; 114; 118; 125; 126; 134; 135; 137; 139; 141; 145; 149; 158; 159; 164; 166; 168; 186; 189-191; 200; 205

Table V. Paper classification according to *Application purpose*

Application purpose	Papers
Productivity	6-8; 11-14; 17; 19; 22-24; 29; 31; 32; 34-37; 39; 40; 42; 43; 46; 48; 52; 53; 55; 56; 58; 60-62; 65; 67; 68; 70; 72; 74; 76; 77; 81; 84; 86-90; 93; 94; 96; 97; 99; 100; 102; 104-106; 109; 110; 112; 115-119; 121; 123; 124; 127; 129-131; 134; 136; 137; 140; 142; 144; 146-148; 151-154; 157; 159; 161; 163; 170; 173-177; 179; 181; 184; 187; 189; 193-195; 198-205
Entertainment	1; 6; 9-11; 15; 16; 18; 24-27; 33; 39; 41; 43; 50; 51; 53; 55; 57; 59; 60; 63; 64; 68; 73; 75; 78; 80; 82; 83; 85; 90; 92; 96; 100; 107-109; 111; 113; 114; 119; 122-126; 132-135; 143; 145; 149; 150; 155; 156; 158; 160; 161; 166-168; 172; 178; 180; 184-186; 188; 190; 192; 196-200; 206
Social interaction	2; 3; 11; 12; 21; 25; 29; 31; 35-38; 44; 45; 47; 51; 54; 64; 66; 68; 69; 71; 79; 91; 94; 105; 106; 111; 112; 118; 120; 123; 124; 127; 133; 136; 140; 150; 151; 156; 163; 169; 174; 175; 178; 182; 184-186; 194; 203; 206
Gaming	1; 3-5; 8; 20; 28; 30; 44; 47; 60; 68; 83; 84; 89; 90; 98; 101; 103; 110; 124; 128; 138; 152; 165; 169; 182-184; 191; 199
Advertising	2; 36; 43; 49; 95; 114; 139; 141; 158; 162; 164; 171; 176

Table VI. Paper classification according to *Location*

Location	Papers
City	1; 3; 7; 23; 25; 39; 50; 51; 61; 68; 69; 71; 90; 91; 94; 101; 103; 108; 109; 114; 118; 120; 123; 124; 132; 133; 140; 157; 164; 182; 184-186; 200
Office	12; 37; 46; 52; 53; 55; 57; 58; 70; 72; 76; 77; 81; 93; 102; 104; 105; 116; 119; 131; 137; 144; 151; 154; 173; 174; 188; 194; 195; 197; 201; 203; 204
University/School	4; 8; 18; 24; 28; 31; 45; 47; 50; 54; 60; 74; 89; 94; 95; 113; 138; 150; 158; 162; 177; 187; 191
Conference	6; 35; 66; 98; 106; 111; 139; 153; 156; 181
Third place	38; 73; 75; 78; 122; 126; 139; 155; 179; 183
Cultural site	5; 7; 22; 64; 65; 67; 79; 111; 168
Shop	43; 134; 141; 171; 176; 178
Lab prototype	2; 9-11; 13-17; 19; 21; 23; 26-34; 36; 40-42; 44; 48; 49; 56; 59; 62; 63; 80; 83-88; 92; 94; 96; 97; 99; 100; 107; 110; 112; 115; 117; 121; 125; 127-130; 135; 136; 142; 143; 145-149; 152; 153; 159-161; 163; 165-167; 169; 170; 172; 175; 180; 189; 190; 192; 193; 196; 198; 199; 202; 205; 206

LIST OF SURVEYED PAPERS, ORDERED ALPHABETICALLY BY FIRST AUTHOR

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Online Appendix to: Interaction with large displays: a survey

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This Appendix provides more details on the classification of the 206 surveyed papers. It first shows five tables (Table II-VI), each reporting the papers classified according to a specific dimension. In each table, a paper is indicated by a number, which corresponds to the paper reference in the List of Surveyed Papers, shown afterwards.

Table II. Paper classification according to *Visualization technology*

Visualization technology	Papers
Rear Projection	3-5; 7-9; 13; 14; 16-19; 21; 30; 39; 44; 46; 48; 50; 53; 55; 56; 59; 63-65; 70; 73; 74; 76; 78; 80; 81; 83; 84; 87; 88; 92; 99; 103; 107; 110; 128; 131-134; 146; 150; 158; 161; 163; 165-172; 174; 179; 180; 185; 186; 189; 192; 197; 201; 206
Front Projection	19; 26-28; 32; 42; 43; 49; 61; 67; 71; 72; 75; 85; 86; 91; 97; 111; 112; 115-117; 129; 130; 135; 136; 138; 142; 143; 147; 148; 152; 153; 164; 168; 170; 171; 174-177; 187; 188; 193; 196; 198; 202; 204
Projection (unspecified)	33; 52; 98; 139; 183
Monitor	1; 2; 6; 11; 12; 20; 22; 24; 25; 29; 31; 32; 34-38; 41; 45; 51; 54; 57; 60; 62; 66; 68; 69; 75; 77; 79; 82; 89; 90; 93-95; 100; 101; 104-106; 108; 109; 113-115; 119; 120; 122-125; 130; 140; 141; 151; 154; 156; 157; 159; 162; 168; 171; 173; 178; 181; 182; 184; 190; 191; 194; 203; 205
Unspecified	10; 15; 40; 47; 102; 118; 127

Table III. Paper classification according to *Display set-up*

Display set-up	Papers
Vertical	1; 2; 5-8; 10-12; 14; 15; 19-21; 23; 24; 27-29; 31-39; 41; 43; 45-47; 49-62; 66; 68; 69; 71-73; 75-77; 79-82; 86; 88-90; 92; 94; 95; 98; 101; 102; 104-106; 108; 109; 111; 113-116; 118-125; 127; 129-134; 136; 139-142; 144-146; 150; 151; 154-159; 162; 166; 168; 171; 173; 174; 177; 178; 180-186; 189-192; 194; 195; 197; 201; 203-206
Horizontal	3; 4; 13; 19; 22; 26; 30; 40; 42; 44; 55; 63; 64; 67; 70; 71; 74; 76; 78; 83; 84; 87; 93; 96; 97; 100; 103; 107; 110; 112; 117; 128; 130; 135-138; 143; 144; 147; 148; 153; 161; 163; 165; 167-170; 172; 174-176; 179; 187; 188; 193; 195; 196; 198-200; 202
Diagonal	48; 65; 152
Floor	9; 25; 75; 91; 126
Other	16-18; 21; 26; 85; 96; 97; 99; 128; 135; 137; 149; 160; 164; 176; 200

Table IV. Paper classification according to *Interaction modality*

Interaction modality	Papers
Touch	1-8; 11-13; 16; 21; 22; 30; 31; 33-42; 44; 45; 48; 51; 52; 55; 59; 61-65; 67-70; 72-74; 76-78; 80; 83-87; 90; 93-96; 99-101; 103; 105; 107-112; 118-120; 122-125; 128; 129; 132-134; 136; 138-140; 143; 146-148; 151-153; 160; 161; 163; 165; 167; 169; 172-174; 176; 178-180; 184; 190; 192-199; 202; 203
External device	2; 10; 11; 15; 19; 23; 24; 26-29; 32; 40; 47; 51; 54; 55; 58; 61; 62; 66; 68; 71; 77; 79; 90; 91; 94; 97; 98; 101; 102; 109; 111; 115; 117; 120; 122-124; 127; 129; 133; 142; 144; 150; 154-157; 161-163; 165; 171; 173-177; 181-185; 187; 195; 197; 199; 206
Tangible object	14; 19; 38; 43; 44; 46; 48; 51; 53; 55; 56; 58; 62; 70-72; 76; 78; 81; 83; 88; 93; 96; 110; 116; 130; 131; 136; 142-144; 148; 161; 167; 169-171; 173; 175; 188; 196; 198; 201; 204
Body	1; 9; 11; 17; 18; 20; 25; 43; 49; 50; 57; 60; 63; 75; 80; 82; 89; 92; 104; 106; 113; 114; 118; 125; 126; 134; 135; 137; 139; 141; 145; 149; 158; 159; 164; 166; 168; 186; 189-191; 200; 205

Table V. Paper classification according to *Application purpose*

Application purpose	Papers
Productivity	6-8; 11-14; 17; 19; 22-24; 29; 31; 32; 34-37; 39; 40; 42; 43; 46; 48; 52; 53; 55; 56; 58; 60-62; 65; 67; 68; 70; 72; 74; 76; 77; 81; 84; 86-90; 93; 94; 96; 97; 99; 100; 102; 104-106; 109; 110; 112; 115-119; 121; 123; 124; 127; 129-131; 134; 136; 137; 140; 142; 144; 146-148; 151-154; 157; 159; 161; 163; 170; 173-177; 179; 181; 184; 187; 189; 193-195; 198-205
Entertainment	1; 6; 9-11; 15; 16; 18; 24-27; 33; 39; 41; 43; 50; 51; 53; 55; 57; 59; 60; 63; 64; 68; 73; 75; 78; 80; 82; 83; 85; 90; 92; 96; 100; 107-109; 111; 113; 114; 119; 122-126; 132-135; 143; 145; 149; 150; 155; 156; 158; 160; 161; 166-168; 172; 178; 180; 184-186; 188; 190; 192; 196-200; 206
Social interaction	2; 3; 11; 12; 21; 25; 29; 31; 35-38; 44; 45; 47; 51; 54; 64; 66; 68; 69; 71; 79; 91; 94; 105; 106; 111; 112; 118; 120; 123; 124; 127; 133; 136; 140; 150; 151; 156; 163; 169; 174; 175; 178; 182; 184-186; 194; 203; 206
Gaming	1; 3-5; 8; 20; 28; 30; 44; 47; 60; 68; 83; 84; 89; 90; 98; 101; 103; 110; 124; 128; 138; 152; 165; 169; 182-184; 191; 199
Advertising	2; 36; 43; 49; 95; 114; 139; 141; 158; 162; 164; 171; 176

Table VI. Paper classification according to *Location*

Location	Papers
City	1; 3; 7; 23; 25; 39; 50; 51; 61; 68; 69; 71; 90; 91; 94; 101; 103; 108; 109; 114; 118; 120; 123; 124; 132; 133; 140; 157; 164; 182; 184-186; 200
Office	12; 37; 46; 52; 53; 55; 57; 58; 70; 72; 76; 77; 81; 93; 102; 104; 105; 116; 119; 131; 137; 144; 151; 154; 173; 174; 188; 194; 195; 197; 201; 203; 204
University/School	4; 8; 18; 24; 28; 31; 45; 47; 50; 54; 60; 74; 89; 94; 95; 113; 138; 150; 158; 162; 177; 187; 191
Conference	6; 35; 66; 98; 106; 111; 139; 153; 156; 181
Third place	38; 73; 75; 78; 122; 126; 139; 155; 179; 183
Cultural site	5; 7; 22; 64; 65; 67; 79; 111; 168
Shop	43; 134; 141; 171; 176; 178
Lab prototype	2; 9-11; 13-17; 19; 21; 23; 26-34; 36; 40-42; 44; 48; 49; 56; 59; 62; 63; 80; 83-88; 92; 94; 96; 97; 99; 100; 107; 110; 112; 115; 117; 121; 125; 127-130; 135; 136; 142; 143; 145-149; 152; 153; 159-161; 163; 165-167; 169; 170; 172; 175; 180; 189; 190; 192; 193; 196; 198; 199; 202; 205; 206

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Online Appendix to: Interaction with large displays: a survey

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This Appendix provides more details on the classification of the 206 surveyed papers. It first shows five tables (Table II-VI), each reporting the papers classified according to a specific dimension. In each table, a paper is indicated by a number, which corresponds to the paper reference in the List of Surveyed Papers, shown afterwards.

Table II. Paper classification according to *Visualization technology*

Visualization technology	Papers
Rear Projection	3-5; 7-9; 13; 14; 16-19; 21; 30; 39; 44; 46; 48; 50; 53; 55; 56; 59; 63-65; 70; 73; 74; 76; 78; 80; 81; 83; 84; 87; 88; 92; 99; 103; 107; 110; 128; 131-134; 146; 150; 158; 161; 163; 165-172; 174; 179; 180; 185; 186; 189; 192; 197; 201; 206
Front Projection	19; 26-28; 32; 42; 43; 49; 61; 67; 71; 72; 75; 85; 86; 91; 97; 111; 112; 115-117; 129; 130; 135; 136; 138; 142; 143; 147; 148; 152; 153; 164; 168; 170; 171; 174-177; 187; 188; 193; 196; 198; 202; 204
Projection (unspecified)	33; 52; 98; 139; 183
Monitor	1; 2; 6; 11; 12; 20; 22; 24; 25; 29; 31; 32; 34-38; 41; 45; 51; 54; 57; 60; 62; 66; 68; 69; 75; 77; 79; 82; 89; 90; 93-95; 100; 101; 104-106; 108; 109; 113-115; 119; 120; 122-125; 130; 140; 141; 151; 154; 156; 157; 159; 162; 168; 171; 173; 178; 181; 182; 184; 190; 191; 194; 203; 205
Unspecified	10; 15; 40; 47; 102; 118; 127

Table III. Paper classification according to *Display set-up*

Display set-up	Papers
Vertical	1; 2; 5-8; 10-12; 14; 15; 19-21; 23; 24; 27-29; 31-39; 41; 43; 45-47; 49-62; 66; 68; 69; 71-73; 75-77; 79-82; 86; 88-90; 92; 94; 95; 98; 101; 102; 104-106; 108; 109; 111; 113-116; 118-125; 127; 129-134; 136; 139-142; 144-146; 150; 151; 154-159; 162; 166; 168; 171; 173; 174; 177; 178; 180-186; 189-192; 194; 195; 197; 201; 203-206
Horizontal	3; 4; 13; 19; 22; 26; 30; 40; 42; 44; 55; 63; 64; 67; 70; 71; 74; 76; 78; 83; 84; 87; 93; 96; 97; 100; 103; 107; 110; 112; 117; 128; 130; 135-138; 143; 144; 147; 148; 153; 161; 163; 165; 167-170; 172; 174-176; 179; 187; 188; 193; 195; 196; 198-200; 202
Diagonal	48; 65; 152
Floor	9; 25; 75; 91; 126
Other	16-18; 21; 26; 85; 96; 97; 99; 128; 135; 137; 149; 160; 164; 176; 200

Table IV. Paper classification according to *Interaction modality*

Interaction modality	Papers
Touch	1-8; 11-13; 16; 21; 22; 30; 31; 33-42; 44; 45; 48; 51; 52; 55; 59; 61-65; 67-70; 72-74; 76-78; 80; 83-87; 90; 93-96; 99-101; 103; 105; 107-112; 118-120; 122-125; 128; 129; 132-134; 136; 138-140; 143; 146-148; 151-153; 160; 161; 163; 165; 167; 169; 172-174; 176; 178-180; 184; 190; 192-199; 202; 203
External device	2; 10; 11; 15; 19; 23; 24; 26-29; 32; 40; 47; 51; 54; 55; 58; 61; 62; 66; 68; 71; 77; 79; 90; 91; 94; 97; 98; 101; 102; 109; 111; 115; 117; 120; 122-124; 127; 129; 133; 142; 144; 150; 154-157; 161-163; 165; 171; 173-177; 181-185; 187; 195; 197; 199; 206
Tangible object	14; 19; 38; 43; 44; 46; 48; 51; 53; 55; 56; 58; 62; 70-72; 76; 78; 81; 83; 88; 93; 96; 110; 116; 130; 131; 136; 142-144; 148; 161; 167; 169-171; 173; 175; 188; 196; 198; 201; 204
Body	1; 9; 11; 17; 18; 20; 25; 43; 49; 50; 57; 60; 63; 75; 80; 82; 89; 92; 104; 106; 113; 114; 118; 125; 126; 134; 135; 137; 139; 141; 145; 149; 158; 159; 164; 166; 168; 186; 189-191; 200; 205

Table V. Paper classification according to *Application purpose*

Application purpose	Papers
Productivity	6-8; 11-14; 17; 19; 22-24; 29; 31; 32; 34-37; 39; 40; 42; 43; 46; 48; 52; 53; 55; 56; 58; 60-62; 65; 67; 68; 70; 72; 74; 76; 77; 81; 84; 86-90; 93; 94; 96; 97; 99; 100; 102; 104-106; 109; 110; 112; 115-119; 121; 123; 124; 127; 129-131; 134; 136; 137; 140; 142; 144; 146-148; 151-154; 157; 159; 161; 163; 170; 173-177; 179; 181; 184; 187; 189; 193-195; 198-205
Entertainment	1; 6; 9-11; 15; 16; 18; 24-27; 33; 39; 41; 43; 50; 51; 53; 55; 57; 59; 60; 63; 64; 68; 73; 75; 78; 80; 82; 83; 85; 90; 92; 96; 100; 107-109; 111; 113; 114; 119; 122-126; 132-135; 143; 145; 149; 150; 155; 156; 158; 160; 161; 166-168; 172; 178; 180; 184-186; 188; 190; 192; 196-200; 206
Social interaction	2; 3; 11; 12; 21; 25; 29; 31; 35-38; 44; 45; 47; 51; 54; 64; 66; 68; 69; 71; 79; 91; 94; 105; 106; 111; 112; 118; 120; 123; 124; 127; 133; 136; 140; 150; 151; 156; 163; 169; 174; 175; 178; 182; 184-186; 194; 203; 206
Gaming	1; 3-5; 8; 20; 28; 30; 44; 47; 60; 68; 83; 84; 89; 90; 98; 101; 103; 110; 124; 128; 138; 152; 165; 169; 182-184; 191; 199
Advertising	2; 36; 43; 49; 95; 114; 139; 141; 158; 162; 164; 171; 176

Table VI. Paper classification according to *Location*

Location	Papers
City	1; 3; 7; 23; 25; 39; 50; 51; 61; 68; 69; 71; 90; 91; 94; 101; 103; 108; 109; 114; 118; 120; 123; 124; 132; 133; 140; 157; 164; 182; 184-186; 200
Office	12; 37; 46; 52; 53; 55; 57; 58; 70; 72; 76; 77; 81; 93; 102; 104; 105; 116; 119; 131; 137; 144; 151; 154; 173; 174; 188; 194; 195; 197; 201; 203; 204
University/School	4; 8; 18; 24; 28; 31; 45; 47; 50; 54; 60; 74; 89; 94; 95; 113; 138; 150; 158; 162; 177; 187; 191
Conference	6; 35; 66; 98; 106; 111; 139; 153; 156; 181
Third place	38; 73; 75; 78; 122; 126; 139; 155; 179; 183
Cultural site	5; 7; 22; 64; 65; 67; 79; 111; 168
Shop	43; 134; 141; 171; 176; 178
Lab prototype	2; 9-11; 13-17; 19; 21; 23; 26-34; 36; 40-42; 44; 48; 49; 56; 59; 62; 63; 80; 83-88; 92; 94; 96; 97; 99; 100; 107; 110; 112; 115; 117; 121; 125; 127-130; 135; 136; 142; 143; 145-149; 152; 153; 159-161; 163; 165-167; 169; 170; 172; 175; 180; 189; 190; 192; 193; 196; 198; 199; 202; 205; 206

LIST OF SURVEYED PAPERS, ORDERED ALPHABETICALLY BY FIRST AUTHOR

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