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Survey Paper: Pervasive Displays for Information Presentation

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Abstract—Weiser's seminal vision of ubiquitous computing had calm information presentation at its heart and identified an important challenge in providing pervasive yet unobtrusive information display while avoiding problems of information overload. Since this vision was first articulated, a range of approaches have emerged for presenting information on pervasive displays and digital screens of varying sizes are now an everyday feature of our environments. Such displays provide significant opportunities for presenting information in-situ to support users in a range of activities, and the growing expectation is that there is constant peripheral access to digital information. In this article we review three different pervasive display technologies used for information presentation: traditional 2D display media, urban media façades, and novel display hardware. Our survey identifies five emerging trends that cross all three technologies: an increasing focus on situatedness, a movement towards non-expert users, growing demand for accessible interaction, a potential for new applications of data, and a difficulty in balancing 'calm' computing against presentation of data at an appropriate granularity and complexity.

1 Introduction

Using pervasive technology for information presentation has been at the core of the ubiquitous computing vision since its inception. In his seminal vision for Ubicomp [33], Marc Weiser observed that our natural environments convey a wealth of information that can be readily absorbed and yet still deliver a positive user experience – by contrast he noted that interactions with comparatively information-poor computing were considerably more frustrating.

> 'There is more information available at our fingertips during a walk in the woods than any computer system, yet people find a walk among the trees relaxing and computers frustrating." – Marc Weiser [33]

Since this challenge was first articulated, the research community has invested significant effort in the domain of so-called "pervasive displays" using a wide range of technologies. Although this term could be considered to envelope a wide range of devices, in this paper we focus on screens embedded into public and semi-public spaces with the explicit purpose of displaying digital content to multiple viewers (typically simultaneously). Such displays range from tablet or TV-style displays that have been affixed to features of the internal or external environment and are visible only within a small distance, to large-scale media facades that are embedded into the very architecture of a space and can viewed from large distances by a huge amount of people. In this article we review three significant classes of pervasive display technologies, focusing on systems designed specifically for presenting information of the type Weiser foresaw (as opposed to, e.g., entertainment/ advertising content): conventional 2D displays, urban media façades, and bespoke or novel hardware. All three technology areas have a rich history of use for information presentation (e.g. displaying news, public transport information) although the expected viewing or interaction models may shape the level of detail or format in which information appears – for example, many of the urban media facade examples discussed provide limited information arranged in a format designed to be primarily artistic or entertainment content.

Conventional 2D displays such as LCD screens and video projections present information to users in a range of settings. Early workplace screens showed information of interest to employees (e.g. [18]), or to support workplace activity (e.g. [2], [3]), and as screen resolutions have improved this continues to be an important application of pervasive displays of this type. Furthermore, as display hardware costs have fallen, 2D screens have become a highly pervasive feature of many public spaces, presenting information to support a wide range of daily activities. For example, most transport hubs now use such information screens to present arrival and departure information, shopping centres use them to alert customers to products that may be of interest, and digital signs in city streets can provide a variety of traffic and event information.

Urban media façades embed display technology into architectural structures which can often provide a more sympathetic information display in established outdoor environments. One such example, the City Bug Report [23], used a visual light display on a city hall to show local citizens information about recent communications between residents and the city administration. Like many media façades, the presented information on the city hall was abstract (each communication was represented by a single light pattern), highly-situated (the building used represented the city administration), and well-suited to ambient information consumption.

Finally, the use of novel display hardware itself can bring a physicality to information presentation that allows both skilled and unskilled users to gain deep insights from even complex information. Such displays are hugely varied in form – an early example, the dangling string [33], took the form of an 8 foot hanging string that spun at a speed that reflected ethernet traffic. More recently, the shape-changing

EMERGE bar-chart display provides a 3D representation of data that can manipulated, filtered and reordered [32].

No one of these three technologies is a panacea for information presentation, but together they provide the opportunity to provide pervasive information display. Although not intended to be comprehensive, we focus on surveying a number of key milestone systems for each technology approach to article provide an overview of the current direction of pervasive information presentation systems and give a grounding in the three technology areas sufficient to understand emerging trends. Despite considerable differences in both the mediums and applications, we identify five interesting cross cutting themes for pervasive displays as used for information presentation.

2 Large 2D Screens and Projections

Large 2D screens and projections proliferate as a means of presenting information in many public and semi-public spaces. Early research focused on the use of single screens in workplace environments; for example, the Learning Communities Newspaper [18] took the form of a web-based application projected in a shared space used by members of the Learning Communities group at Apple. News stories were submitted by group members, via email, to inform other members and guests about their project work and events.

Deployments of one or more isolated displays (as opposed to tiled multi-screen environments) have continued to be important in the workplace. For example, the AwareMedia [2] deployment of ten displays (mostly large touchscreens) was designed to raise awareness and support messaging within the surgical ward of a hospital. The screens were required to be very information-heavy detailing the location of individuals, the schedule for a space and current relevant surgical records, as well as providing video and messaging between locations. Evaluation interviews three months into the deployment suggested that the displays were a useful tool for supporting and informing behaviour.

Another approach using 2D screens and projections is the creation of multi-screen environments that combine multiple screens or projectors to build visually-immersive environments for information presentation at very large scales; such displays are particularly useful for the visualization and analysis of large complex datasets. For example, early CAVEs, a set of virtual-reality environments were constructed from three or more projected displays [9] that created a walk-in cube-shaped room. Interactions with the information visualizations in the CAVE were supported through a variety of hand-held input devices (e.g. data gloves, joystick), and trials demonstrated use in a wide range of information-intensive applications (e.g. 3D medical imaging, architectural walk-throughs and exploration of astrophysics simulation data). Similar deployments have been created using traditional panel displays (e.g. the WILD room [3]).

Beyond workplace and laboratory environments conventional displays now abound. The CityWall [27] research screen was deployed in Helsinki, Finland to show information during large events, and supported multiple simultaneous interacting users through it's large multi-touch display. Large networked research deployments, composed of multiple screens, are also well-established. For example, the e-Campus deployment at Lancaster University uses almost fifty screens across the University campus to show a variety of relevant information such as bus times, local weather, press releases and event details [12]. The majority of displays in the network are 40″ traditional LCD screens that have been affixed to walls inside campus buildings (e.g. residential areas, lecture theatres). By contrast, the UBI-hotspots [17] in Oulu, Finland (which provide a wide array of information and applications) features twelve custom-built display units that are installed in indoor and outdoor city centre locations. Large-scale networked display deployments are also commonplace in the advertising domain, for example `www.infoscreen.de`.

Projections are also a common approach for creating temporary installations in urban spaces. For example, a recent projection onto the Empire State Building in New York[1] used the building as a platform for raising awareness of endangered species. The projected display used forty stacked projectors to create a 57 x 115 metre display that could be viewed from considerable distance and looped through digital images of endangered species in order to act as a ″weapon of mass instruction″ that informed the local public.

As LCD and projected displays are deployed in increasingly variable spaces the challenge of managing the information to be shown also increases. Space users are not typically homogenous (perhaps varying over the course of day or week) and are engaged in different tasks – providing display content to inform this wide user base poses significant challenge. Furthermore, as displays move from isolated nodes to large-scale networks like those described above, the variety of locations add to the challenges associated with a highly-varied audience. Two approaches can help improve the relevance and efficacy of such displays: the first, *situatedness* relates to the tailoring of displayed media to the specific location of the screen – this might vary from simply tailoring the clock or weather to local conditions, to displaying community-relevant content, and even to displaying hyper-local travel information (e.g. the next bus to depart from the specific bus stop at which the display is located). The second, *personalisation* refers to the adaptation of content for the specific user (or group of users) stood in front of a display (e.g. to show feeds from their preferred news source or to show the time of the next bus back to their homes). Research suggests that users are increasingly expecting to see situated content [6], and demographic information provided by video analytics systems is beginning to enable personalised digital media on public displays.

Overall large 2D screens and projections provide a very accessible technology for information presentation that can be in embedded in most indoor and outdoor locations, as reflected in the wealth of such screens in our everyday environments. Although cheap and accessible, the installation of these displays can disrupt the aesthetics of a space. As an alternative approach, in urban public spaces, projections are

1. as reported by http://www.digitalsignagetoday.com/articles/digital-signage-sends-call-of-the-wild-at-the-empire-state-building/

often used for turning building facades into large screens without equipping the building with extensive technology, in particular when creating displays with a 3D form factor. The following section addresses such projected displays as a category of media facade.

3 URBAN MEDIA FAÇADES

As large 2D screens have moved into cities, they have been increasingly embedded in the fabric of the very buildings themselves. Known collectively as media façades, such installations have rapidly increased over the last decade [14], [15]. Media façades are a prominent example of how we experience urban spaces and how information can be displayed and be made interactive. The research community has already made rich contributions in understanding urban spaces, as well as the role and opportunities of media façades. However, designers and researchers are often in a rush to create new installations and remediate previous media forms [4] and conceptual approaches for urban spaces. Such an approach is not necessarily sensitive to concerns of people, place, architecture or urban design, suggesting the need for new understandings of these designed objects, and the way they shape our experience of built and urban environments [30]. Mid-sized urban screens such as video walls and digital billboards are often just used as digital replacements for analog billboards. Due to their technical capabilities, they provide the advantage of displaying rapidly changing content, including animations and videos.

In contrast to video walls, media façades are usually very large in size. Due to their physical and digital properties, as well as the public setting they are usually situated in, we have to face novel challenges when designing and developing digital content for media façades. The size of a media façade can vary from moderately small façades of $50m^2$ like the Academy of Fine Arts Saar[2] in Saarbücken, Germany, to medium-sized ones like the ARS Electronica Center[3] in Linz, Austria, covering $5000m^2$, or very large ones, like the Allianz Arena[4] in Munich, Germany, with an area of $25,500m^2$. As a result of their enormous size, media façades can be visible from great distances resulting in broad exposure of the content displayed on the façade. Dalsgaard and Halskov explored various types of media façade installations, identifying eight key challenges that need to be faced in such a public context [10]. These challenges consider a wide range of issues, including that due to the public context, urban settings call for new or adapted forms of interfaces. Displayed content has to suit the medium. It has to match the technical properties of the façade and it needs to support the potentially intended interactions. Furthermore, stakeholder interests need to be balanced. This can be a critical issue, since the majority of media façades are owned by companies or public institutions enforcing strict rules about their presence in public. Within this respect, it has to be taken into account that due to the physical properties of such large-scale urban screens, presented content and visualized data is exposed to a large audience in public space. Together with the huge variety of supported media façade resolutions — they are often very low compared to regular computer screens and situated public displays — this is one of the most important constraints for visualizing data on urban screens. Visualizing data on large-scale screens in urban spaces is therefore a challenging task. Although tools exist for developing and prototyping content and visualizations for media façades [13] of arbitrary complexity — even supporting interactivity — it is still very uncommon to visualize complex or even people-related data. Besides displaying image content in the form of digital advertisements, a common way of visualizing data in urban spaces is simply communicating quantitative data, such as traffic information, weather or air conditions, as well as throughput of various infrastructures. Usually, the data is viualized in an ambient fashion using color schemes and abstract animations. Using concrete numbers and detailed information is rather rare.

In [23], Korsgaard and Brynskov described their *City Bug Report* installation in Aarhus, Denmark. Their deployment explored the concepts of digital policy, transparency, and the impact of digitisation on the changing roles of city administration and the (digital) public [23]. The installation took the form of a media façade composed of thirteen LED pixel arrays mounted on the exterior of the city hall tower in Aarhus. Simple colour sequences were used to represent communication between citizens and the city administration providing a semantic connection to an online platform for citizen feedback and reporting issues within the city. The façade presented a visualisation of open records on civic communication between the city departments and citizens. While this was an ambient visualisation of public data showing colored dots around the tower, only those that were familiar with the system were able to understand the communicated data. The majority of passersby perceived the installation as a simple light installation.

An early and well-known media façade installations visualizing image data was the *Blinkenlights* project in Berlin, Germany [14]. The upper eight floors of an office building were turned into the at that time world's biggest interactive computer screen. To control the content, people could use their mobile phones to call a dedicated phone number which, when connected, allowed them to use their phone's keypad to either control a virtual cursor on the façade or activate a previously uploaded animation. The only restriction for the visualized data was the comparably low resolution of 8x18 pixels. Another common data visualization in urban spaces is the presentation of passerby movement patterns. The movements are usually tracked with cameras and they are often mapped to animated silhouettes or animated lights. For example, the installation *12m4s* from LAb[au][5], featured an interactive media façade installation based on the average walking speed [22]. This architectural intervention used the movements of passersby to generate a real-time visualization. The researchers assumed an average walking speed of twelve meters in approximately four seconds and the movements of passersby were tracked in real-time with cameras to generate a visual (3D particles) and auditory (granular synthesis) scape on the façade, based on the captured image data and ultrasound sensors. The visu-

2. http://www.hbksaar.de
3. http://www.aec.at
4. http://www.allianz-arena.de
5. http://www.lab-au.com

alization was based on the position, orientation and speed of a passersby. Similarly, the building of the organization *La Vitrine Culturelle* in Montreal, Canada, is equipped with a small, low-resolution media façade of approximately $23m^2$ consisting of 35000 RGB LEDs that change their color as a reaction to the movements of passersby [15]. By connecting the interaction to the movements of passersby, the installation provides various animations and media content. When walking past the façade, the walking direction is mapped to animated arrows indicating the walking direction. When people stop and stand in front of the façade, they can create further animations by body gestures. These animations range from snowflakes popping up around the user's silhouette, to movable light spots.

In additional to light-emitting media façades that can be compared to common digital displays, mechanical media façades — where the outer surface of the building consists of mechanical elements that can be physically altered — sometimes come with data visualization as a side effect [14], [15]. When the mechanically movable elements are used as shades adapting to the current position of the sun, their particular position reflects the position and intensity of the sun in a rather abstract way.

4 Bespoke and Novel Display Hardware

Both CAVE-like configurations and urban display deployments are typically built using conventional display technologies in which flat, 2D pixel arrays (e.g. LCD screens) provide high-resolution visual output. However, early information presentation prototypes that emerged around Weiser's vision for 'calm' computing [34] often took more novel forms based on non-traditional hardware and the use of novel display hardware continues to be a valuable medium for information presentation.

An early example, Natalie Jeremijenko's Dangling String [34] comprised of an 8 foot piece of plastic spaghetti (string) that hung from a stepper motor connected to a nearby ethernet cable. As data was transmitted over the network, the electrical signals caused the motor to turn resulting in movement of the string and yielding a peripheral audible and visual indication of the level of traffic. Since this early work, ambient displays have taken a variety of forms using natural and mechanical materials. For example, the LaughingLily [1] provided an artificial plant mechanised to reflect the types of conversation occurring in a meeting room (silence, productive conversation, argument) and the more recent Clouds installation at the Open University [28] used twenty-four custom built spheres to display the number of people using the stairs and elevator in the building. The spheres were hung from the ceiling and were equally divided into two halves (differentiated through use of different colors): half represented elevator use and half use of the stairs. Each set of twelve spheres could be moved closer to the ceiling or floor to reflect the changing use of stairs and elevator; vertical distance between the Clouds indicated the difference between the number of people taking the stairs versus those taking the elevator.

Although useful for all kinds of peripheral information presentation, the physicality of many novel displays provides an ideal medium for scenarios such as data visualisation as users can manipulate the presented data allowing them to gain deeper insights; indeed, researchers have recently identified a role for such hardware in promoting engagement with public displays, and encouraging reflection on the information displayed [5]. One such example combined a traditional digital screen-based data visualization with physical data plates cut to the shape of the line graphs associated with subsets of the data; these two data mediums were combined to form a single box-shaped display that was deployed in urban space. Study of the user interactions showed that the presence of physical data plates resulted in more comparisons between different data subsets when compared to an identical deployment with only the digital display and therefore led users to generate much deeper insights about the data [5].

Whilst the above example combined a traditional 2D screen with a set of physical but static data representations, the next generation of displays will take a different form again: their physical geometry will dynamically change shape, reconfiguring their presence in 3D space to better represent the underlying content. Actuated shape-changing displays fundamentally transform our understanding of 'displays' from a flat 2D pixel arrays, to physically-dynamic visual outputs. These displays use our visual and tactile senses to exploit the perceived affordances inherent in everyday physical objects [11]. For data visualization, this means displays will feature an additional information channel—the physical dimension—to better convey features and meaning, while exploiting the viewers rich visual and tactile senses. These novel shape-changing displays move towards Sutherland's vision for *The Ultimate Display* [31], where a computer controls the existence and form of matter.

The majority of current examples of shape-changing displays are 2.5D displays—flat surfaces that host actuated physical pins to generate deformed display surfaces. Taher [32] reviews the literature of shape-changing displays used for data presentation[6], noting that such displays are typically controlled using motorized pins, pneumatics, or shape-memory alloys; with resolution varying from a few physical pixels (<10) to 900 [11]. As a method of capturing the shape-change capabilities of different displays, Roudaut et al. [29] describe 'shape-resolution', analogous to measures of screen-size, resolution, etc. that consumers are familiar with in typical displays.

Much like traditional displays, many shape-changing displays are built as generic output devices, with *Data Physicalization*—"physical artefacts whose geometry or material properties encode data" [20]—just one use-case. However, to explicitly explore this domain, Taher et al. constructed EMERGE [32], a physically-dynamic bar chart consisting of 100 self-illuminating bars that vertically actuate to create physical 3D data representations (Figure 1). Users have available to them a range of interactions to directly and indirectly manipulate data points (including pulling and pushing bars, and interacting with axis labels) to facilitate standard information visualisation functions of annotation, filtering, organization, and navigation. In a similar vein, Follmer et al. [11] demonstrated physical representations

6. A continually evolving list of shape-changing interfaces is available at www.shape-change.org.

of mathematical functions using the 900 actuating bars of inForm.

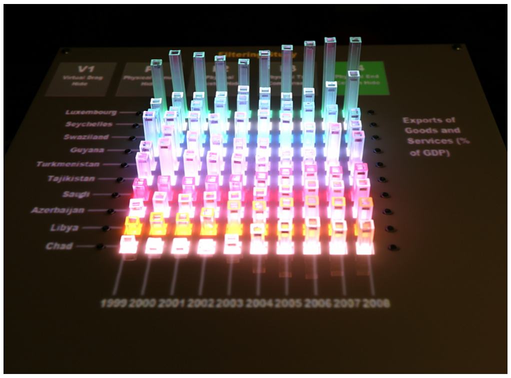

Fig. 1. EMERGE, a physically-dynamic bar-chart [32].

As a first step towards commercialization of physical shape-changing interfaces, Tactus Technology's Phorm (`www.tactustechnology.com`) extrudes small buttons from an iPad's display to aid typing on touch-screens. Expansion of this concept—pumping micro-fluids into a screen overlay—or by using a modular shape-change toolkit such as ShapeClip [16], would allow developers to transform any traditional display into a novel physically-dynamic data visualiser.

An alternate view on shape-changing interfaces is the use of developing display technologies such as Augmented Reality (AR), Virtual Reality (VR), and Holographic displays to present 'untouchable' digital content either immersively (VR) or overlaid onto the real world. For example, to overcome the challenge of presenting high-resolution visual output in the same space as physical output, Sublimate [24] augmented a shape-display with AR, demonstrating virtual mesh manipulation, geo-spatial data, and wind tunnel flow. To generate 3D path visualizations, LeviPath [26] levitates and moves, in mid-air, multiple small objects using acoustic standing waves. Finger tracking facilitates indirect input in order to manipulate the placement of levitating objects. Augmenting more traditional objects for additional information presentation is more commonplace with a number of commercial products available (e.g. `www.layar.com`, `www.wikitude.com`).

The use of novel display hardware for information presentation has significant potential to enable 'calm' interaction with the ever-growing set of information now presented to users in all aspects of their daily lives. Although research prototypes have continued to be developed since Weiser's early vision, many have been highly tailored to a specific information presentation goal and few have made it to deployments outside of the lab. Technologies such as AR, VR and shape-changing displays have the potential to generalise to numerous information presentation scenarios (e.g. researchers recently proposed the use of AR displays in domestic environments for human memory augmentation [8]); in particular, the use of shape-changing displays provides an accessible presentation medium that does not require the use of personal wearables or devices. However, this next generation of display technology is still immature and faces significant hurdles before it is suitable for mainstream deployments. The biggest of these challenges is improving the scale and resolution of physical display hardware. While progress is being made in both the research and commercial sectors, like traditional displays, the 'price per pixel' will reduce as technology develops and demand increases. Such higher resolution shape-displays will both better represent the required data, and allow significantly larger datasets to be rendered. In the meantime, combinations of display technologies (e.g. as Sublimate's use of high-resolution Augmented Reality display and physical output) can provide an intermediate step for this hardware development [24].

5 Analysis

The three presented technology classes for pervasive information display each have something to offer – no one approach currently appears as the ideal solution. Current deployments often use conventional LCD screens, but media façades and more varied display hardware are attracting considerable interest for accessible and engaging presentation of information to users. Despite obvious differences in three mediums we believe that a number of cross-cutting trends emerge from the surveyed literature: (1) an increasing emphasis on situatedness, (2) growing accessibility and a wider user base, (3) support for interaction, (4) new application areas, and (5) challenges in managing user attention.

5.1 An increasing focus on situated displays

Early information displays were typically based on dedicated presentation hardware that had little connection with its setting. However, as displays become more varied and more commonplace, users have a growing expectation that a display will have some sense of 'situatedness', i.e. that it will have a connection the space in which it is embedded [7]. For example, in the conventional display domain, a clear shift can be observed from immersive VR-based systems such as CAVE [9] to situated displays that specifically represent changing activities in a space [21]. Media facades in particular are designed to be embedded into an existing architectural space, exploiting its characteristics, and therefore offer clear potential for situatedness, and indeed recent deployments such as the 2014 City Bug report [23] have realized this. Similarly, although innovations in shape-changing displays can provide support for general information presentation, a long-standing trend for novel hardware displays has been the presentation of information in a situated manner (e.g. dangling string [34], Clouds [28]).

In-situ information presentation has a number of advantages over other forms of information provision in that it offers users increased levels of trust in the relationship between the physical space and the data being presented (users typically associate ownership of a display with the space in which it is deployed [7]), can rely on the physical space to frame the information presented and, when techniques such as projection are used the physical space can become part of the visualization itself.

5.2 The rise of non-expert users

A further trend is the growing set of varied users that may encounter information displays. Embedded in research environments, many early displays had limited accessibility for the general population but the growing accessibility of displays has led researchers to accommodate a diverse viewer audience. For example, the recent CityWall deployments was explicitly designed to support users from experts to children and senior citizens [27]. Equally, many media façades can be appreciated by users with varying degrees of the information presented; at one level they can simply be considered as an aesthetic improvement to the space (as reported in [23]), but as users develop an understanding of the visualization they can read more of the information contained within. Movement towards an increasingly data-driven society is likely to see a rapid increase in demand for data visualizations for non-expert users, and we believe that pervasive displays will play an important role in meeting this need.

Beyond novel hardware, the public nature of many pervasive displays means they have huge potential for accessible information and may prove to be an important tool in helping to avoid the creation of a so called "digital-divide" based on the information availability.

5.3 Support for interaction and experimentation

Interaction has long been an important theme for pervasive display researchers, and it is now commonplace for deployments to support some form of user interaction. As interaction has emerged as a more prominent feature of pervasive display deployments there has been a clear shift from relatively static information presentation to highly interactive systems. Whilst early interactive systems relied on touch screens and dedicated input devices (e.g. mice, data gloves, joysticks), many now feature interaction with the display via smartphones [6], [14] or through direct physical manipulation [32]. The ability to interact with data can help transform a pervasive information display from a simple ambient awareness tool to a sophisticated data-access point for viewers enabling browsing and potential experimentation with the data being visualized and leading to new insights [5]. The production of interactive data visualizations on media facades in urban settings is particularly interesting as this poses significant new challenges – in some cases a display may be visible by hundreds or thousands of nearby citizens, providing interactivity for both the large scale of the physical display and its large user base will require significant innovation.

More generally though, trends across all three technologies indicate that in the near future most pervasive displays will support interaction and viewers will assume an ability to explore, control and interact with the information presented to them.

5.4 Support for new applications

Early information presentation applications of pervasive displays were largely focused on supporting the workplace. More recently news and advertising information have become commonplace. However, with the trend towards situated displays, and a wide user base, a number of new applications have started to emerge. Perhaps the most common of these are applications for behaviour change in which visualization of previously unseen data is used to try and encourage viewers to modify their current behaviour – often for health or sustainability reasons. Examples include Breakaway [19] and Clouds [28]. Breakaway [19] was a small cutom-hardware desk sculpture that moved into a slouching pose to reflect the inactivity of a desk occupant; once the worker took some time away from their desk, the sculpture would return to an upright position. The Clouds installation at the Open University [28] combined both conventional LCDs and custom display hardware to encourage use of the stairs in preference to the elevator. The installation of 24 display spheres (described in Section 4) was complemented by an array of plasma screens that gave a detailed representation of recent stair and elevator usage.

While the potential for behaviour change applications is clear there remains a question as to the long-term effectiveness of such interventions and subsequently it is not obvious the extent to which they will become widely deployed. However, we do expect new applications for data visualization to develop as new display technologies emerge.

5.5 Increasing difficulty in managing user attention

Weiser's original vision of calm computing [33] (i.e. interaction with digital devices where the interaction between is designed to occur in the user's periphery rather than at the center of attention) is often seen as being at odds with the increasing trend towards displays embedded in the environment that compete for viewers' attention. Research has shown that modern viewers appear to look at pervasive displays for very short periods of time ($<$ 2 seconds) and many have become accustomed to ignoring them altogether – a phenomenon known as "display blindness" [25]. To combat this display owners and content producers (in particular advertisers) have attempted to develop systems that are ever more engaging and attempt to attract viewers' attention. Such a battle for user attention seems a far cry from the idea of displays fading into the background as part of the fabric of everyday life.

This difficulty in managing user attention arises in many areas of pervasive displays but is likely to be of particular consequence when these displays are being used for presenting complex information sets as these will often require significant time for the user to assimilate and comprehend. In situations where users actively seek out displays and wish to engage with the data being shown this is not a problem. However, where data visualizations are being used for applications such as ambient awareness or behaviour change this is likely to present a serious challenge. We expect that this problem will continue to grow until common techniques for communicating levels of interest or expected viewing durations emerge.

6 Concluding Remarks

Information presentation through pervasive displays has long been an important focus for ubicomp. Consumption of information (e.g. as generated through social networks and the IoT) is of growing importance, and as we move towards data- and information-rich societies the challenge of providing pervasive information access without cognitive overload is an increasingly significant area of research.

Pervasive displays can help shape interactions between users and growing pools of information, supporting them in making complex inferences and prompting a wealth of new opportunities. However, the choice of display medium is an important factor in determining the reach and usability of information. Current pervasive display research is often segmented based on the technologies involved: commercial products make 2D screens readily available, embedded technologies allow information presentation in urban environments through media façades, and novel hardware allows tangible and bespoke representations of data. However, it is clear that these technologies will exist as part of a comprehensive display eco-system with which users interact with information. As a result, awareness of research across technology segments together with an appreciation of common trends is likely to be of importance to a wide range of research challenges going forwards. In this article we have provided a summary that crosses technology segments to identify trends of importance to current and future researchers.

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