A Survey of Pervasive Displays for Information Presentation

This survey of three different pervasive display technologies used for information presentation—traditional 2D display media, urban media facades, and novel display hardware—identifies five emerging trends that cross all three technologies.

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Using pervasive technology for information presentation has been at the core of the ubiquitous computing vision since its inception. In his seminal article on ubicomp, 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.[1] In 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.*

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, here we focus on screens embedded into public and semipublic 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 short distance, to large-scale media facades that are embedded into the very architecture of a space and can be viewed from long distances by a huge number of people.

In this article, we focus on systems designed specifically to present information of the type Weiser foresaw (as opposed to entertainment or advertising content, for example), reviewing three significant classes of pervasive display technologies: conventional 2D displays, urban media facades, and bespoke or novel hardware. All three technology areas have a rich history of use for information presentation (displaying news, public transport information, and so on), although the expected viewing or interaction models can shape the level of detail or information formatting. For example, many of the urban media facade examples discussed provide limited information arranged in a format designed primarily for its artistic or entertainment qualities.

No one of these three technologies is a panacea for information presentation, but together

Published by the IEEE CS ■ 1536-1268/16/$33.00 © 2016 IEEE

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they offer the opportunity to provide pervasive information display. Although not intended to be comprehensive, this survey focuses on key milestone systems for each technology approach, providing an overview of the current direction of pervasive information presentation systems and identifying 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.

Large 2D Screens and Projections

Large 2D screens and projections are proliferating as a means of presenting information in many public and semipublic spaces. Early research focused on the use of single screens in workplace environments; for example, the Learning Communities Newspaper[2] 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 multiscreen environments) have continued to be important in the workplace. For example, the AwareMedia[3] deployment of 10 displays (mostly large touchscreens) was designed to raise awareness and support messaging within the surgical ward of a hospital. The screens were information-heavy, detailing the location of individuals, the schedule for specific areas of the ward, and current relevant surgical records, and providing video and messaging between locations. Evaluation interviews three months into the deployment suggested that the displays were a useful tool for supporting staff and informing their behavior.

Another approach using 2D screens and projections is the creation of multiscreen 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 cave automatic virtual environments (CAVEs) were constructed from three or more projected displays[4] 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 (such as data gloves or a joystick), and trials demonstrated use in a wide range of information-intensive applications (including 3D medical imaging, architectural walkthroughs, and exploration of astrophysics simulation data). Similar deployments have been created using traditional panel displays—such as the wall-sized interaction with large datasets (WILD) room.[5]

> Although this was an ambient visualization of public data... only those familiar with the system understood the communicated data.

Beyond workplace and laboratory environments, conventional displays now abound. The CityWall[6] research screen was deployed in Helsinki, Finland, to show information during large events. The screen supported multiple simultaneous interacting users through its large multitouch display. Large networked research deployments, composed of multiple screens, are also well-established. For example, the e-Campus deployment at Lancaster University uses almost 50 screens across the university campus to show a variety of relevant information such as bus times, local weather, press releases, and event details.[7] The majority of displays in the network are 40-inch traditional LCD screens that have been affixed to walls inside campus buildings (including residential areas and lecture theaters). By contrast, the UBI-hotspots deployment[8] in Oulu, Finland, (which provides a wide array of information and applications) features 12 custom-built display units that are installed in indoor and outdoor city center locations. Large-scale networked display deployments are also commonplace in the advertising domain (see, 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 used the building as a platform for raising awareness of endangered species.[9] The projected display used 40 stacked projectors to create a 57 × 115 meter 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 presented information also increases. Space users are not typically homogenous (perhaps varying over the course of a day or week) and are engaged in different tasks, so providing display content to inform this wide user base poses a significant challenge. Furthermore, as displays move from isolated nodes to large-scale networks (such as those we've described), 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 (such as the next bus to depart from the specific bus stop at which the display is located). The second, *personalization,* refers to the adaptation of content for the specific user (or group of users) standing in front of a display (for example, 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 increasingly expect to see situated content,[10] and demographic information provided by video analytics systems is beginning to enable personalized digital media on public displays.

Overall, large 2D screens and projections provide an accessible technology for information presentation that can be embedded into 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 often used for turning building facades into large screens without equipping the building with extensive technology, particularly when creating displays with a 3D form factor.

Urban Media Facades

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 facades*, such installations have rapidly increased over the past decade.[11,12] Media facades are a prominent example of how we experience urban spaces and how information can be displayed and made interactive. The research community has already made rich contributions in understanding urban spaces and the role and opportunities of media facades.

However, designers and researchers are often in a rush to create new installations and remediate previous media forms[13] and conceptual approaches for urban spaces. Such an approach is not necessarily sensitive to concerns about people, place, architecture, or urban design, suggesting the need for new understandings of these designed objects and how they shape our experience of built and urban environments.[14] 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 facades are usually very large. Due to their physical and digital properties, as well as the public setting in which they're usually situated, we face novel challenges when designing and developing digital content for media facades. The size of a media facade can vary from moderately small facades of 50 m^2, such as that at the Academy of Fine Arts Saar in Saarbrücken, Germany (www.hbksaar.de); to medium-sized ones, such as the one at the ARS Electronica Center in Linz, Austria (www.aec.at), covering 5,000 m^2; or very large ones, such as the one at Allianz Arena in Munich, Germany (www.allianz-arena.de), with an area of 25,500 m^2. As a result of their enormous size, media facades can be visible from great distances, resulting in broad exposure of the content displayed on the facade.

Peter Dalsgaard and Kim Halskov explored various types of media facade installations, identifying eight key challenges that need to be faced in such a public context.[15] 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 must match the technical properties of the facade and support the potentially intended interactions.

Furthermore, stakeholder interests must be balanced. This can be a critical issue, because the majority of media facades are owned by companies or public institutions enforcing strict rules about their presence in public. Consequently, it's important to understand that the presented content and visualized data will be exposed to a large audience in a public space. Together with the huge variety of supported media facade resolutions—they're often very low compared to regular computer screens and situated public displays—this large-scale data exposure is one of the most important constraints for visualizing data on urban screens.

Although tools exist[16] for developing and prototyping—and even interacting

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with—content and visualizations for media facades of arbitrary complexity, it's still 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, weather, and air conditions. Usually, the data is visualized in an ambient fashion using color schemes and abstract animations. Using concrete numbers and detailed information is rather rare.

In "City Bug Report: Urban Prototyping as Participatory Process and Practice," Henrik Korsgaard and Martin Brynskov described their installation in Aarhus, Denmark.[17] Their deployment explored the concepts of digital policy, transparency, and the impact of digitization on the changing roles of city administration and the (digital) public.[17] The installation took the form of a media facade composed of 13 LED pixel arrays mounted on the exterior of the city hall tower in Aarhus. Simple color 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 facade presented a visualization of open records on civic communication between the city departments and citizens. Although this was an ambient visualization of public data showing colored dots around the tower, only those that were familiar with the system understood the communicated data. The majority of passersby perceived the installation as a simple light installation.

An early and well-known media facade installation visualizing image data was the Blinkenlights project in Berlin, Germany.[11] The upper eight floors of an office building were turned into the world's biggest (at that time) 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 facade or activate a previously uploaded animation. The only restriction for the visualized data was the comparably low resolution of 8 × 18 pixels.

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Another common data visualization in urban spaces is the presentation of passerby movement patterns. The movements are usually tracked with cameras and are often mapped to animated silhouettes or animated lights. For example, the installation 12m4s from LAb[au] (www.lab-au.com) featured an interactive media facade installation based on average walking speed.[18] This architectural intervention used the movements of passersby to generate a real-time visualization. The researchers assumed an average walking speed of 12 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 facade, based on the captured image data and ultrasound sensors. The visualization was based on the position, orientation, and speed of a passerby.

Similarly, the building of the organization La Vitrine Culturelle in Montreal, Canada, is equipped with a small, low-resolution media facade of approximately 23 m^2 consisting of 35,000 RGB LEDs that change their color as a reaction to the movements of passersby.[12] By connecting the interaction to the movements of passersby, the installation provides various animations and media content. When walking past the facade, the walking direction is mapped to animated arrows indicating the walking direction. When people stop and stand in front of the facade, they can create further animations through body gestures. These animations range from snowflakes popping up around the user's silhouette, to movable light spots.

In additional to light-emitting media facades, which can be compared to common digital displays, mechanical media facades—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.[11,12] 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.

Bespoke and Novel Hardware

Both CAVE-like configurations and urban display deployments are typically built using conventional display technologies in which flat, 2D pixel arrays (such as LCD screens) provide high-resolution visual output. However, early information presentation prototypes that emerged from efforts to attain Weiser's vision for "calm" computing[19] often took more novel forms based on nontraditional hardware, and the use of novel display hardware continues to be a valuable medium for information presentation.

An early example is Natalie Jeremijenko's Dangling String,[19] comprised

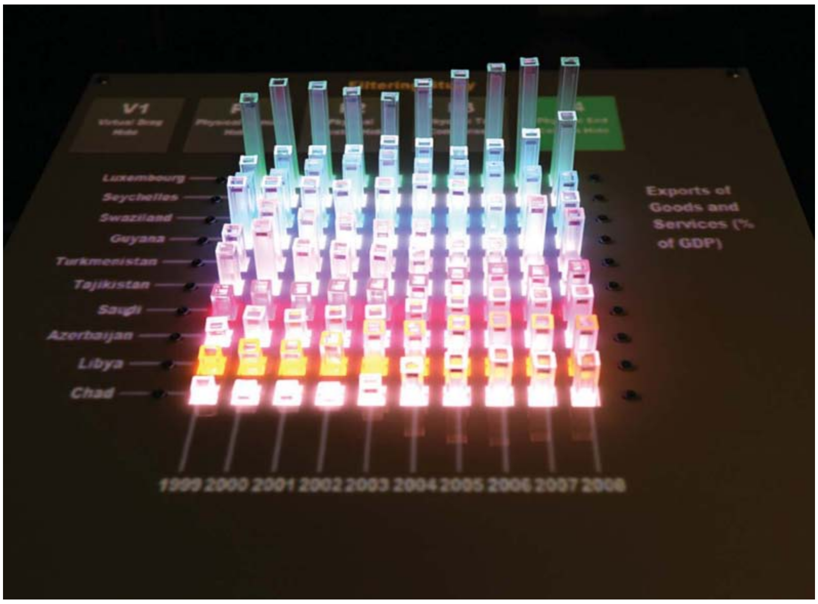

Figure 1. Emerge, a physically dynamic bar chart.[25] Users can directly or indirectly manipulate data points. (Source: Faisal Taher; used with permission.)

of an 8-foot piece of plastic spaghetti (string) hanging 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[20] provided an artificial plant mechanized to reflect the types of conversation occurring in a meeting room (silence, productive conversation, or arguments), and the more recent Clouds installation at the Open University[21] used 24 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 the other half represented use of the stairs. Each set of 12 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 visualization, because users can manipulate the presented data, letting them 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.[22] 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; the plates therefore led users to generate much deeper insights about the data.[22]

While these examples combined a traditional 2D screen with a set of physical but static data representations, the next generation of displays will take a different form—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.[23] 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 toward Ivan Sutherland's vision for the "ultimate display,"[24] 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. Faisal Taher and his colleagues review the literature of shape-changing displays used for data presentation,[25] noting that such displays are typically controlled using motorized pins, pneumatics, or shape-memory alloys. (A continually evolving list of shape-changing interfaces is available at www.shape-change.org.) Furthermore, their resolutions vary from a few physical pixels (< 10) to 900.[23] As a method of capturing the shape-change capabilities of different displays, Anne Roudaut and her colleagues describe "shape-resolution,"[26] analogous to measures of screen-size, resolution, and so on, that consumers are familiar with in typical displays.

Much like traditional displays, many shape-changing displays are built as generic output devices. For example, the emerging area of *data physicalization* deals with "physical artefacts whose geometry or material properties encode data."[27] To explicitly explore this domain, Taher and his colleagues constructed Emerge,[25] a physically dynamic bar chart consisting of 100 self-illuminating bars that vertically actuate to create physical 3D data representations (see Figure 1). Users can directly or indirectly manipulate data points (including pulling and pushing bars and interacting with axis labels) to visualize the information through annotation, filtering, organization, and navigation. In a similar vein, Sean Follmer and his colleagues demonstrated physical representations of mathematical functions using the 900 actuating bars of inFORM.[23]

As a first step toward 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 touchscreens. Expansion of this concept—pumping micro-fluids into a screen overlay—or using a modular shape-change toolkit such as ShapeClip,[28] would let developers transform any traditional display into a novel physically dynamic data visualizer.

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 augmented a shape-display with AR, demonstrating virtual mesh manipulation, geospatial data, and wind tunnel flow.[29] To generate 3D path visualizations, LeviPath levitates and moves, in mid-air, multiple small objects using acoustic standing waves.[30] Finger tracking facilitates indirect input to manipulate the placement of levitating objects. Augmenting traditional objects for additional information presentation is more commonplace, with a number of commercial products available (see, for example, www.layar.com and www.wikitude.com).

Using 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 generalize to numerous information presentation scenarios (for example, researchers recently proposed using AR displays in domestic environments for human memory augmentation[31]). 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, as with 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 (such as Sublimate's use of high-resolution AR display and physical output) can provide an intermediate step for this hardware development.[29]

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Cross-Cutting Trends

The three presented technology classes for pervasive information display each have something to offer—no single approach currently appears to be the ideal solution. Current deployments often use conventional LCD screens, but media facades and more varied display hardware are attracting considerable interest for accessible and engaging presentation of information to users. Despite obvious differences in the three mediums, five cross-cutting trends emerged from the surveyed literature: an increasing emphasis on situatedness, growing accessibility and a wider user base, support for interaction, new application areas, and challenges in managing user attention.

An Emphasis 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 commonplace, users have a growing expectation that a display will have some sense of situatedness—that is, it will have a connection to the space in which it's embedded.[10]

For example, in the conventional display domain, a clear shift can be observed from immersive VR-based systems such as CAVE[4] to situated displays that specifically represent changing activities in a space.[32] Media facades in particular are designed to be embedded into an existing architectural space, exploiting its characteristics and therefore offering clear potential for situatedness. Indeed, recent deployments, such as the 2014 City Bug report,[17] have realized this vision. 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 (such as Dangling String[19] and Clouds[21]).

In-situ information presentation has a number of advantages over other forms of information provision. First, 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]). Second, in-situ presentation can rely on the physical space to frame the information presented. Finally, when techniques such as projection are used, the physical space can become part of the visualization itself.

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A Rise in Nonexpert Users

A further trend is the growing set of varied users encountering 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 deployment was explicitly designed to support users, ranging from experts to children and senior citizens.[6] Equally, many media facades can be appreciated by users with varying degrees of understanding of the information presented. At one level, they can simply be considered as an aesthetic improvement to the space,[17] but as users develop an understanding of the visualization, they can read more of the information contained within.

Movement toward an increasingly data-driven society is likely to see a rapid increase in demand for data visualizations for nonexpert users. We expect pervasive displays to play an important role in meeting this need. The public nature of many pervasive displays means they have huge potential for accessible information and could prove to be an important tool in helping to avoid the creation of a so-called "digital-divide" based on information availability.

Increased Support for Interaction and Experimentation

Interaction has long been an important theme for pervasive display researchers, and it's 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. While early interactive systems relied on touchscreens and dedicated input devices (such as mice, data gloves, and joysticks), many now feature interaction with the display via smartphones[11,33] or through direct physical manipulation.[25] 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 that enables browsing and potential experimentation with the data being visualized, leading to new insights.[22]

The production of interactive data visualizations on media facades in urban settings is particularly interesting, because it poses significant new challenges. In some cases, a display might be visible by hundreds or thousands of nearby citizens, so 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.

The Emergence of 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 toward situated displays, and a wide user base, new applications have started to emerge.

Perhaps the most common of these are applications for behavior change in which visualization of previously unseen data is used to try and encourage viewers to modify their current behavior—often for health or sustainability reasons. One example is Breakaway,[34] a small custom-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 the desk, the sculpture would return to an upright position. Another example is the Clouds installation at the Open University.[21] It 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 earlier) was complemented by an array of plasma screens that gave a detailed representation of recent stair and elevator usage.

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

Increased Difficulty in Managing User Attention

Weiser's original vision of calm computing (that is, interaction with digital devices where the interaction is designed to occur in the user's periphery rather than at the center of attention)[1] is often seen as being at odds with the increasing trend toward 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 (less than two seconds), and many have become accustomed to ignoring them altogether—a phenomenon known as "display blindness."[35] To combat this, display owners and content producers (in particular, advertisers) have attempted to develop systems that are ever more engaging in an 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, which 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 behavior 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.

Information presentation through pervasive displays has long been an important focus for ubicomp. Consumption of information (as generated through social networks and IoT, for example) 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 facades, 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 ecosystem in 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 forward.

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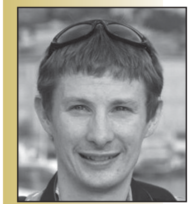

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