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# New challenges in display-saturated environments

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FEATURE ARTICLE

# New Challenges in Display-Saturated Environments

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We live in a world in which our physical spaces are becoming increasingly enriched with computing technology. Pervasive displays have been at the forefront of this progression and are now commonplace. In this paper, we focus on the natural end-point of this trend and consider the case when displays become truly ubiquitous and saturate our physical environments. We use as motivation a state-of-the-art display deployment in which mobile users navigating the space are simultaneously exposed to many hundreds of displays within their field of view and we highlight a number of new research challenges.

## INTRODUCTION

Our everyday physical spaces are becoming increasingly technology-rich – featuring significant amounts of pervasive computing infrastructure such as wireless access points embedded into the environment. This is particularly evident in the widespread deployment of digital signage that has been driven by the falling cost of hardware and the difficulty of reaching the general public through fragmented conventional media. While such signs have traditionally provided simple push-based advertising to passers-by, a new generation of displays is emerging that provide highly personalised, interactive and networked experiences [6]. We can identify a number of clear trends in recent display deployments:

(i) Increases in the quantity and size of displays being deployed.

(ii) Networked displays becoming the norm, creating larger deployments and new content distribution opportunities.

(iii) Increased physical integration of displays into the built environment.

(iv) Reduced time when viewers do not have a display within their field of view.

These trends are leading to the emergence of technology-rich spaces that feature unprecedented numbers of embedded displays, either arranged to form very large video walls or distributed throughout the environment. For example, in spaces that we are currently exploring viewers can see multiple pervasive displays from any single viewpoint in the space. These displays include a large network of smaller displays distributed throughout the space and a single high-definition video wall in excess of over 650 displays. In contrast to typical media facades, viewers constantly experience a high variety of differently-scaled displays as they navigate through the space. We term such environments *display-saturated environments* and informally define them as *environments in which the display density is such that users typically have multiple displays in their field of view at any point in time*, i.e. as users navigate the physical space displays are omnipresent – seeing a display becomes the norm not the exception.

We believe the emergence of display-saturated environments represents the natural end-point of existing trends and raises a number of important new challenges. In this paper we present the first exploration of the field of display-saturated environments. Based on our early experiences of researching in such environments we provide clear examples of how they are fundamentally different to existing display deployments and detail a number of new research challenges that saturated environments raise.

## A CASE STUDY

Our motivation for exploring display-saturated environments stems from our work in the context of the Suntec Convention & Exhibition Centre in Singapore. The convention centre covers 42,000 m$^2$ spanning seven levels of which some are exclusively used for large-scale conventions, concerts and other events (attracting up to 800,000 visitors over a few days), whilst others are used for smaller-scaled events such as meetings and conferences. The convention space features a large number of pervasive displays composed of two distinct display deployments: the world's largest high-definition display wall ("The Big Picture"), and a network of more than 160 smaller pervasive displays.


Figure 1: The Big Picture at Suntec Convention & Exhibition Centre – one of the world's largest high-definition video walls showing interactive content during a large event.

The Big Picture is composed of a total of 664 displays (55'' and full HD), over 80 meters wide and three stories high (Figure 1). Due to its location at the main entrance to the convention centre it has a high visibility to venue visitors and passers-by. Escalators on either side of the display wall serve as the main gateway into the convention centre. The content schedule typically consists of a mix of 30-90-second-long advertisement videos. The second display deployment consists of over 180 smaller-scaled pervasive displays (32-60 inches with full HD resolution) scattered across the convention venue. These displays typically serve as interactive information touchpoints, digital signage for room numbers and meetings, digital guidance and way-finding systems and advertisement billboards. The network of pervasive displays is controlled by a centralised software system while a separate set of software controls The Big Picture.

Additionally, the convention centre is equipped with sensing technology primarily designed to capture visitor mobility patterns and audience behaviour. Example sensors include Wi-Fi access points for location tracking (based on our prior work [10]), closed-circuit TV (CCTV) capable of capturing audience behaviour and dedicated visitor counters for a subset of entrances to the venue. Suntec provides access to control interfaces for the display infrastructures and sensing data through appropriate APIs – supporting the development of novel forms of proximity detection and interaction modalities for context-sensitive display applications that span across both display deployments.

To better understand the implications and requirements of display-saturated environments, we developed an interactive display application for The Big Picture allowing the audience to 'tweet the wall.' This case study has enabled us to capture a set of challenges and opportunities in working in such display-saturated environments that differ significantly to our experiences in working with small-scale public display networks – both in terms of the scale of individual displays and the number of public displays deployed in an environment. For example, novel forms of content scheduling approaches specific to display saturated environments can be explored through the availability of fine-grained and real-time location tracking capabilities of viewers.

# THE CHALLENGE OF SATURATION

We believe that the emergence of display-saturated environments, such as Suntec, raise significant new research challenges in the field of pervasive displays.

## Content Creation

The current state-of-the-art in content creation for pervasive display deployments consists of the production of short video sequences, static images or web-based content. The use of video in particular tends to be preferred when high-quality content is needed as it allows the use of a wide range of artistic tools and techniques to enhance the appearance of the content. However, the tools utilised for content creation are designed for use with single displays and small-scaled displays. In addition, content creation and scheduling tools for digital signage systems assume that content will be consumed by viewers on single displays – the consumption of content across a network of displays has not been considered. However, saturated environments differ in the size and number of displays for which content needs to be created and the relationship between the display and its environment. They demand new content creation tools that can:

1. support the creation of content for very large displays at appropriate resolutions (e.g. video walls with an effective resolution of 21 times ultra HD),
2. enable content creators to simulate different viewer perspectives to understand the overall visual impression created when their content is deployed in a physical space,
3. allow the creation of content that spans across networks of displays and supports the experience of non-linear media while moving across the space, and
4. facilitate the creation of interactive experiences that utilise viewer mobility tracking technology throughout the space such as the "Magic Pixel" displays [16].

These types of tools simply do not exist – the closest equivalent would, for example, be the tools used by modern games designers to author immersive experiences in virtual environments, yet these only partially address the requirements described above. Our experiences from the case study suggest that high profile displays demand particularly high-quality content (for our Twitter application, professional designers from Suntec assisted us in the creation of the content template) due to the large audience. With the increasing complexity of content creation, the cost for content creation grow leading us to believe an increasing demand for systems that support the sharing and sale of content within display networks [6].

## Interaction

In relation to interaction with users, display-saturated environments differ from traditional display deployments in two key ways. Firstly, the scale of displays (both the physical size of large displays and the number of smaller-scaled displays) and the size of typical audiences may be several orders of magnitude greater than typical research deployments. Secondly, in saturated environments the start and end of a user's interaction or engagement with a display may be unclear. Traditional pervasive display deployments consist of well-proven audience behaviour models in which viewers first pass by a single or small set of displays, see and react to the content, and perform subtle interactions prior to directly interacting and engaging with a screen [13]. In a highly display saturated environment where displays are omnipresent, however, the initial three stages of passing by, viewing and reacting, and interacting may fuse to a single element in which viewers have no choice but to view, react and interact with the entire display environment – interaction zones specific to individual displays [15] will be overlapping and leading to unclear viewer intentions that cannot be mapped to specific displays. Furthermore, in traditional deployments viewers leaving the viewing area of a screen are deemed to have finished their interaction. In contrast, viewers leaving the viewing area of a display in a saturated environment are already within the viewing area of a large number of other screens – opening up the possibility of very long-lived interactions that span tens or hundreds of displays.

To highlight the impact of these issues, consider the new challenges that arise in addressing three very basic elements of user interaction. Firstly, *how should pervasive display environments communicate the potential for interactivity to viewers entering the environment?* Attracting attention with public displays and kiosks is a well-known challenge and described as the "first click problem" [12]. Previous research has considered the use of stimuli such as viewer silhouettes to attract passers-by and announce the interaction capabilities of a display [13]. However, it has been well studied that displays already compete with other media and stimuli over the attention of a passers-by [15]. The use of attract sequences or traditional paper signage to communicate interactivity would be an addition to the already high number of stimuli, and further scale poorly in an environment that is over-saturated with displays [5]. More modern techniques such as the use of viewer representations (in which mirror images of passers-by are projected on the display itself) have been successfully proven to attract viewers and efficiently communicate interactivity [15]. In contrast, display saturated environments are often crowded with large audiences, introducing further scalability challenges in the visualisation of mirrors whilst still providing place for interactivity. Additionally, large crowds are known to have the opposite effect on drawing viewers to interact displays risking public embarrassment [2]. Perhaps most crucially, the increase of different types of stimuli competing for the attention of a passers-by can quickly lead to a cognitive overload [20] – especially due to the fact the environment itself is already filled with rich media (i.e. digital displays).

In our case study, we experienced very little interest from the audience in engaging with The Big Picture using Twitter as a platform. Though we made interactivity visible through large writing on The Big Picture itself, our observations showed that the audience appeared very target driven in visiting the exhibition instead of dwelling in the entrance area. We believe that our initial observations may be further evidence to support our hypothesis for the need for new techniques for communicating interactivity in the context of rich environments. We note that additional factors may have led to limited interactions including an unclear value proposition of the application offered to viewers.

The second challenge area lies in the *identification of new interaction techniques for display-saturated environments*. Researchers have typically focused on the use of touch, gesture, gaze, pointing device or mobile phone to support interaction. However, in the context of The Big Picture or large display networks, none of these approaches scale well. Touch is inappropriate for large screens or large audiences. Similarly, research has shown that the presence of others inhibits the use of gesture enabled displays [8] even assuming that sufficient physical space in front of the display could be found in which a viewer could perform the necessary gestures. Gaze is similarly limited regarding audience numbers as most gaze tracking systems only able to track a single user, and may imply potential risks for the audience specifically regarding "public embarrassment" [2]. The use of pointing devices that overlay real (or virtual) "laser" pointers on the screen suffer from many of the identification challenges raised earlier. Moreover, the scale of many display-saturated deployments mean that new techniques are required to support basic operations such as selection and dragging over very large physical areas (many tens of metres) and across displays – far beyond the sizes considered in typical video wall research.

## Scheduling

Scheduling of content in pervasive display systems addresses the basic question of deciding when and where to show a particular content item. This is a particularly challenging question as it requires addressing the concerns of a large number of stakeholders (including display owners, content producers, multiple viewers and bystanders), understanding the context of displays and viewers, selecting or generating content items and determining appropriate schedules for both individual displays and across entire display networks. In traditional display deployments, the scheduling of content is typically performed manually by users creating time-lines and playlists of content for individual displays. The support for networks of displays typically consists of the ability for grouping displays into units that all show content according to the same time-line.

Display-saturated environments raise new challenges in all aspects of scheduling. Firstly, the number of content items is likely to increase substantially due to a greater proportion of user generated content and the emergence of open display networks that encourage new content providers [6]. This increase in volume of content complicates issues such as meeting inter-item constraints, e.g. those that govern the placement of adverts for competing brands.

Secondly, the use of fixed times for content presentation are likely to become redundant as display owners focus instead on showing content when particular viewers are present. Indeed, recent research is starting to demonstrate the feasibility of new forms of scheduling that focus on creating schedules that are oriented towards viewers [14]. For example, such systems would be able to support scheduling of content across a network of displays in such a way as to ensure that users see the maximum number of unique content items, see content items in a specific order or see newest content first. In display saturated environments, however, content scheduling can become highly complex. In addition to the large number of displays distributed throughout the space and located in close proximity to each other, other factors including conflicting interests of individuals, the displays' contextual information and date and time may have an influence on the scheduling of content on individual displays. Typical content scheduling systems are limited in their ability to consider large sets content requirements and constraints whilst still offering the ability of dynamically changing the content schedule based on external factors.

Finally, the mix of physically large displays in combination with smaller-scaled displays open up entirely new ways of laying content out on displays, further increasing the range of scheduling options. While these new scheduling requirements can be addressed by hand for a small number of displays it would not be possible to manually create display schedules for the number of displays found in a typical saturated environment. The creation of scalable, automated scheduling systems that automatically determine which content is appropriate to show based on the audience, display location and other contextual information is thus a key challenge for future display environments.

## Privacy and Personalisation

Personalised and targeted content is supported in many modern pervasive display settings and typically achieved using video analytics to capture information on audience demographics. Within the context of research systems, proximity- and map-based solutions offer ways in which users can trigger personalised content on nearby displays. As the density of displays and the audience size increase, developments in these technologies will be required to support personalisation, e.g. by developing very fine-grained location tracking and display system software that supports rapid responses to enable walk by personalisation [6]. With such technologies, however, new threats emerge relating to fine grained location tracking and the viewer's ability to assert plausible deniability for a specific piece of content decreases [6]. Furthermore, we note that the potential consequences of any inadvertent disclosure of personal information on a screen increase with the size of an audience in a given area.

Supporting personalised content in saturated environments raises research challenges beyond just maintaining viewer privacy. For example, *how should display real-estate be shared amongst very large numbers of potential viewers?* Simple approaches based on spatial or temporal multiplexing do not scale well as viewers would either need to wait a significant period of time to see their content or would have to find their content amongst a very large set of displayed content items. Researchers have explored alternative solutions for multiplexing content on large displays such as the “Magic Pixel” [16]; a display technology that can simultaneously visualise different content to viewers present in the vicinity of the display. Future research has to prove whether such solutions scale to display-saturated deployments.

Finally, a unique challenge in environments with large audiences relates to the impact of selective personalisation where only a subset of the currently present audience receives personalised content (e.g. due to limited knowledge about the interests). The implications for the remaining set of people not perceiving a personalised experience are unclear (e.g. potential disadvantages). For example, would the audience group not receiving personalised content feel disadvantaged or slighted that the environment ignored their presence? In this case the overall impact of personalising may be negative—questions that have yet to be studied in depth.

## Audience Engagement and Analytics

One of the key challenges in digital signage research is the evaluation of the effectiveness of pervasive display deployments and, in particular, understanding the extent to which viewers engage with pervasive displays. Measuring display effectiveness has been the subject of significant prior research, e.g. by Rodgers et al. [18] and more recently by Alt et al. [1]. Such research typically shares a number of common characteristics in considering relatively small-scale deployments (either a single or small number of displays), limited audience sizes (research in engagement frameworks, for example, consider small numbers of concurrent viewers), restricted physical areas (most engagement frameworks focus on viewers as they interact with a display in a limited physical space), and serialised content (engagement frameworks assume a single item of content is visible to users at any point in time – where multiple content items need to be displayed this is typically achieved through multiplexing in the temporal domain).

In saturated environments, new measures of audience engagement will be required that consider the high density of displays distributed across spaces and significantly increased audience sizes. In particular, concepts such as display blindness appear much less relevant when displays are deployed throughout a space at a density that it is simply impossible for a viewer to avoid glancing at a display. In addition, video analytics are non-trivial when the density of people increases if the goal is to track the movement of individuals and groups throughout the environment (across cameras and displays) and to accurately identify their engagements with displays and other visitors. For example, in the context of Suntec, visitors are forced to walk towards The Big Picture and therefore face the large display wall in order to enter the convention space. Upon entering Suntec, a large number of smaller-scaled displays are deployed at positions at which visitors must walk by and are likely to face – but not necessarily glance at – a display. Both conditions introduce challenges of using simple face counting algorithms to accurately count viewers who intentionally glance at a display.

As a result, our experiences suggest that new metrics and techniques are required suitable for measuring engagement and interaction. To understand the effectiveness of the display wall in the context of our study, we had to code the video recordings for much richer behaviours of visitors: *looking at display*, *looking at phone*, *looking around*, *in conversation*, *idling*, and *other*. In order to differentiate between *looking at display* due to the fact that a person walked towards the display, and that the person was actually engaging, we believe that capturing the *duration of looking at the screen* in combination with the viewer’s behaviour prior to glancing at the screen (e.g. idling) are essential. This is based on prior research that showed that people typically look at the screen between 0.318 [4], and 1-2 seconds [9] to be aware of its content. Combining this measure with the viewer’s dwell times and locations may allow further insights into the level of engagements with displays throughout the entire space.

Finally, we note that in the digital signage domain, most research focuses on how users engage with the content on such displays and not on how the presence of the displays impacts on users’ abilities to undertake other tasks. For example, does the increase of screens installed in an environment enhance or diminish the short-term cognitive abilities of viewers within the space? Many older readers will have grown up being told to “turn the television off while doing their homework”. What does it mean for a generation that can never turn off the displays in their environment? These issues will require new techniques for measurement and analysis as pervasive displays become ever more widespread.

### Deployment Challenges

Creating instances of display-saturated environments raises a number of new deployment challenges. Firstly, such deployments typically incur a significant financial and environmental cost and the benefits of such deployments are harder to quantify – at present there are no simple analytics tools for measuring the effective conversion rate for a digital advert for example. In particular, it is extremely difficult to understand the cost-benefit trade-off of increasing the density of displays in an environment and hence it is hard for owners and commissioners of display systems to know when they have deployed enough displays. In related domains researchers have attempted to define models that support the quantification of the return of investments. For example, in retail environments "customer value proposition" [17] models exist that describe the importance of "contributing to the symbolic value of the shopping experience" [17] by deploying additional technology in a space – ultimately leading to a higher customer satisfaction and consumption. Such models, however, define value proposition very abstractly and fail to clearly describe the relationship between financial investments (e.g. into pervasive displays) and the return of investment for the retail owner (e.g. increase of purchases as a result from the investment).

The second challenge relates to the public's perception of broken digital signs. With the number of displays the number of display failures inevitably increases in any environment. At present, failures in digital displays are often perceived as harmful to the reputation of the display owners and hence steps are taken to repair displays rapidly in order to ensure the perception of a fully functioning network. This is particularly true for high-profile displays such as The Big Picture: our observations showed that tourists often use the large display wall as a background for photographs and there is considerable pressure to ensure the screen's continuous operation. Large display saturated environments will therefore likely draw higher costs regarding the maintenance of the display network in its entirety.

Finally, we note that one consequence of the move towards display-saturated environments is to raise the barrier to entry for researchers in this space. In particular, while existing display research can be conducted relatively cheaply, creating an environment with hundreds or thousands of displays requires substantial investment in both display hardware and physical real estate.

## RELATED WORK

The ubiquitous computing vision has long predicted environments, in which computing systems will be omnipresent – even letting the user forget that they are interacting with a computing system as they become woven into the fabric of everyday life. Indeed, displays in the form of pads, tabs and boards were an important element of Weiser's vision.

In recent years pervasive displays have become an area of significant research interest and numerous lab studies and small-scale deployments have explored specific areas of pervasive displays including interaction, application design, systems software, analytics, video walls, media facades and societal issues [5]. In addition, a number of research groups have created long-lived deployments that are particularly valued as the time-scales over which they have been operated means that novelty effects are minimised when conducting user studies. Examples include the e-Campus deployment at Lancaster University consisting of approximately 60 displays in a campus setting and the UBI-Hotspot infrastructure at Oulu with a number of touch-enabled displays scattered throughout public spaces in the city (see [5] for summaries of these deployments).

These deployments, however, do not begin to approximate display-saturated environments in which displays are ubiquitous and present at all times. The closest work to creating saturated environments can be found in the field of immersive virtual reality, as initially described by Slater and Wilbur [19] and early work on display-rich smart rooms such as the Stanford iRoom that provided a collaborative and interactive work environment [11].

Issues of scale and physical integration have been explored by researchers investigating media facades in urban spaces [7], and prior research has identified the importance of integrating such deployments into the physical environment [3]. However, such work tends to focus on engagement within a limited viewing area with a single display rather than considering how users navigate through physical spaces with multiple displays such as a modern shopping mall.

## CONCLUSIONS

In this paper, we describe a brave new world in which displays of all shapes and sizes are everywhere and shared by an enormous audience. We are motivated by the question "*How can these displays be used to provide both individual and group benefits?"* Asking this question reveals numerous lines of research that are both extensions of existing research (video analytics, selecting the right content for a particular user etc.), as well as facilitating new threads of research (the effect of targeting just one person in a crowd, seamlessly merging content for multiple users over a large display, etc.).

Underpinning all of these questions is the need for a new exploration of the value proposition that pervasive displays offer and the development of new models that explain the use of this new communications media for effective communications. Such models could be based on prior work that has focussed on the exploration of the 'richness' of media and suggests that the 'richness' of media (e.g. the use of video, text, or speech) have an influence on the ability of people to perform computer-mediated tasks [20]. Transferring traditional media richness theories into display saturated environments emphasises the need for carefully choosing the level of engagement with viewers to ensure effective communications.

We showcased our initial work at Suntec Singapore, which consists of many shared displays (ranging from small-scale to very large-scale displays) and a large visitor base (some events attracting hundreds of thousands of visitors). The initial experiment confirms our belief that display-saturated environments are fundamentally different from our prior experiences with smaller display deployments. With this insight, we posed new research questions that can hopefully spark exciting future research.

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