A Systematic Review of Ambient Display Modalities, Physical Forms and Interactivity

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***Abstract*—A systematic review of 459 Ambient Displays, reported in 410 publications between 1996 and 2016 was used as the basis for an analysis of the high-level design features associated with the technology. An analysis of these displays considers three main aspects: the modalities used to display information, the physical form of the displays and the level of implemented interaction. The paper provides a longitudinal overview of the various forms of Ambient Displays over a twenty-year period. This allows for the provision of a comprehensive timeline of past work in the field of Ambient Display and establishes a sound basis for further reviews or studies related to this technology.**

Keywords-Ambient Display; Peripheral Display; Systematic Review, Evaluation; Modality.

I. INTRODUCTION

Ambient Displays or Ambient Information Systems are designed as everyday, peripheral information sources that visualise useful data in a way that can be attended to when possible [1]. They are designed to display abstracted, non-critical information on the periphery of a user's attention [2] [3]. They should be non-obtrusive and try not to overload the senses [4] [5] while also considering the aesthetic appeal of the display and the need to be seamlessly embedded within an everyday environment [2] [6] [7].

The field of Ambient Display was motivated by Calm Technology [8], a desire for less intrusive displays in a noisy world of dynamic and ubiquitous information. The technology, under different names, has been studied since about 1996 and is most commonly referred to as Ambient Displays, Ambient Information Systems, Peripheral or Pervasive Displays [9]-[12].

There have been several narrative reviews of the technology in the past [1] [7] [13]-[30]. However, these narrative reviews do not attempt to cover the majority of historical examples of Ambient Display. This paper is designed to address this gap and categorise key design features based on the analysis of results from a systematic review [31] that identified 459 Ambient Displays published in 410 studies between 1996 and 2016. This historical analysis supports a fuller description of the common attributes of Ambient Display in a field comprised of disparate systems that has evolved over time. Providing a comprehensive timeline of historical studies into the field of Ambient Display offers a sound basis for detailed meta-analysis of the technology and acts as an introduction to the field's progression across the design, development and evaluation of Ambient Display.

While some other studies have also taken a systematic approach [31]-[33], these works focus on restricted portions of the domain and thus describe a more limited set of the overall number of Ambient Displays. This study takes a more expansive approach, assuming that further insights may be gained by a systematic categorization of a large, longitudinal sample of this display technology.

The systematic review identifies three broad design categories of Ambient Displays, the modalities used to display information, the physical form of the display itself and the level of interaction implemented. It serves to highlight some key differences in the types of Ambient Displays and suggests gaps in the field.

This analysis begins next in Section 2 which discusses previous naming conventions and definitions for the technology, which leads to the systematic review methodology that is documented in Section 3. Sections 4, 5 and 6 discuss each of the major design attributes of the technology discovered through the review process including; modality (see Section 4), physicality (see Section 5) and interaction (see Section 6). This leads to discussion of conclusions and future work, which are presented in Section 7.

II. NAMING CONVENTIONS AND DEFINITIONS

The definition of Ambient Display technology is difficult as there are no consistently accepted terms used to describe these systems in the existing literature [1]. This includes the key features of the technology, which can be described in divergent ways while still being interpreted as aligning to the ideals of Calm Technology [8]. So, just what is an Ambient Display, and how has the technology developed over time?

Common overarching names for this type of display technology include Ambient Displays, Ambient Information Systems, Peripheral or Pervasive Displays [9]-[12]. There are some reoccurring themes within the previously suggested definitions of the technology. These include the display of potentially useful [10] [36] information [1]-[6] [11] [19] [34]

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[36]-[41] in one's periphery [4] [34] [56] [57] [61] through aesthetically designed systems [2] [6] [7] [10] that do not impose on the user or become intrusive [4] [5] [19] [34] [39] [43].

These divergent attributes suggest the need for a more structured review process, to understand how the domain has developed over time and to highlight general categories of these technologies. Therefore, this review aimed to document a high volume of previous displays and quantify them into broad design categories that would inform how the key design features of such displays have developed over time.

III. METHOD

A systematic review was designed to analyze a large body of published work related to Ambient Displays. This was intended to cover a twenty-year period beginning with the suggestion of Calm Technology in 1996, through to the end of 2016.

The disparate nomenclature of the technology had to be addressed early when selecting terms used to query the academic databases. A pragmatic approach was taken in selecting Ambient Display, Ambient Information System, and Peripheral Display as key terms for search. This decision was based on the common use of these naming schemes. Since this search identified over fifteen thousand articles, it was decided not to include further terms.

These terms were queried in four separate academic databases; ACM Digital Library, IEEE Xplore, Scopus and Web of Science. The attributes of the search query used in each database are shown in Table 1.

Searching across these three databases resulted in over fifteen-thousand documents (n=15,693), which required further assessment for determining their relevance to the study. Only papers that documented a specific Ambient Display design, implementation or discussed theoretical concepts relating to the technology were included.

As a next check, all publications were assessed to determine if the system described was consistent with two typical definitions of Ambient Display (see Table 2). This process acted as a further pre-screening of the literature that did not align to the intentions of this research.

TABLE I. ATTRIBUTES OF THE QUERIES USED TO SEARCH FOR RELEVANT LITERATURE

Databases	ACM Digital Library, IEEE Xplore, Scopus and Web of Science
Years	1996 – 2016
Document Types	Journal Articles, Conference Papers, Works in progress
Language	English
Keywords	Ambient Display, Ambient Information System, Peripheral Display

TABLE II. THE TWO DEFINITIONS USED IN THE INITIAL ASSESSMENT OF LITERATURE

Definition 1	"Ambient displays are abstract and aesthetic peripheral displays portraying non-critical information on the periphery of a user's attention." [2]
Definition 2	"Ambient Information Systems are designed as everyday, peripheral information sources that visualise useful data in a way that can be attended to when possible." [1]

Publications that were found to conform to either of these definitions were considered further to determine if the described technology conformed to the original ideals of Calm Technology [8]. Advertising displays and displays relating directly to digital signage were excluded. Finally, publications describing systems with high levels of user-interaction, such as computing games or interactive information systems were excluded.

This screening process resulted in 410 unique documents that were judged as being most relevant to this study. Most of the literature was found to relate to the development and evaluation of Ambient Display (n=254) or the development of Ambient Display (n=115). The remaining literature was found to relate to the evaluation of Ambient Display (n=7) and a subset of studies (n=34) that discuss the theory or classification of the technology.

Found within these studies were 459 Ambient Displays that were classified according to three general attributes which were found to reoccur across these implementations. These attributes were the modality, the physical form and the level of interaction designed for each of these displays. These document references, the data used in Figures 1-3 and discussed in this paper have been made available in a public data repository for open access [31].

IV. DISPLAY MODALITIES

Almost since the beginning of Ambient Display in 1996 [8], there has been the associated notion of Ambient Media [44]. This has implied that diverse modalities might be used to encode data and display information across a range of senses. As might be expected, across the 459 Ambient Displays the modalities were diverse [31] (see Figure 1). Although, only about 12% of these were identified as multimodal displays (n=54). By contrast, 76% of the displays provided only a light-based mode, implemented using physical lights, projected images or traditional computer screens (n=348). Other approaches included object movement (n=32), sound (n=12), olfaction (n=2) temperature (n=2) or vibration (n=9).

In total, 87% (n= 398/459) of the reviewed systems were found to use some form of light for output. The majority (n= 348) of these implementations used light as the single output medium. A smaller subset of displays (n=49) incorporated light as part of a multimodal presentation. While the use of light was the primary media used for output, some systems adopted more novel modalities, including the use of smell

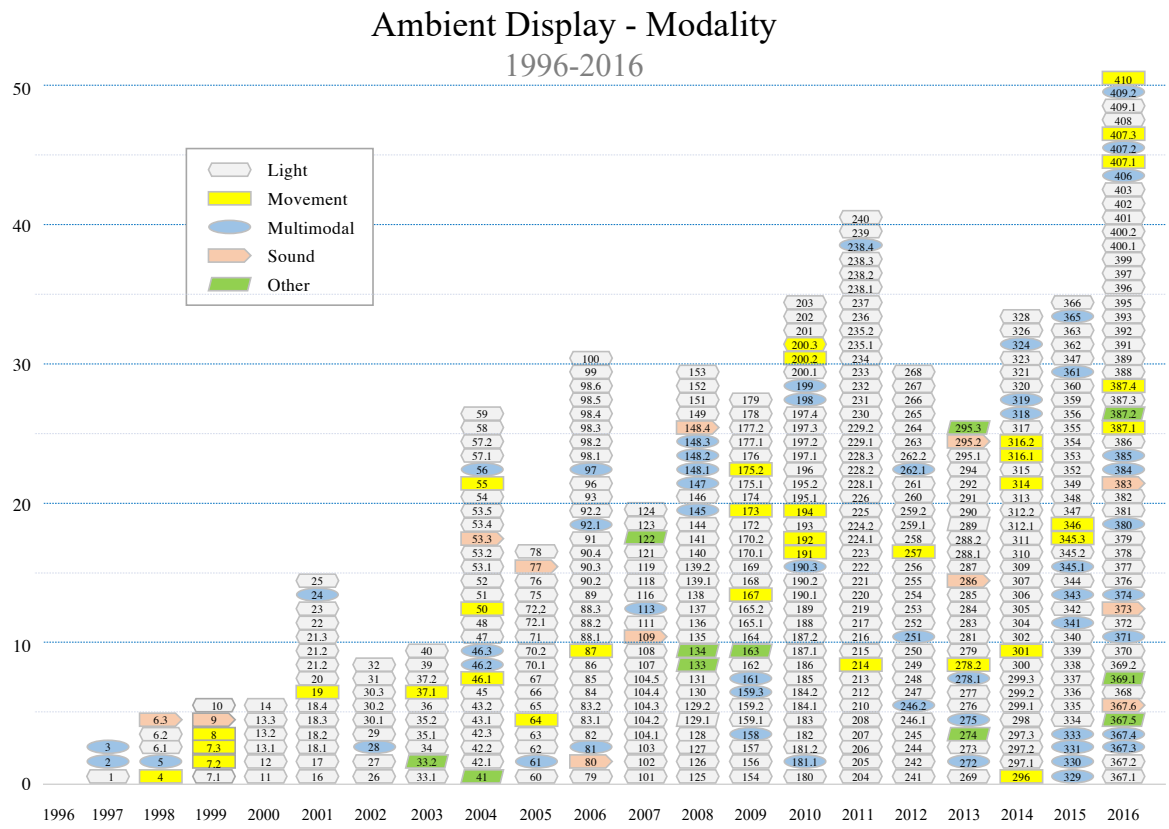

Figure 1. Distribution of Ambient Displays over time, classified by modality. The numbers directly reference identifiers in the systematic review data [31]

(n=3), sound (n=53), vibration (n=13) and temperature (n=6). These novel displays often depart significantly from typical computer systems.

In the scope of this review, only a few implementations were identified that solely make use of sound for output (n=12). This result is somewhat unexpected given the ambient nature of sound and the opportunities afforded by sonification that allows encoding of abstract data into non-speech sounds [45].

V. PHYSICAL FORM

The review also identified a broad range of physical forms that could be described in two general categories. Firstly, there are those that make use of screen or projection technology for output. Alternatively, there are displays that are more tangible or sculptural in form and are categorized as object-based Ambient Displays. The distribution of these two different hardware types was largely even across the domain with 49% (n=224/459) being screen-based and 51% (n=235/459) being tangible display objects (see Figure 2).

These screen-based implementations typically used off-the-shelf LCD, CRT monitors or projection technology. Computer-driven displays permit considerable flexibility around the selected data mapping. These screen-based displays tend to use either natural metaphors or symbols for encoding data. The focus tends to be in mapping layers of information into art-like compositions, typically in the form of pictures or posters [6]. Often these systems adopt a wall-based, 'Informative Art' approach [6].

This Informative Art approach is well documented where screen-based technologies are typically used to visualize a live data source by enhancing the attributes of an existing artwork. For example, the work of Piet Mondrian has been the inspiration for a dynamic display where the volume of email received is represented through the size of colored shapes [6].

Around 51% of all reviewed Ambient Displays were found to make use of tangible objects. Given their sculptural nature these displays were found to take numerous forms and use a range of modalities. The distribution of modalities across object-based displays was similar to the domain as a whole, with a high proportion of light-based systems.

Due to their physical nature, these displays are also referred to as being sculptural in form [3] and could be classified as Tangible User Interfaces [35]. This group of Ambient Displays are implemented using diverse hardware that ranges from augmented household objects through to more complex custom-built artefacts. The creation of these

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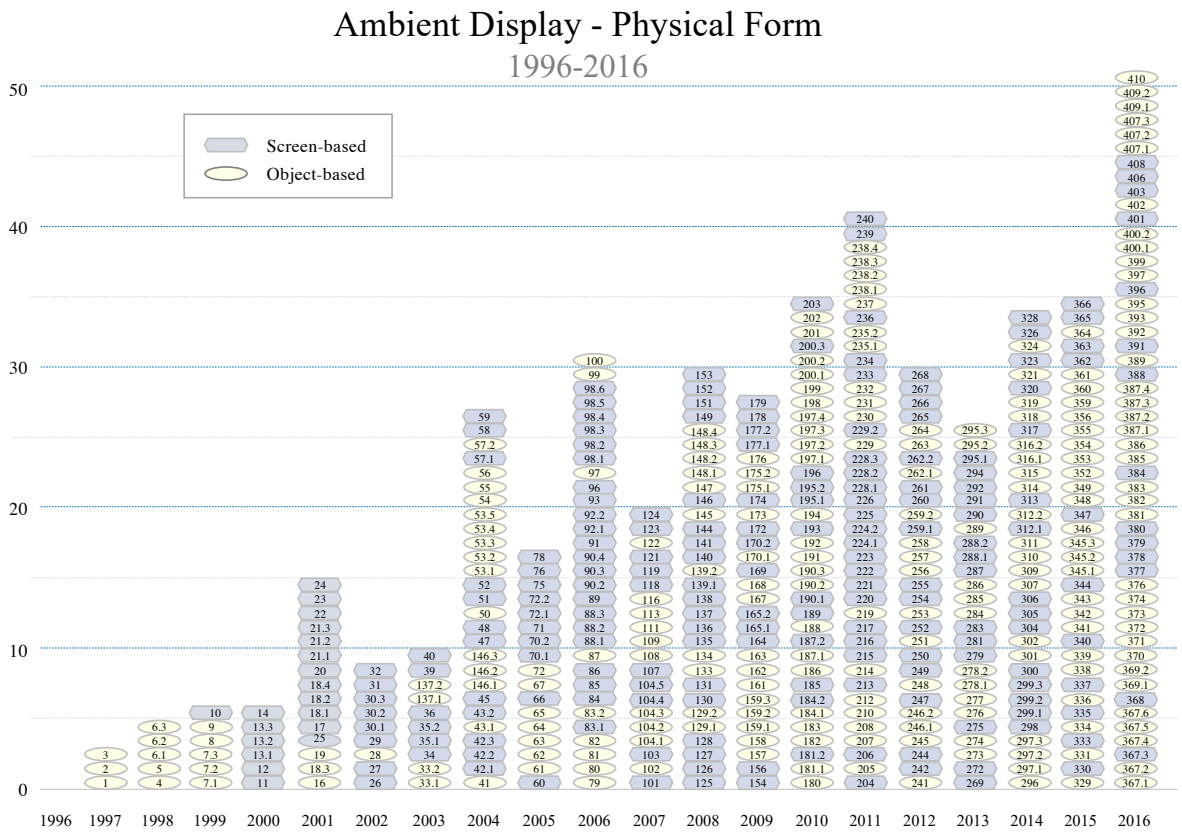

Figure 2. Distribution of Ambient Displays classified by physical form. Numbers directly reference identifiers in the systematic review data [31]

displays typically combines off-the-shelf technologies or requires custom hardware to be built. Unlike screen-based displays, the amount of information that can be displayed on object-based displays is usually limited as these displays only support a few attributes of information [3]. As a result, the time and effort required to build these tangible objects may be greater than using off the shelf display hardware, although more tangible forms may allow for a further subtle visualization through display mechanicians that may not be light based. This approach is well documented in an early example of the technology, the ambientROOM where sound and object-based projections are used to visualize data [35].

VI. INTERACTIVITY

Ambient Displays are typically designed to function with no direct input from the user. This non-interrupting, approach follows the basic tenants of Calm Technology. Therefore, these displays might be expected to remain fully ambient and only output information. However, some systems while predominantly ambient, also support a low level of direct interaction. In contrast to fully ambient systems, displays that provide a minimal level of interactivity are classified as semi-ambient.

The systematic survey identified 58% (n=266/459) of the reported systems as fully ambient, accepting no input from the user. Such systems, by design are intended to not interrupt the user's primary attention and remain peripheral. Many of the traditional examples of Ambient Displays, such as the Dangling String [8] have no direct interaction. They reside within their environments presenting information without need or support for user input.

Despite this non-interactive expectation, the inclusion of active or passive interaction features were still reasonably common (42%, n=193/459). These semi-ambient systems still aim to remain peripheral but possess interactive capabilities that may move the system to the centre of the user's attention for short periods of time. The intent is to allow momentary interaction from the user so they can configure, enhance or in some other way manipulate the function of the display. For example, to change the display features, connect to another data source, or change the data mappings.

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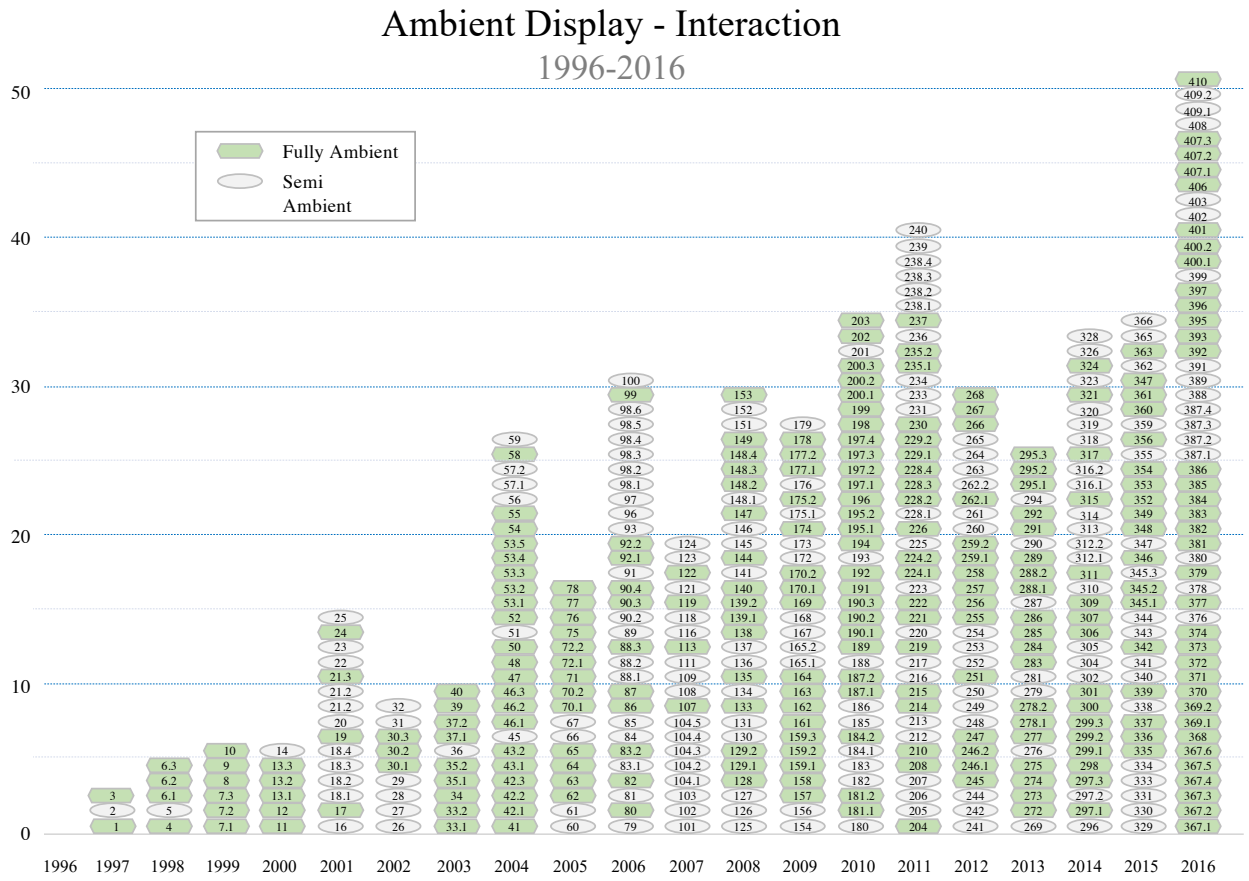

Figure 3. Distribution of Ambient Displays over time, classified by interactivity. Numbers directly reference identifiers in the systematic review data [3]

These semi-ambient systems adopt several interaction methods to enhance the function of the Ambient Display. This includes the use of buttons, touch screens, local sensing technologies, body movements and eye contact. These interaction events are typically optional and are usually designed to change the on-screen visualization or enable additional interactive features. While the inclusion of interaction into Ambient Displays may increase their utility in some situations, display designers are typically conscious of the effect that excessive interactivity may have on the peripheral nature of the device.

A good example of the novel approaches taken to reduce the imposition of potential interactive features is in the Ambient Widget [40], where interaction is optional depending on the user's distance from the device. While being far away from the device, the user will be presented with information in a subtle and visual manner as in other more traditional Ambient Display implementations. As they move closer, the user will be granted the option for more direct gesture-based interactions with the display [40], limiting the requirement of interaction to those who desire more detailed information than presented by the device's more ambient mode.

VII. CONCLUSION AND FUTURE WORK

This longitudinal review of the field of Ambient Display highlights the great diversity in display modality, visualization approaches, form and levels of interaction. In this systematic review we categorized a large subset of these displays across the three broad design dimensions of; modality, physical form and level of interaction.

These displays adopt a range of modalities including light, sound, object movement, object manipulation, vibration and olfaction. Seventy-six percent of the displays used light as the only modality for output. This diversity in modality is indicative of recent advancements in the field where display development remains common along with the exploration of various output modalities. Some contemporary examples include: low resolution light displays to visualise energy usage [46], ambient lights that visualise stress levels [47], monitoring of weather conditions through an LED enabled sculpture [48], signalling of driving decisions through coloured light

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[49], presenting peripheral information through emerging augmented reality technologies [50], visualising heart rate through a light emitting wearable device [51], displaying information through plant [52] or human [53] shadows and to engage people with dementia through Ambient Displays [54]. While these recent developments in the field are indicative of the technologies covered in this review an analysis of literature from 2017 and onwards represents an opportunity for further research.

When categorizing the Ambient Displays by form about half of the displays used standard screen-based display technology, while the other half were based on tangible everyday objects. There is a clear divide here between the two types of display. Two distinguishing features of these groups are the greater complexity of information that can be displayed using screen-based devices and the limited range of information opportunities and bespoke development requirements for tangible objects.

The final category considered interaction level and identified 58% of the displays to be fully ambient while 42% provided some low-level of interaction. In terms of utility, the non-interactive displays are most aligned to the principles of Calm Computing, as the user is not distracted from their primary task by engaging with the display. The inclusion of interactive features may seem counterintuitive to the creation of peripheral technologies. However, these systems usually try to adhere to the tenets of the Calm Computing by limiting the frequency of interaction, allowing voluntary interaction or providing more passive methods of interfacing.

In addition to these themes, it was found that most of the Ambient Display literature simultaneously considers the design, development and evaluation of the technology (n=254). This results in limited studies relating to non-implementation specific evaluation methods and literature discussing the theory underpinning the field. In this sense, there would be opportunity for further research regarding these more theoretical areas of the domain in a field dominated by practice-based studies.

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