Beyond the Tyranny of the Pixel: Exploring the Physicality of Information Visualization

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Abstract

This paper consists of a review of contemporary methods that map and materialize abstract data as physical artifacts. With computing technology and the access of information influencing every aspect of our everyday lives, one can question the current habit of information displays to 'simulate' real world metaphors, and whether information could instead be conveyed by approximating the analogue and tangible characteristics of our daily experiences. This paper introduces five different degrees of 'data physicality', which differ in the level of abstraction of how data is mapped and perceived by human senses: ambient display, pixel sculptures, object augmentation, data sculptures and alternative modality. This categorization demonstrates the potential of information visualization as a communication medium in its own right, which proliferates beyond the ubiquitous pixel-based, light-emitting surfaces of today.

Keywords **info-aesthetics, data sculpture, pixel sculpture, multi-modal visualization, ambient display**

1. Introduction

Since its conception about 15 years ago, the field of information visualization has mainly focused on the representation of data on screen-based output media. Information visualization methods are specifically designed to augment the perception of *abstract data*, data that possesses no inherent spatial layout or presence in the physical world. Because abstract data has no natural counterpart that can be graphically reproduced, the visualization challenge consists of the design, development and evaluation of novel data mapping metaphors for presenting information in an easily perceivable and understandable way. The use of digital computer screens and projections for this purpose possesses several obvious strengths, including their quick, dynamic frame-rate, their huge and detailed resolutions, and their capability to immerse people within a virtual representation that almost cannot be distinguished from that of reality. However, as we observe the implications of computing penetrating every aspect of our everyday lives, one can question the continuous push towards using the graphical power of screens to simulate "real world" visuals for representing inherently "abstract" information. In today's information society, data access has become pervasive, and many people are already exposed to computer screens longer than they face nature or other human beings. For all the obvious qualities screens and projections enjoy, they still require dedicated and large flat surfaces, brightly illuminate their surrounding environment, are generally task-obtrusive and attention-grabbing, and often remind us of productivity tools rather than a calm medium that encourages contemplation, analysis and reflection. Therefore, the question can be asked why information displays, especially those placed in a public context, should mimic the discrete nature of computers by utilizing pixel-based graphics. By considering the inherent capabilities of many material objects to communicate meaning and functionality by the natural affordances they possess, visualization developers could consider alternative presentation media by learning from how humans experience and interpret the world around them. In other words, we claim that what a pixel-less display might lose in resolution and information bandwidth, it could make up in a richer, more intriguing and memorable experience that nonetheless communicates complex information and insight.

This paper reviews the conceptual spectrum of representing abstract information in a physical way, ranging from ambient display over data sculptures to approaches that reach beyond the stimulation of our visual sense, in an attempt to explore the potential of information visualization as a rich and multi-faceted communication medium in its own right.

2. From Insight to Experience

2.1. Traditional Information Visualization

An information visualization method is uniquely characterized by a predefined set of *data mapping rules*. Every data mapping rule determines how a single data element, containing data attributes, data values and reciprocal relationships to other data elements, is translated into perceivable graphical form. Generally, each data element corresponds to a single visual element, such as a point, line (1D), shape (2D), or object (3D), which then becomes altered by transformation operations (e.g. location, shading, direction, …) according to the data values it contains. The exact nature of these rules tends to be determined by the application developer, who is mainly motivated to optimize the *effectiveness*, the accuracy and completeness which users achieve specific tasks, and *efficiency*, the resources expended in relation to the effectiveness criterion, of specific user tasks. This focus to measure and optimize performance solely captures functionalistic concerns, so that in most visualization applications of today, the role of the user experience not necessarily is considered. As an indirect result, most published information visualization applications do not describe the *design rationale* behind the choice of data mappings (such as the nature and meaning of the chosen metaphor, color palette, shape proportions, screen design, etc.). In fact, most visual metaphors seem to be based on a *genius design* approach (that is by a designer who is seemingly so talented to know intuitively what works and what not), complemented by integrating parts of best-of-practice examples, or learning from published scientific insights that model the qualitative correlations between human cognition and visual perception, such as from visual cognitive sciences [27], visual Gestalt Laws [28] and visual design guidelines [24].

2.1. Information Aesthetics

While traditional information visualization seems focused to optimize the performance of finding insights in large, multidimensional or temporal datasets, the concept of visualization is also being pushed in a process of *democratization* and mass-media *popularization*. Recently coined under the term "casual" [19], "artistic" [26] or "information aesthetic" [12] visualization, it seems a subfield is currently emerging that is concerned about representing information in more pleasurable ways, turning data exploration and insight discovery in an engaging and educational experience. Most works aim to exploit visual and interactive aesthetics to increase their comprehensibility, while also broadening the definition of "data insight" towards a more artistic intent.

Data art is a more artistically inclined form of information aesthetics, and consists of data representation that deliberately obscure their understandability by integrating elements of ambiguity and subjectivity in the data mapping process [12]. Data art tends to communicate circumstantial elements 'about' underlying principles of (versus patterns and trends 'inside') the dataset, by exaggerating or highlighting very specific and predefined data phenomena. Such visualizations are generally self-motivated or commissioned by advocacy groups, non-governmental organizations and museums, which typically aspire to popularize a predefined message, or communicate a subjective interpretation of the data to a wide, lay public.

What drives the current exploration of non-screen presentation media? Firstly, the underlying motives of *data subjectivity,* exemplified by information aesthetic visualization and data art. Secondly, the increasing amount of designers and artists who are becoming educated in the latest computing technologies, and vice versa, computing experts who have become educated in design principles by studio-based, creativity-driven course units. In addition, there exists a continuous drive for originality and novelty, to explore the potential of new materials and state-of-the-art technologies, to combine cross-disciplinary practices, and ultimately, to become the very "first" artist to effectively imagine, develop and build a working installation that employs an original material to communicate an interpretable meaning. Lastly, the prototyping of such technological advanced installations has been made possible by significant developments in both hardware and software authoring tools, which recently have become affordable, more designer-friendly (e.g. including sketching, visual programming), and are actively supported by large, open communities. New hardware developments have empowered enthusiastic designers to program micro-electronics, sensors and actuators, an area previously reserved for the expert or dedicated home hobbyist.

3. From Pixel to Human Sensation

For the purpose of maintaining the consistency and clarity of the arguments, most of the examples in this section will be focused on the materiality of *water* as an alternative presentation 'medium'. Water was chosen for its ubiquity across diverse contexts, and its natural aversion against high-tech, electronic technology.

3.1. Ambient Display

The exploration of alternative, non-screen presentation media to represent information is neither novel nor recent. The original definition of *ambient display* proposed to turn everyday architectural spaces into "interfaces" by changing the state of the physical matter, solids, liquids and gases that they contain by data-driven values [29]. Early research endeavors include the Water Lamp [5], which consists of a decorative physical fixture that projects ripple shadows reflecting electronic network activity, and WaterCalls [17], which represents emergency call waiting cues by the level of water captured in glass bowls (see Figure 1). More recent ambient display projects have since returned to the traditional screen, which are reinterpreted as forms of electronically enhanced artistic paintings rather than work displays [21]. Other ambient display systems exploit the high resolution of the screen to represent everyday objects (like a beach or the sea), which can change depending on temporal data streams [15].

Ambient display is a calm, non-obtrusive and opportunistic technology that reveals meaningful information for users who are willing to invest both time and effort to interpret its metaphorical data mappings.

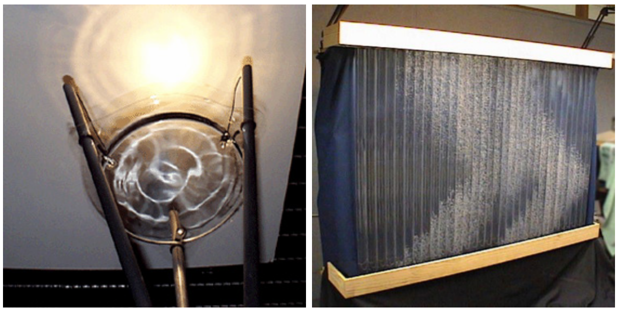

Figure 1. Ambient Display. Left: Information as water ripples, Water Lamp [5]; Right: Air bubbles as pixels, Information Percolator [10].

However, ambient displays tend to be limited in the amount of information that can be shown and updated regularly. In addition, some evaluation studies have revealed that although the comprehension of an ambient display increases over time, people are not necessarily retaining their initial interest in the display, as the display usage decreases over a longer term period [23].

3.2. Pixel Sculpture

A popular solution towards increasing the information bandwidth of an ambient display while maintaining its physical and aesthetic qualities focuses on substituting screen pixels with an array or matrix of real physical objects. The term *pixel*, which originates from “picture element” (with the abbreviation “pix” for “pictures”), refers to the smallest single component of a graphical image. A pixel can thus be understood as the universal standard visual unit for any singular *sample*, which, observed in a larger collection of equal members from a distance, merges together to form a distinct intelligible image. Therefore, pixels are not necessarily understood to be screen-based. A popular example includes the televised Olympic opening ceremonies that often exploit the cumulative visual effect of orchestrating large amounts of people in recognizable visual patterns. One of the earliest examples of a mechanically-driven and computationally-controlled physical pixel display includes Rozin’s famous Wooden Mirror, which consists of an array of dynamically rotating wooden blocks. The Information Percolator [10], one of the earliest ambient displays, is based on a similar approach by synchronizing rising air bubbles captured in a row of water tubes to depict icons and vertically scrolling text (Figure 1).

In the context of water as a presentation medium, Bitfall [20] synchronizes falling water drops to display text and symbols, while Eavesdripping [18] represents textual network conversations by the succession of well-located water drops falling on, and rippling, a flat water surface. The potential realm of pixel sculptures is immense, and currently includes matrices of ping pong balls, rotating car side mirrors, patches of electro-statically charged hair-like strands, inflatable balloons, and knitted textiles. The natural opposite of water, fire, has also been tamed as pixels.

Figure 2. Pixel Sculpture. Left: Falling water drops at Bitfall [20]; Right: Animated fire pixels, Pyrotechnic Infernoptix [16].

Digital Pyrotechnic Infernoptix [16] (Figure 2) is an installation capable of controlling a 12x7 array of flame-throwing nozzles to depict text and iconic animations. At the end of this conceptually spectrum probably lies the Clothesline Display [1], consisting of over 250 male boxer shorts that depict textual mobile phone messages.

These examples show how most pixel sculptures are specifically designed to intrigue and amaze a large and captivated audience, insofar that the pixel ‘medium’ often triumphs any (informational) message that it attempts to communicate. The mechanical noise, size, and spectacular visual effects that result from animating large amounts of physical objects negate most practical visualization application scenarios. However, these projects also demonstrate how the use of a physical material as a communication medium allows for the inclusion of rich, cultural connotations that evoke user curiosity, fascination and engagement. Some of the issues involved in pixel displays include the fragility and complexity of the involved technologies, its relatively low pixel resolution and update frequency, and, in the case of water, the inability to persist a static display state.

3.3. Object Augmentation

An alternative direction for presenting information in a physical but peripheral way consists of *augmenting* or *superimposing* everyday objects with information. This approach shows a potential future of *ubiquitous visualization*, a world with unobtrusively integrated and intuitively understandable information “reflections”. Recent developments in this direction are mostly driven by user-centered interaction design research, which is mainly interested in the use of everyday objects because of their immediate closeness and emotional connotations to end users. Shown in Figure 3, the HeatSink [2] faucet illuminates a water stream according to its temperature, while the DataFountain [25] installation maps the actual currency rates to the relative size of three sprouting water fountains. The potential of overlaying everyday objects with information reaches far beyond water, and varies between animated building facades, cooking pans that highlight the ideal frying temperature, over plants that change their growing direction towards the most used garbage bin [11], and smart toasters that burn the actual weather forecast in your morning bread.

Figure 3. Object Augmentation. Left: Water color as temperature, Heatsink [2]. Right: Fountains as exchange rate, DataFountain [25].

3.4. Wearable Visualization

The continuous search for new forms of visualization media has recently started to focus on clothing, jewelry and other wearables, and even the human body itself. With the miniaturization of computing technology and the human urge of pervasive, always-on information access, researchers have developed different hard- and software architectures that can be easily integrated into everyday garments. As a special form of object augmentation, *wearable visualization* focuses on the use of miniature computing devices that can be worn on the human body over long periods of time, aiming to inform the wearer as well as any other person in the immediate vicinity of specific data. The technology involved differs from portable screens on common mobile devices, in that they are specifically designed to be unobtrusively integrated and extensively worn. However, the practicality of wearables is often negated by the necessity for relatively bulky energy sources to drive the displays. Approaches in wearable visualization tend to experiment beyond the use of pixel-based screens, instead exploring state-of-the-art actuators such as LED lights, electroluminescent wires, thermo-chromatic inks, shape-changing materials such as shape memory alloys, or even air inflatables. Shown in Figure 4 are Puddlejumper [4], a raincoat with electro-luminescent panels that light up as water lands on it, and Fashion Victims [6], a unique handbag that emits liquid ink depending on the mobile phone usage in its vicinity.

3.5. Data Sculptures

The *data sculpture* concept is different from other physical visualization approaches in its focus to "embody" the data in a perceivable presence, shape or form. That is, the sculpture is a direct *externalization* of the data, and possesses no other direct functionality than conveying meaning to onlookers. Because of the obvious limitations of recognizing meaning from physical form, people are forced to interpret these data-driven objects by the *affordances* they convey. Abstract information is reinterpreted as an abstract matter that is captured and implicitly translated in objects that can be touched, explored, carried or even possessed, like the memories symbolized by souvenirs, jewelry or art in general.

Figure 4. Wearable Visualization. Left: Rain-sensitive Puddlejumper [4]. Right: Mobile phone depending Fashion Victims handbag [6].

The use of *affordances*, the properties of an object that influences how it can be used, is a potentially powerful "visual" cue to convey meaning, as it foregoes higher-level visual abstraction and enables multi-sensory human sensations and subjective emotions.

Often, the data mapping metaphor employed by a data sculpture may not be immediately understandable, but is instead meant to be discovered through reflecting on the nature of how the data is embodied in a physical form. It is often the act of reflecting itself that brings forward unforeseen associations, which can then be considered the "data insights" that are communicated by the "visualization". While some data sculptures embody the underlying data by a directly related physical artifact (e.g. water consumption represented as the amount of water in a glass), others choose to intentionally make non-obvious connections between the *signifier* (the artifact) and what is *signified* (here, the data or the meaning of the dataset). The disconnection between these two concepts is then exploited to provide for a thought-inducing visual impression (e.g. the world population as a pile of rice), or to provoke a stark contrast with the underlying meaning of the data (e.g. an amount of death people as eatable candy). For instance, Email Erosion [3] creates a data sculpture by spraying a forceful and eroding jet of water unto a block of foam, depending on the amount and content of email spam. Similarly, PulsArt [8] shows the levels of activity of family members by varying the amount of water running down blocks of salt, slowly carving out material as a physical trace of historical activity (see Figure 5).

3.6. Alternative Modality Display

The field of *alternative modality* or *non-visual visualization* targets the stimulation of our other four human senses to communicate abstract information. Scientific research in this area is mainly motivated out of the wish to: (1) support visually impaired people, (2) enhance the immersion and fidelity in Virtual Reality (VR) and gaming applications, (3) augment existing visualization scenarios (e.g. for alarm, monitoring or notification applications), or (4) investigate additional sensorial modes that support users to understand critical information more efficiently by increasing the sensorial bandwidth beyond the visual sense.

Figure 5. Data Sculpture. Left: Spam email controlled foam erosion [3], Right: Human activity-depending water erosion, PulsArt [8].

Current issues include the stimulation of human senses beyond a single person, and more importantly, the question *how* to map information values into non-visual sensations that somehow can be intuitively understood.

2.3.1. Sound. Data-driven sound stimulation, also known as *sonification* or *auditory display*, uses non-speech sound to perceptualize dynamic information to the user. Generally, an increase or decrease in some level of information is reflected by an increase or decrease in sound characteristics such as pitch, amplitude or tempo. Besides the well-known example of the Geiger counter, many other sonification works exist, as research in this area has grown in an independent academic community.

2.3.2. Touch, *tactile* or *vibrohaptic display* interfaces are able to communicate information through the use of *haptic rendering* methods. The most familiar approach includes force feedback devices (e.g. SensAble Phantom) or body-worn garments [13] that generate spatial movements or sensations (e.g. pushing, pulling or sliding) that can be felt, and potentially interpreted by a user. Some of the obvious issues in haptic rendering include resolving the level of skin sensitivity, which typically differs on an individual level and varies over the surface of the human body, and the relatively narrow spectrum in vibration intensity between sensory and pain thresholds. Interesting examples range from the Haptic Shoes project [9], wirelessly vibrating shoe soles that communicate stock market data, to Constraint City [22], a mechanical corset that deliberately inflicts pain to the wearer, depending on the signal strength of closed off, encrypted wireless networks nearby. More artistic approaches explore alternative sensory stimulations for larger audiences in public settings by “transmitting” skin actuations, such as temperature: the Perpetual Tropical Sunshine [7] installation consists of about 300 150W infrared light bulbs that convey the real-time climatic conditions in faraway places to a large audience.

2.3.3. Smell visualization or *olfactory display* promises the communication of meaning through the use of odors. *Odor* is a potentially powerful sensorial cue for the strong informational relationships between human memory and olfactory stimuli it is able to provoke. Smell has been proven to induce strong personal memories and human emotions, as well possesses the ability to improve accurate recall when a person was exposed to similar odors during learning.

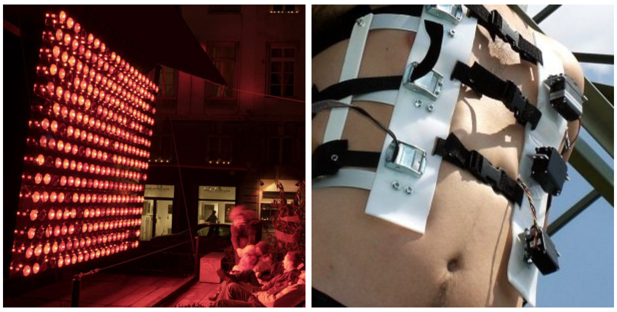

Figure 6. Alternative Modality. Left: Simulating remote climatic conditions, Perpetual Tropical Sunshine [7]. Right: Feeling network constraints via pain, Constraint City [22].

Three important problems for this modality to carry information efficiently involve (1) the *creation* of smells, or the choice of the fundamental basis “RGB” smells that in combination generate any odor possible, (2) the *dissipation* of smells, overcoming its relatively slow “frame rate” to quickly dissipate and be replaced by other smells, and (3) the *sharing* of smells, the characteristic of odors to spread over spaces in so far that separate users who share the same space cannot receive different information channels. One remarkable solution for these issues proposes a “smell cannon”: a custom-made device that shoots small puffs of scented air directly towards the position of the user’s nose [31].

2.3.4. Finally, **taste** stimulation or *edible interfaces* foresee a future in which computers can reproduce *flavors* by the dynamic generation of chemical substances that can eventually be eaten. Although most people only refer to taste by degrees of sour, sweet, salty and bitter, taste has the potential to become a relatively high-dimensional and sensitive human input channel for abstract information. TasteScreen [14] is a device that drips controlled quantities of flavoring unto a screen’s surface that taste appropriately to the current user’s tasks or displayed images. Infococktail [30] is a custom-made machine that mixes tasteful and colorful cocktails according to the home colors of sports teams and their end score at recent competitive games.

Conclusion

In our current information society, it will take not long for data communication to be pushed outside of the digital screen, towards our everyday physical reality experiences. This paper is a first step to rethink the role of what alternative, non-screen displays can play in conveying information in the context of miniaturized, ubiquitous and calm computing. As information visualization moves away from its traditional, expert, and computer graphics background, and becomes a social communication medium in its own right, new opportunities open up to use novel technologies as facilitators or carriers to communicate meaning. The challenge is then how to translate digital information in physical counterparts in compelling and understandable ways, depending on the purpose of the representation, its audience, spatial settings, and the underlying dataset.

Because of its opportunistic characteristics and physical proximity to everyday human activities, *physical visualization* inherently has the quality to directly inform people when decisions are made, to allow people to explore cause-and-effect relationships and to provide people with enjoyable, but contextually related experiences that could motivate and encourage. Therefore, one of the most compelling application areas for physical visualization includes persuasive computing, which focuses on using modern technology to change people's opinions or attitudes, or encourage long-term, persistent behavioral changes by providing real-time information within relevant spatial contexts. This paper proposed a sequence of categories that gradually varied in how data is materialized or visualized in physical form, and described how humans are able to perceive information and understand meaning through interpreting the resulting physical artifacts. A set of existing visualization examples demonstrated the wide potential range of physical abstraction and sensorial stimulation, and described the most important issues involved in pursuing such approaches. By becoming aware of these considerations in the alternative information applications of tomorrow, we could augment our data addicted society beyond the light-emitting, rectangular surfaces of today towards visualizations that are enjoyable, memorable as well as practical and understandable.

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