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ABSTRACT

This paper details the design and implementation of a new type of display technology. Display Blocks are a response to two major limitations of current displays: dimensional compression and physical-digital disconnect. Each Display Block consists of six organic light emitting diode (OLED) screens, arranged in a cubic form factor. We explore the possibilities that this type of display holds for data visualization, manipulation and exploration. To this end, we accompany our design with a set of initial applications that leverage the form factor of the displays. We hope that this work shows the promise of display technologies which use their form factor as a cue to understanding their content.

Author Keywords

Cubic Display, Display Technology, Data Visualization, Tangible Exploration, Physical Interaction.

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation: User Interfaces – User-centered Design; I.3.1. Computer Graphics: Hardware Architecture – Three-dimensional displays.

General Terms

Design, Experimentation, Human Factors.

INTRODUCTION

Screens are everywhere. Sitting at a café table, one might have at least three screens within peripheral view – perhaps a laptop and a cellphone side by side on the table, and a television screen in the background. As computing has become pervasive, screens have both proliferated and accumulated functionality. They have colonized other traditional media as in the case of print (transformed into ebooks or interactive versions of newspapers and magazines for tablets) and have permeated a large variety

of fields, ranging from medicine to retail. Throughout this evolution, from the first cinema projection to the most advanced medical imaging device, the fundamental shape of screens has not changed much: they continue to be rectangular and flat. These features have shaped the way we consume information: they have influenced the delivery, the interfaces to access it, and, ultimately, information itself.

Figure 1. Two Display Blocks.

As screen technologies become increasingly widespread, it is our belief that designers should evaluate the validity of current form factors and explore new shapes and configurations. Expanding upon visualization metaphors, such explorations have the potential to contribute to a broader ecosystem of output devices.

Our works seeks to lay the foundation for designing such alternative output technologies. We do so by identifying limitations of current display technologies and conceptualizing, designing and building a new display technology that addresses them. Display Blocks (Figure 1) are a collection of cubic displays that are easy to manipulate and that support new types of visualization. The design is not intended to be substitutive of current display technologies; instead, it seeks to expand the palette of display technologies for visualizing content in different ways. We hope that our work will inspire others to explore more of these limitations, and to enrich interfaces – not only from the input perspective but also by thinking about output as a design variable.

The work contained in this document was partially presented to CHI'12 as a work-in-progress [15]. We have since expanded the scope of the research and finalized the prototype.

LIMITATIONS OF CURRENT DISPLAY TECHNOLOGY

While research has tried to improve the way that we visualize information and our means of interaction with these visualizations, there has been minimal exploration into how novel form factors could better adapt to content (thus encouraging its exploration). In this section, we detail two limitations of current display technologies that we addressed with the design of Display Blocks: dimensional compression and physical-digital disconnect.

Dimensional Compression

There is only so much that a flat display can represent. A plane has two dimensions, and, therefore, any representation whose object exceeds two dimensions will need to be simplified. For instance, when we watch a movie, we see frames one after another. Each individual frame is two dimensional, but they play in a sequence; hence their third dimension becomes time. Therefore, when we play a movie on a flat screen we are losing this third dimension; we lose the reference to the previous frame – because we can only see one frame at a time. This dimensional simplification is not necessarily undesirable; for instance, it enables filmmakers to use cuts that transition between scenes in order to establish narratives. However, such simplification can be hindering as well. For example, when viewing a movie of a teacup being dropped to the floor, it would be easier to infer the acceleration of a tea cup if we can see more than just the current frame of the movie. Photographer Edward Muybridge was one of the first artists to make this point in his multi-frame photographs of moving animals and people. Of course, most movie goers are not interested in the acceleration of the objects appearing in a movie, but in a classroom environment this could be a useful method for helping students to understand physics principles.

One of the objectives of our work is to design a type of display that goes beyond flat representation to offer multiple perspectives on its content – a display that solves the ambiguity problems resulting from dimensionality compression and that is also versatile enough to be used with many types of data.

Physical-Digital Disconnect

Because of their shape and use, we might think of planar screens as windows to other worlds – whether the cinematic narrative of a movie or our finances on a spreadsheet. Windows are used in a very specific way: we look through windows, rather than manipulating them. Because of this, screens are well-suited for passive media. On the other hand, when we try to use screens in an active medium such as computing, most setups still require external controls such as the keyboard and the mouse for interacting with content. This division between content, the screen, and manipulation, the keyboard and the mouse, divorces input and output functionality; yielding a decoupled experience. In some cases, this divide is necessary or preferable – i.e. when we compose documents, the familiar feel of keys on a keyboard enables us to type without looking down. In other cases, however, this division can constrain the potential for more intuitive interactions with content.

Early personal computers were work stations consisting of a screen, a keyboard and a mouse. This configuration relies heavily on the aforementioned window model, as the screen is a rectangular, flat and immovable gateway to the digital. Computers have since lost the constraint of immobility as we transitioned to laptops. However, from a user point of view, the window model remained unaltered; the screen was still meant solely for information consumption and required the use of the same external devices for interaction. This new form factor did, however, bring with it an interesting functional detail: we could close laptops to turn them off. Closing an object – i.e. a book – is a common way to signal that we are done using it. This feature begins to weaken the window model by appealing to the physicality of the screen, and its shared nature with other objects around us.

More recently, touchscreens, widely found in phones and tablets, have incorporated a variety of sensing capabilities that have enabled devices to be aware of how they are being manipulated. These improvements have started to bridge the previous divide between physical and digital in computing devices. The most prominent of these sensing capabilities are multi-touch surfaces. By allowing users to manipulate content with their fingertips, these devices collocate input and output. Other sensor technologies further enhance the richness of interactions by allowing access to device-relative data, such as orientation and geolocation. This new generation of devices defies the window model; however, it is still built on top of it. While we are able to interact with the content in a richer way, this content is still framed in a flat rectangular surface.

In our opinion, the next frontier is to modify the shape of display technology. The shape of an object tells us a lot about the object itself. If we take a knife, for example, we know immediately where to grasp it; it almost describes, with its shape, how it is supposed to be used. Similarly, display technologies could make their use apparent through their shape. Instead of building interaction on top of existing display technologies, we should strive to create displays that inform us of their use and content. Display Blocks is one such attempt at creating a differently shaped display along with several types of more "graspable" content.

RELATED WORK

In order to place the Display Blocks research in context, we begin by discussing the opportunities afforded by multiple perspective visualization. We then contextualize how the

shape of a display can be leveraged as a cue to its content and to encourage exploration. Finally, we discuss a series of examples of multifaceted displays to lay the landscape of existing related devices.

On Data Visualization and Multiple Perspectives
The exponential growth in complexity and volume of data generates a need for continuous improvement in data visualization techniques that allow us to deal with larger volumes and greater complexity. Researchers agree that providing multiple perspectives on data can help us to both navigate and understand it better [12, 19]. However, as pointed out by Baldonado et al. [1], the arrangement of these perspectives has to follow certain criteria to guarantee the audience's understanding. In many cases, when multiple perspectives are presented on a flat screen, we are not offered any cues as to how they relate to one another. And, even when this relationship is explained, there are limited ways to do so clearly and directly.

Multifaceted displays, such as Display Blocks, have the potential of cohesively juxtaposing multiple data perspectives in a single object. The shape of the device can inform the viewer about the relationship between each of the faces. For example, if we place two screens at a ninety degree angle, we can infer that the information displayed on the screens has an orthogonal relationship. This relationship could either be literal – orthogonal perspectives on the same object, like top view and front view – or metaphorical – liberal versus conservative political perspectives if we are reading a news article.

Of Screens and Objects
Object characteristics which invite particular uses are known as *affordances* [6,13]. If integrated properly into a digital device, affordances can encourage the manipulation and understanding of the information displayed onscreen - just as the design of a knife helps us understand how to hold it.

A screen, as an object, has certain affordances; a screen is a frame to content, and, as already discussed, it builds upon our understanding of windows. As a consequence of this perceptual parallelism, we tend to assume that the content of a screen is subject to the same physical laws as the surrounding environment. When, for instance, we explore a three-dimensional object in a display, we assume that the parts that are closer to the top of the screen are higher and that gravity pulls objects to the lower part of the display. This establishes a tacit cognitive contract with viewers. Described by Slater et al. [20], this cross-reality phenomenon is called *presence* – the projection of self into a virtual environment.

While presence describes the projection of physical expectations into the digital world, other research has explored how physical objects can be leveraged to manipulate digital content. Building atop the aforementioned idea of affordance, Fitzmaurice et al.

introduced the concept of graspable interfaces [5] – physical objects that interface with computers to promote more meaningful human-computer interactions. Further work on socalled *tangible interfaces* by Ishii and Ullmer [7] investigated how users can leverage their acquired intuition about certain objects to better understand digital systems. The rationale behind this body of research is to provide physical handles to digital content, strengthening the connection between the screen and the physical objects that surround it.

Recent years have shown how these two concepts – presence and tangible interfaces – are converging in the same object. As display technology is embedded in devices alongside touch, acceleration and rotation sensors, we continue to project our physical expectations into the digital world. Now, however, the same device is able to be leveraged as a handle for manipulating and exploring digital content. We believe that the implications of this coupling of input and output have the potential to go beyond physics simulation-based games to engage users in novel, more intuitive ways to explore data.

In approaching Display Blocks, we aimed to build upon our perception of screens as objects and the implications of a cubic arrangement for visualization and manipulation of data. We were interested in exploring the convergence between input and output in screen-based interfaces and how the arrangement of displays may be perceived as an affordance to their content.

Non-Planar and Cubic Displays: Uses and Applications
There are a variety of projects that have explored the effects that large, static non-planar displays have on their audiences [2,3,4,8]. Across this body of work, there seems to be a common trend in the coupling of display shape and its impact on the audience, as if the shape facilitates the function. This resonates with the concept of affordance and can be used to design more specific, task-oriented types of displays.

Several cubic displays have been developed for visualizing three-dimensional content [9,21,22]. However, none of them, even those that are handheld, are self-contained and some even require users to wear additional technology for tracking purposes – like cameras or other sensory peripherals. These two factors potentially hinder the manipulation possibilities that these devices have to offer. In the design of Display Blocks, we strived to create a completely self-enclosed technology that conserves the full manipulative characteristics of the display. Additionally, all of the the above-mentioned displays are solely used to visualize volumetric information in a fish tank virtual reality manner.

We believe that the cubic shape is well-suited for many other types of visualization and designed a wide variety of novel applications to demonstrate this. Others have also proposed concepts in that realm [10,16]. We created Display Blocks as a platform that can support the

implementation of this visions and new ones yet to be imagined.

A couple relevant instances of cubic display and application pairing are *A Cube to Learn* and *CubeBrowser*. *A Cube to Learn* implements a quiz-like interface in a cubic display [23] and *CubeBrowser* explores the affordances of the cube for picture navigation [24]. This research offers coherent examples of using the manipulative properties of a cubic display for interaction. It is our goal offer some continuity to this line of research both contributing a more compact and manipulable design as well as a full variety of user cases.

DESIGN

In this section, we offer an overview of the design process that we followed to create Display Blocks. We started by compiling a design framework. We then applied it to propose a specific concept for such a display. Finally, we developed a series of applications that illustrate the possibilities of Display Blocks as a platform.

Framework

We began the design process for Display Blocks by defining three guidelines to improve upon the two aforementioned limitations of current display technologies – dimensional compression and the disconnect between physical and digital:

- Enable the visualization of multiple perspectives on data. This can facilitate easier exploration and understanding of data, especially if the design of the display is used as a cue to the relationship between these perspectives.

- Leverage the affordances of the physical design of the display to inform a user of its function.

- Create applications that take full advantage of the chosen form factor.

We believe that these principles, despite being delineated to guide the design process of Display Blocks, may also be relevant to others designing similar systems.

Concept

Building upon the three design guidelines above, we ideated Display Blocks: a set of handheld cubic displays that are able to visualize multiple perspectives on their content. A Display Block is composed of six screens arranged in a cubic manner. Each display on the cube is in sync with the other five, enabling coordinated visuals across the device.

This display configuration enables the representation of data from a variety of points of view – addressing the first design guideline. The form factor fits comfortably into an open hand and is able to detect basic gestures for interacting with content – covering the second design principle. Finally, we conceptualized and programmed a series of applications that demonstrate the potential of such a device – fulfilling the third design criterion.

The Shape: A Cube

When exploring the possibilities of new shapes for displays, we decided to start with a basic shape to better assess the potential of a three-dimensional display before moving on to other, more complex, shapes. As one of the basic shapes – alongside others like the sphere, the cone, the wedge, the cylinder, the pyramid and the torus – the cube embodies the perfect balance between manipulation and control. A cubic shape is static and stackable – as opposed to the sphere, which rolls, or the cone, which only has one flat side. Cubes are also symmetric in all axes – unlike wedges or cylinders – making them modular and orientation-independent. Moreover, the fact that, in a cube, all of the faces are clearly delimited provides a reference when framing content.

The design of Display Blocks seeks to leverage the accumulated knowledge that users have of similar objects. One example is a construction brick; the same way we can build a wall from multiple bricks, Display Blocks can be stacked to form larger structures as well. The shape of a cube also has a history of association with playfulness. Dice have accompanied the gaming experience for millennia and more recent toys, like the Rubik's Cube, are examples of how cubes are present in play.

Building on users' familiarity with cubes in a more abstract sense, are orthographic perspectives – the basis of schematic and blueprint representation – which can be aligned with the faces of a cube. This can be leveraged to understand the relation between content projected in different faces as it is an affordance of the form factor of Display Blocks.

The Size: Handheld

Display Blocks are designed to be a series of handheld devices, enabling easy manipulation. Holding a device in their hands, users are able to easily rotate it and reveal its different sides. Thus, creating a self-enclosed, autonomous device was crucial to offering unencumbered exploration of content. The final design supports not only single device manipulation but also holding multiple devices at once. For this purpose, the devices must be easy to manipulate using only one hand; this way, users can compare cubes side-by-side, adding even more richness to the navigation of data.

Applications

We have accompanied the design of Display Blocks with a series of applications that leverage the physical properties of this novel display. In doing so, we have focused on creating applications that are optimally experienced in this form factor. The original series of applications are described in detail in the following paragraphs.

Orthographic Projection

This application enables exploration of three-dimensional models by mapping orthographic perspectives onto the respective faces of the cube. While this is not an accurate three-dimensional representation in the way that a

hologram or fish tank virtual reality is, it enables the three-dimensional representation in the way that a hologram or fish tank virtual reality is, it enables the exploration of orthographic projections in their natural arrangement – that is, as if the objects represented were actually inside the cube and being projected out onto the faces. We are interested in how users relate to a model that they can hold in their hands as opposed to one displayed on a flat screen. Furthermore, by combining multiple Display Blocks, we allow users to explore objects that are best understood when they can be deconstructed. For example, if one were to compose a larger cube from eight of the displays in order to represent a beating heart, one could remove one of the cubes to look inside a ventricle. An image of the application visualizing a person's head is shown in Figure 2.

Figure 2. Display Block running the Orthographic Projection application.

Building Blocks

This application explores how Display Blocks could be used as dynamic building blocks. Their cubic shape makes them easy to stack and group of them into different arrangements, making them suitable for customization purposes. Consequently, we can think of this volumetric display as a construction material - like a brick. If we build a wall with these novel bricks, we can change the wallpaper by sending a new image to be displayed on all of the screens. Projection mapping systems – such as Shader Lamps [18] – enable similar applications, but they require accurate calibration techniques; therefore, they are extremely sensitive to motion. By embedding the digital representation in the object, we can eliminate this problem. Pushed to the limit – by reducing and replicating these dynamically textured bricks – we could even realize

customizable matter. A series of texture possibilities for the cube can be seen in Figure 3.

Figure 3. Display Block running the Building Blocks application (three different textures).

Multi-Dimensional Visualization

Display Blocks enable a new way of visualizing complex relationships, such as that between multiple dimensions like time and space. For example, the proposed device could show a video playing on one of its faces, while it shows the approaching frames on lateral displays. Similarly, while the front side of the cube could display an animation of a circle being drawn, the lateral displays could decompose this motion over time into a sinusoidal wave (as seen in Figure 4). This latter example could be useful for understanding physical phenomena such as the relation between speed and acceleration of a projectile.
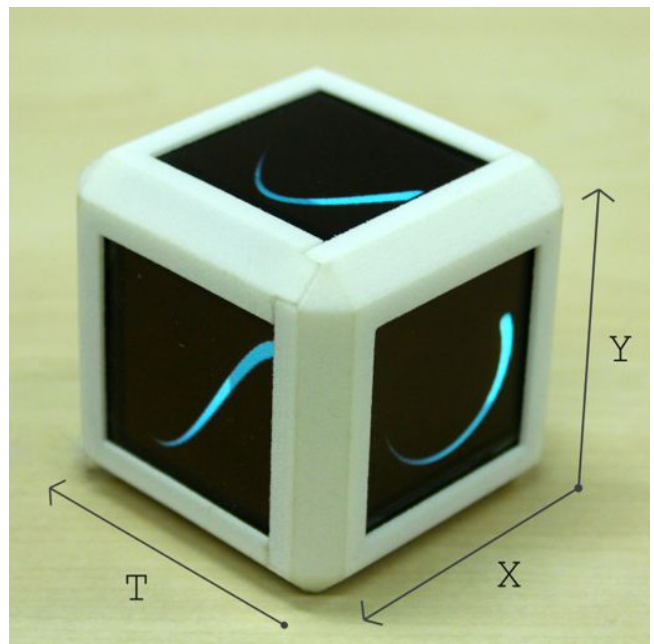
Figure 4. Display Block running the Multi-Dimensional Visualization application.

### Multi-Perspective Data Visualization

A single piece of data can be represented in a variety of ways. For example, if the piece of data is a person, we might want to know her name, see a picture or find out her role in an organization. Similarly, if the piece of data is a word, we could translate that word into a variety of

languages. This application explores how the multiple interpretations of a piece of data could be better understood when mapped to the different faces of a volumetric display. This capitalizes on the metaphorical relationship between faces and perspectives. The tangible aspect of the display enables playful and comparative explorations. Going back to the example with words, with multiple cubes, one could even construct entire sentences; by then rotating the cubes, she could translate an entire sentence into another language, word-by-word.

The design of Display Blocks resulted from an effort to marry application, form factor and underlying technology in order to create a novel display that presents information in more intuitive ways. Moreover, the applications demonstrate the versatility of the technology, which can be leveraged for multiple purposes across many disciplines.

SYSTEM DESCRIPTION
To construct the prototype for Display Blocks, we have designed both the hardware and software from scratch, and ensured custom assembly of the system. The core concept is respected throughout each of these layers, as we have maintained control over all design variables and their integration. In this section, We describe the technology behind Display Blocks in detail: hardware, software and assembly.
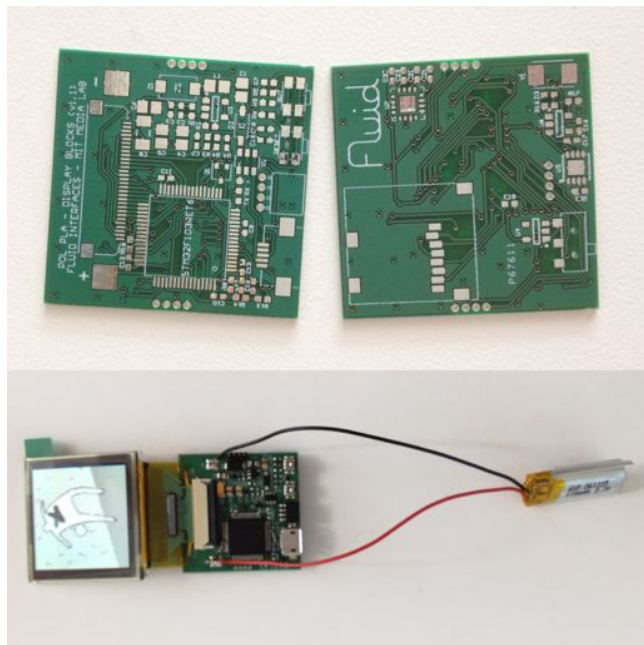
Figure 5. Front and back of the board before assembly and assembled circuit for one of the faces.

Hardware
With the design of Display Blocks, we aimed for a compact, self-enclosed device that enables untethered manipulation. Ideally, to achieve the perception of continuity between faces, the displays that cover each face

of the cube should be the only visible part of the device; the rest should be hidden. To attain this, all of the supporting components for the screens to operate, including the battery, fit inside the cubic display. Custom circuit boards were created to that end, as seen in Figure 5.

Each face of a Display Block contains the following components:

- An OLED display. The size of the displays used is 1.5 square inches and the screen area is 1.25 square inches. The model used has a resolution of a 128 x 128 pixels and a color definition of 262,000 colors.

- One 32-bit ARM microcontroller (STM32F106RET6).

- One micro secure digital card (MicroSD Card) and its reader. The SD Card is used for memory storage to allocate video and images.

- One accelerometer, to detect basic interactions such as shaking.

- One lithium-ion battery and battery management circuit.

Software
Each Display Block requires a very specific data flow. For each face, the system must be capable of accessing memory to retrieve images or videos and to be able to display graphics on the OLED screen. On a cube level, each face must be able to synchronize with the rest in order to coordinate graphics. To that purpose, the Display Blocks software encompasses three main functionalities:

- Graphics capability: implementation and optimization of a protocol to address the 8-bit interface of the OLED display.

- Memory management: interfacing with an SD card through a serial peripheral interface (SPI) optimized for video capability.

- Synchronization with other faces: custom protocol implementation for synchronizing graphics throughout all faces of a cube.

The software written for Display Blocks has been developed as a C library. It can support any type of basic drawing functionality, image display and video playback. We implemented the four showcase applications (Orthographic Projection, Multi-Dimensional Visualization, Multi-Perspective Data Visualization and Building Blocks) building on top of the library, plus a shake gesture that allows users to switch between applications.

Enclosure
We designed a 3D printed case for the final ensemble (as seen in Figure 6). The design of this enclosure is intentionally as minimal as possible to emphasize the displays as the focus of each Display Block. The enclosure covers the rim of each display, keeping them bound into a cube shape while allowing a clear view of the content on each of the displays. The case was designed with a flat

bevel that makes it comfortable to hold and roll through the fingers of an open hand.
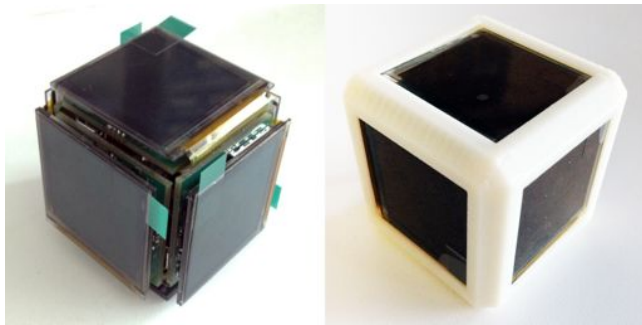
Figure 6. To the left the hardware ensemble, to the right the final encased prototype.

FUTURE WORK
We believe the Display Blocks prototype shows promise for a variety of uses, making a solid case for alternative display design. There is, however, still a lot to explore within the scope of Display Blocks. We see this first series of prototypes as an initial stage of research – one that served as a proof of concept and that yielded a robust prototype that can be leveraged to explore new functionality. We are excited by the prospect of developing this technology further in a variety of directions. In this section, we analyze the main possibilities for expanding beyond the current Display Blocks platform in terms of applications and interaction capabilities.

Applications
One of the most promising future directions for the work of Display Blocks is to continue expanding the landscape of applications. The design of applications is a double-edged sword: it helps to showcase the advantages of the device, but simultaneously, it exposes technical limitations of the platform that could be improved upon. A couple of especially appealing fields for future applications are gaming and social media. As introduced in the design section, the shape of a cube evokes the notion of play. We see games like LevelHead [14] or Tsumiki [17] as being very well-suited for such a platform. Similarly, as relationships tend to be of a multi-faceted nature, the shape of Display Blocks may be especially well-suited for social applications. Although it is not our intent to turn Display Blocks into a gaming platform nor a social media support, we do believe that broadening the spectrum of applications can strengthen the case for this novel screen form factor.

Interaction
The current prototype of Display Blocks and the initial applications designed for it have already revealed a need for increased interactive capabilities. Potential areas for improvement (as it pertains to interaction) fall into three overarching categories: sensing, connectivity and spacial awareness.

Sensing
The current capability for direct manipulation in the Display Blocks prototype is somewhat limited – accelerometer data is used to detect when the device is being shaken. We seek to add other sensing capabilities to increase the bandwidth for direct manipulation of content. Turning whole faces into pushbuttons or adding touch sensing on top of the current infrastructure will enable the selection of content and the recognition of basic gestures to manipulate parts of the content. Coordinating these sensing capabilities across the different faces could enable even richer manipulation of content – i.e. manipulating multiple dimensions at the same time.

Connectivity
Connecting Display Blocks to one another, to different devices such as cellphones, tablets or computers and, ultimately, to the internet would open up a variety of new interaction possibilities. Allowing cubes to communicate with adjacent cubes in a similar fashion to Siftables [11], for example, would expand the possibilities when interacting with multiple Display Blocks. Connecting Display Blocks to other devices would support the creation of hybrid systems that capitalize on the familiarity of traditional screen-based interaction, but that benefit from the unique visualization capabilities of Display Blocks. Finally, internet connectivity would enable a variety of improvements to the current prototype, ranging from data access to cloud services.

Spatial Awareness
By knowing their position in space, the cubes could act as volumetric windows into a digital reality. That is, a cube that knows its exact coordinates in space could display the portion of a digital world matching those same coordinates. This would be especially interesting with a series of cubes, allowing one to explore complex three-dimensional environments just by positioning the cubes in space. Investigating different tracking techniques – for example, magnetic-based position detection or signal triangulation – could enable these kind of interactions.

CONCLUSION
We believe that the design of display technologies can make a difference in the way we consume and interact with data. Display Blocks is an attempt at creating a novel type of display that addresses some of the limitations we encountered in current display technology. We focused our efforts on visualizing multiple perspectives on data so as to invite exploration of content. We have received very positive early feedback both on the concept and on the first prototype, confirming that an interface like Display Blocks can influence the way we manage and visualize information.

We see Display Blocks as part of a palette of visualization devices. When one works with clay, one can use a variety of tools depending on what one wants to achieve; similarly, when one deals with the representation of data, one should have access to a broad set of display technologies. It is our hope that Display Blocks may inspire others to explore form as a design variable in the creation of novel displays. Furthermore, we look forward to seeing similar approaches applied to an ecosystem of technologies that better appeal to our shared human nature.

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