Embodiment in Data Sculpture: A Model of the Physical Visualization of Information

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ABSTRACT
Information is becoming pervasive in the contemporary society, and is increasingly saturating the visual senses and the cognitive efforts of the lay masses. As our attention for visual impulses and cognitive effort has become more competitive, new approaches are being pursued to convey information to people in memorable and intuitive ways. With human's inherent proficiency in comprehending the physical affordances present in the real world, some researchers and designers are investigating how meaningful insights can be conveyed by way of "sculpting" data.

This paper proposes a domain model to establish the concept of *data sculpture* as a data-based physical artifact, possessing both artistic and functional qualities, that aims to augment a nearby audience's understanding of data insights and any socially relevant issues that underlie it. This paper also proposes a model of *embodiment* to capture and analyze the wide and multi-layered spectrum of existing data sculptures. In this model, the introduced concepts of metaphorical distances are used as a means to measure embodiment in data sculpture. The models provide groundwork for useful design principles for effective information communication of socially relevant, data-driven insights to a large, lay audience using data sculpture.

Categories and Subject Descriptors
E.4 **[Data]**: Coding and Information Theory; H.5.1 **[Information Interfaces and Presentation]**: Multimedia Information Systems

General Terms
Design, Human Factors, Theory.

Keywords
Data Sculpture, Information Visualization, Embodiment, Tangible Representation.

1. INTRODUCTION
In the western societies of today, information is regarded as a central force in driving social and economic development. Information is becoming so pervasive that it is moving into almost every aspect of our daily lives. Many different types of information have been distributed to screen-based media, such as stock market data and demographic statistics, which all compete for people's attention and contemplation. In parallel, the field of *information visualization* has produced, in the last 15 years, theoretical and practical methodologies that aim to support people – usual experts in their respective fields – in understanding the underlying principles from large, complex datasets [1] of commercial or social value. Furthermore, there is an emerging theme in the field of data visualization to *democratize* the access of information to large cohorts of lay, or non-expert, people. This recent movement represents a significant step away from the traditional focus on developing visualizations for well-defined, marrow, expert tasks, and data mining tools targeting only the professionally trained experts [2]. It is still an open question, however, how insights from the field of information visualization can be used to effectively inform, educate a non-expert audience, or even capture their attention, sufficiently engage their interests and maintain their curiosity.

Physicality plays a key role in understanding our environment because humans are inherently proficient in interacting with the real world using mainly auditory, visual and tactile senses. In this context, the currently pervasive, traditional screen-based approach is relatively limited in the sense that it is unable to capture the rich experiences attributed to physicality, for it lacks the capability to stimulate any other senses than the visual [3]. In contrast, the interpretation of an everyday physical object tends to rely on its *affordances,* tangible properties of an object that influence how it can be used. We believe that affordances are potentially powerful perceptual cues for representing information in a physical form. Similar to the use of *visual* cues in traditional visualization, affordances have the capacity to be interpreted in a functional way, thereby conveying informational meaning, as they forego higher-level visual abstraction.

This paper will propose *data sculpture* as an alternative approach to communicate information to a mass, lay audience. It is based on the assumption that abstract information can be captured and implicitly represented by physical objects which can be touched, explored, carried or even possessed, much like the memories symbolized by souvenirs, jewelry or art in general [4]. Accordingly, a data sculpture acts as an externalization of data, as it aims to capture the imagination and engage the interpretative powers of its audience through both its functional and artistic qualities. Thus, a data sculpture is able to indirectly convey data-related insights, and encourage people to reflect on social and cultural impacts that surround the conceived dataset.

Based on an analysis of 43 existing data sculptures, this paper presents a conceptual model that describes the embodiment between data and its direct physical representation. *Embodiment* is based on the measurement of the distance between metaphor and data and between metaphor and reality. We believe that this model is a useful tool to learn how complex information can be conveyed by a memorable, reflective yet insightful experience using physical objects.

2. BACKGROUND

2.1 Democratization of Information Access

'Traditional' information visualization focuses mainly on providing effective means for expert users to interact with datasets that are complex in terms of size, dimensionality or time-variance. More recently, several information visualization projects have emerged that share the aim to 'democratize' information access by providing a means for lay audiences to share, explore and annotate socially relevant datasets, such as ManyEyes [5], Swivel [6], and Data360 [7].

Driven by the desire to communicate socially-relevant messages to the masses, many artists and political advocates have created graphical and physical visualization works throughout history. For example, The Royal British Legion has set up arrangements of wooden crosses (red poppy flowers attached) at the Field of Remembrance, which represents tragic loss of soldiers and the horrendous scale of deaths as a result of the British wars (Figure 1, left) [8]. A Year in Iraq [9], shown in Figure 1(right), conveys a similar insight about the losses of military personnel incurred in Iraq using a graphic-based approach. A large array of iconically-depicted soldiers, marked by dates of their deaths, presents to the audience a calendar-like, frequently occurring, systematic destruction of "insignificant" lives in the Iraq war.

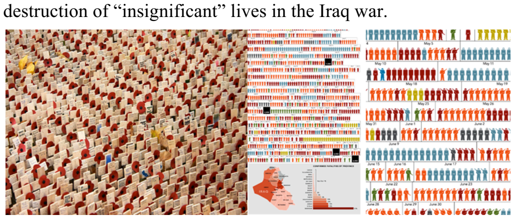

Figure 1. Deaths of military personnel due to wars: (Left) Wooden crosses with poppy flowers, Field of Remembrance London. (Right) Coalition deaths in the Iraq war.

A scale-model of the slave ship Brooks, shown in Figure 2(left), was used to highlight the inhumane conditions that African slaves were subject to. This early example of data sculpture demonstrates the anti-slavery plea by recreating the horrors of slave trade on a tangible model – the imprisonment of an alarming number of human beings in the hull of the ship. In Figure 2(right), the cross-section plans of another slave ship [10] advocates the same abolitionist views using a graphic-based approach.

The physical qualities of data sculpture, as demonstrated in the examples, contributes to the democratization of information access by providing the audience with a tangible connection between their knowledge and experience in the real world, and the underlying issues represented by the physical data sculpture. In general, data sculpture connects to the audience by possessing the physical qualities unique to real objects, which may include *physical properties*, *materiality*, and *nuances*. The tangible model of the slave ship, for example, possesses *physical properties* such as the perception of depth - showing how densely the slaves were packed into multiple layers of the ship's hull, *materiality* – using wood to resemble the look and feel of the real ship, and *nuances* – the weathering of the material which gives a sense of history. Data sculpture is capable of conveying socially-relevant issues, such as the dire consequences of war and slavery, to lay masses through our tactile and visual senses.

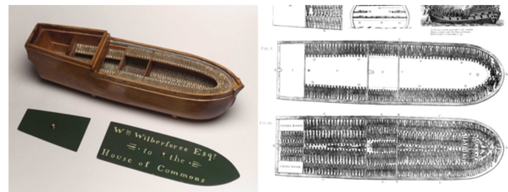

Figure 2. Advocacy for abolition of slave trade aided by information visualization: (Left) Physical model; (Right) Diagram.

2.2 Aesthetics & Physicality

Understanding how to enhance the representation of insights by incorporating aesthetics into information visualization is one of the top ten unresolved information visualization problems [11]. Data sculpture relates to the recently emerging visualization subfield of *information aesthetics* [12], *artistic visualization* [13] or *casual visualization* [14], through its data-oriented nature and the merging focus on aesthetics and functionality. One of the earliest manifestations of artistic data-driven sculptural forms includes the field of *ambient display*, which reinterprets everyday architectural spaces into "interfaces" by changing the state of the physical matter that they contain [15]. Ambient displays not only stimulate the audience's visual senses, but also their sense of smell and touch, providing physical qualities similar to those which data sculpture aims to exploit.

The miniaturization of microchip technology has proliferated *tangible computing* devices into the public space, which provides the ground for a seamless translation between the *virtual* (worlds of atoms and bits) and the physical (the real world which the user lives in), making virtual data directly manipulable and perceivable from the physical representation [16]. Tangible computing has extended the artistic and functional qualities of information visualization beyond the screen and into the physical reality. In parallel to the development of devices, several conceptual frameworks exist, capable of describing the structure of physical interfaces [17, 18], the ways that physical objects are able to link to digital information [19], and the influential factors that determine the joining of the physical representation and the virtual data [20]. The recurring theme amongst existing frameworks from the field of tangible computing emphasizes the coupling of *physical representation* and *digital data*, which becomes the focus for our model of embodiment in data sculptures.

2.3 Embodiment & Metaphor

The term '*embody'* means to be an expression of, or give a tangible or visible form to, something abstract [21]. Embodiment has already been identified as one of the key factors in *data-oriented artifacts* that consist of both virtual and physical components [22-24].

In data sculpture, embodiment describes the expression of abstract data in physical representation through the process of *data mapping*. In information visualization, and by extension, in data sculptures, data mapping describes the process of translating data values to representations using metaphors. In such processes, metaphors become manifested in representations and draw associations between the abstract data and the perceiver's prior knowledge or experiences [25, 26]. Metaphor is defined as a concept that is regarded as representative or symbolic to another concept. The primary function of a *metaphor* is to help people conceive an unfamiliar domain in terms of another familiar domain through drawing connections of similarity between the two [27]. For example, the project "Of all the people in the world" (Figure 3) maps one person living in the world to one grain of rice, which establishes rice grains as the metaphor for demographic statistics - drawing a connection between data about people and what they eat [28].

Figure 3. Rice grains represent demographic data. (REF)

2.3.1 A System of Signification

Semiotics theory describes the *signifier* as the material or physical form of the *signified*, an abstract idea, as something which can be seen, heard, touched, smelt or tasted [29, 30]. In data sculpture, the *physical representation* is the *signifier* and the *dataset* is the *signified*. Three perspectives on the relationship between signified and signifier have been identified [29], which form a foundation for analyzing metaphors in data sculpture:

1. **Symbolic.** The signifier does not resemble the signified, the relationship must be learned from conventions, for example: language, numbers and traffic signals.
2. **Indexical**. The signifier is directly connected in some way (physically or causally) to the signified - signifier smoke signifies fire, and blood signifies injury or death.
3. **Iconic.** The signifier resembles or imitates the signified, sharing some similar qualities. Imitative movements, portraits and realistic sound effects are all examples of iconic relationship.

These relationships are used as criteria for measuring the embodiment in data sculpture, which will be described in our model of embodiment for data sculpture in Section 3.2.2.

2.3.2 A System of Tangible Interaction

In the field of tangible computing, the research into the use of *metaphor* has been based on the theory that users naturally relate what they are experiencing to what they already know [31]. Accordingly, a recognizable metaphor should possess all the following three criteria that determine its *basic-level concept*:

1. **Single Mental Image.** The first criterion states that the metaphor must be easy to identify and must correspond to a single mental image. For example, 'chair' is a single mental image for it typically refers to a sitting device with four legs and a backrest; 'furniture' is arbitrary because it does not evoke an image of a particular type of furniture.
2. **Affordance.** The second criterion states that the metaphor must function at both 'motor' and 'cultural' level, that is, people should know how to interact with it. For example, a rope is understood to afford attachment to other objects, and invites pulling.
3. **Intuitiveness.** The last criterion states that the metaphor must be something people are familiar with before going through extensive professional training or education – intuitive enough so that the lay mass audience can understand. For example, people are familiar with the metaphor of 'green plants' but not 'jet engine'.

With respect to the three criteria, metaphors that deviate from the basic-level concept will be less recognizable to people, because they form weaker connections with their previous knowledge and acquired experience. These 3 criteria will form the basis for scaling the coupling between the data and the representation in our model of embodiment, described later in Section 3.2.2.

3. MODEL OF PHYSICAL REPRESENTATION OF DATA

3.1 Data Sculpture Domain Model

The unique characteristics of data sculpture and closely related areas of research are mapped in Figure 4. The relevant areas of research include *information visualization*, *tangible user interfaces*, *visualization art*, and *interactive art*. The context under which these areas are considered is that they are all directly driven by, or indirectly inspired by, the visual representation of abstract data. The model is defined by two attributes that identify each area's relative position in the model:

1. **Focus** indicates whether the works are more oriented towards a medium for artistic expressions or as tools for improving productivity in goal-based tasks, such as identifying the best performing stocks.
2. **Manifestation** describes whether the work takes a relatively more virtual approach (i.e. using "bits and bytes" on screens and projectors to display the representation) or a more physical approach (i.e. using "atoms and matter" in real objects).

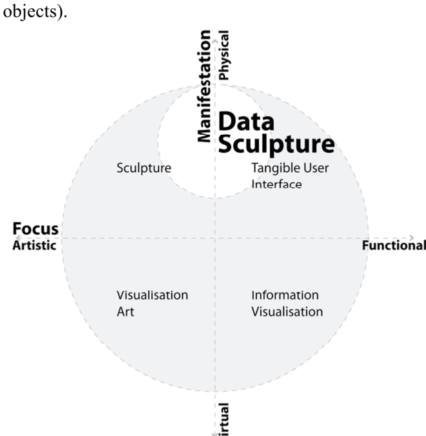

Figure 4. Data Sculpture Domain Model, which situates data sculptures in the general concept of data representation.

3.1.1 Analysis of Domain Model

Tangible User Interfaces & Sculpture. Data sculpture shares the *physical qualities* of sculptures (i.e. a three-dimensional artworks) and tangible user interfaces (i.e. user interfaces that provide access to and manipulation of digital information through the direct interaction with physical objects [16]). Such examples include The Atomium [32] in Figure 5(a), a sculpture installation, movement of mechanical arms responding to audience's proximity, a visualization of movements surround it; and Sensetable [34] in Figure 5(b), an innovative tangible user interface prototype for the exploration of and interaction with graphical data visualizations. Due to its greater concern with the physical representation of data, data sculpture is focused more on the representation of data through its physical form.

Information Visualization. Data sculpture shares the *functional qualities* of information visualization, that is: the representation of abstract data in a form that facilitates human interaction for exploration and understanding [1]. An example of information visualization is All of Inflation's Little Parts [35] in Figure 5(d) which gives us much insight into the composition of an average American's living expenses. However, unlike information visualization, data sculpture achieves this purpose through physical affordances rather than the visual cues via the screen-based approach.

Visualization Art. Data sculpture shares the *artistic qualities* with visualization art, which is the mapping of data for artistic expressive purposes [13]. In Figure 5(c), American Varietal [36] is an example of visualization art, which has all its form and color derived from US state and county demographic information. Extending visualization art, data sculpture exploits the physical aspects of artistic expression.

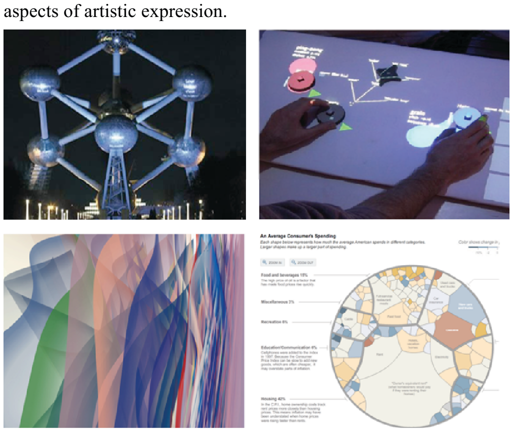

Figure 5. Clockwise from top-left: (a) a sculptural representation of the mean position of atoms and the binding forces in an iron crystal [32]; (b) a visual representation of cause and effect of tangible interaction [16]; (c) an artistic representation of demographic data [36]; (d) a functional representation of living expenses [35].

A more precise definition of data sculpture has emerged from the domain model: *a data sculpture is a highly data-oriented physical form, possessing both artistic and functional qualities, to augment facilitates an audience's understanding of the underlying data and issues.*

3.2 Embodiment Model

In this paper, we propose a conceptual model of *embodiment* in data sculpture (Figure 6). Embodiment, as defined in Section 2.3, influences how data sculptures convey insights to the audience and how, in turn, the audience perceives and interprets the metaphorical presence conveyed by the data sculpture. As mentioned in the previous Section 2.3, the model relates to the deconstruction of metaphor as a system of *signification* and as a system of *tangible interaction*. Similarly, the proposed model takes into account both the metaphorical distance from *data* and from *reality*

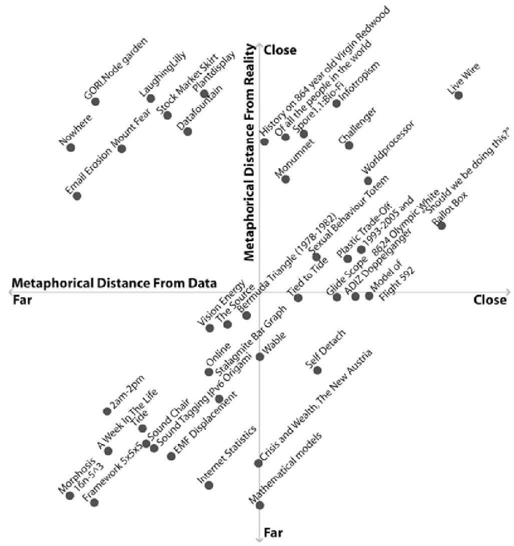

Figure 6. Model of embodiment in data sculpture, mapped along 2 characteristics: the metaphorical distance from data and the distance from reality.

3.2.1 METHODOLOGY

Due to the nature and relative novelty of data sculptures, no dedicated sources exist. Therefore, we were forced to based the model on the analysis of real-world data sculpture projects found from various, mainly online sources of creative and commercial origins. A total of 43 works that satisfy our definition of data sculpture have been short-listed. Our proposed concept of *metaphorical distance* was developed through a process of elimination, having started with 10 common salient attributes, such as *form*, *ambience* and *data complexity*. These attributes were further refined into two attributes, which best reflect the concept of embodiment and uniquely determine the relationship between the representation (signifier) and the data (signified). For example, in the Datafountain project [37], currency exchange rates are represented by the relative height of three water sprouts. The 'water' metaphor does not intuitively resemble anything directly related to the currency exchange rates, which translates to a *large* metaphorical distance from data. Accordingly, when considering the reality, in which the data sculpture is perceived, as a point of reference, 'water' has a *short* metaphorical distance because it is a basic-level concept.

Our model relies on following three axioms:

1. Data sculpture is a system of *physical representation* and *abstract data* coupled by a relationship called *embodiment*.
2. *Metaphor* is a contributing factor to embodiment and can be gauged by *metaphorical distances* from the *data* and *reality*.
3. Different modes of *embodiment* determined by different *metaphorical distances* in data sculpture can affect the *informative value*.

3.2.2 Metaphorical Distances

Metaphorical Distance From Data is a derivative of the three modes of relationship found in a system of *signification* (see Section 2.3.1). Here, we interpret signifier and signified as physical representation and abstract data respectively:

1. A *symbolic* relationship between the physical representation and the abstract data signals a least relevant metaphor (with respect to data), thus furthest away from data.
2. An *indexical* relationship is equivalent to a very relevant metaphor, which translates to the shortest metaphorical distance from data.
3. Lastly, the *metaphorical* distance from an iconic relationship will sit half way between the distances associated with symbolic and indexical relationships.

Three case studies are summarized in Table 3-1 to exemplify this approach. The three selected examples (Figure 7) epitomize the data sculptures that represent the average and extremes (far and close) of metaphorical distance from data.

Table 3-1. Case studies of data sculptures summarizes how the metaphorical distance to data is determined.

Data Sculpture	*Metaphor*		*Relationship*	*Distance*
	Data	*Representation*		
Live Wire [38]	Network activity through Ethernet cable	Movement of a cable/string	Indexical	Close
Wable [43]	Web services access patterns	Bar chart	Iconic	Moderate
Nowhere [40]	Search queries	Formation of landscape	Symbolic	Far

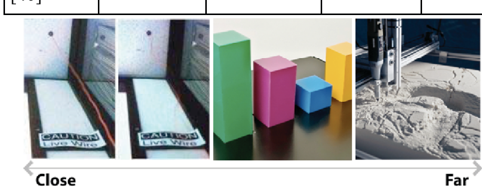

Figure 7. Metaphorical distances from data, from left to right: (left, Live Wire) closest; (middle, Wable) moderate; (right, Nowhere) far.

Metaphorical Distance From Reality is as an indicator of how the metaphor reflects an audience's knowledge and experiences about the real world. The distance is determined by the criteria of basic-level concept of the chosen metaphor (see Section 2.3.2). When a metaphor satisfies all three criteria (of *single mental image*, *affordances*, and *intuitiveness*), it is most identifiable with the physical reality, thus it has a short metaphorical distance from reality. A metaphor moves further away from reality when it satisfies the three criteria of basic-concepts to a lesser degree. Case studies are presented in Table 3-2, and Figure 8.

Table 3-2. Examples of data sculpture and its metaphorical distance to reality.

Data Sculpture	*Metaphor*		*Satisfied Criteria*	*Distance*
	Data	*Representation*		
Live wire [38]	Network activity	Movement, being 'alive'	Single mental image, affordance, and intuitive	Close
Plastic Trade-Off [41]	Flow of money between stock markets	Pipes, tubes	Affordance, single mental image	Moderate
Mathematical Models [42]	Mathematical concept	Geometric surface	None	Far

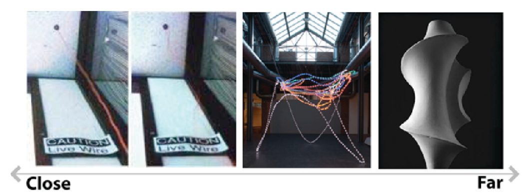

Figure 8. Metaphorical distances from reality, from left to right: (left, Live Wire) closest; (middle, Plastic Trade-Off) moderate; (right, Mathematical Model) far.

3.3 MODEL ANALYSIS

The model has established three main categories of data sculptures by metaphorical distances: far from data but close to reality, close to both data and reality, and far from both data and reality. Furthermore, three groups of data sculptures have been identified across the three categories on the basis of the metaphor types: *natural phenomenon, imitation,* and *abstract space/movement*.

3.3.1 Far from Data and Reality

Based on our analysis, all 43 projects have been positioned along the two axes of metaphorical distance to data and to reality. One group of data sculptures occupies the bottom-left region of the model (Figure 9) because they are characterized to be far from data and reality measured by metaphorical distance. The individual sculptures in this group predominantly share the use of abstract surfaces, volumes and movements, which means directly identifiable or intuitive metaphors are absent. The model also identifies a subset of this group, including Wable [43], Internet Statistics [44], and Crisis and Wealth [45] which all directly extend known elements of *information graphics* into the physical realm. Wable (Figure 10, right) closely resembles the appearance of a bar graph – rectangular prisms dynamically alter their height due to a user's fluctuating online activities. Another subset of this group emphasizes *spatial arrangement* in its representation to reflect the location-based nature of the data, some examples include: A Week in the Life [46], Sound Chair [47], and EMF Displacement [48]. For instance, A Week In The Life (Figure 10, left) conveys the mobile phone usage in different areas of Berlin by mapping the frequency of usage as the rising cascading layers with reference to the location of each call.

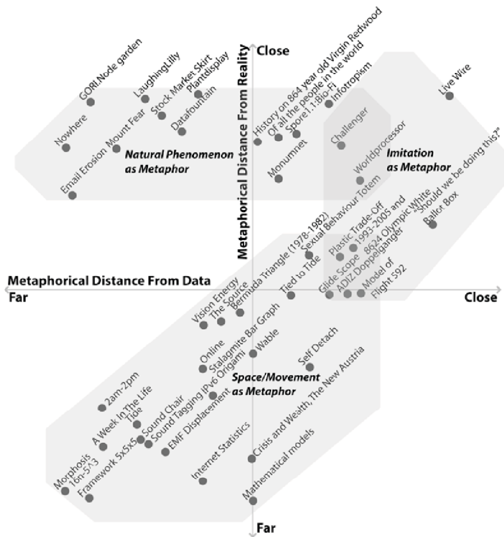

Figure 9. Data sculptures highlighted and categorized according to relative proximity, identifying several distinct types of metaphors used in the physical representation of data.

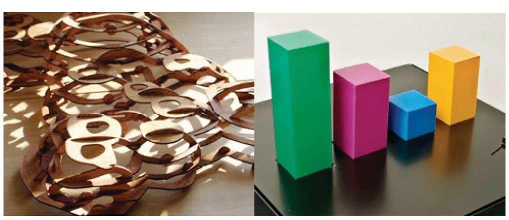

Figure 10. (Left) Physical spatial arrangement represents location-based data; (Right) Extending familiar graphic-based techniques into physical reality.

3.3.2 *Far from Data but Close to Reality*

Another distinct group of data sculptures seems to adopt *natural phenomena* as the core driver of the metaphor. In other words: most of these metaphors may or may not relate to the data, but closely resemble the real world. Data sculptures such as Laughing Lily [49], Plantdisplay [50], GORI.Node Garden [51], and Infotropism [52] use plants as metaphor in their representations, although the data has no direct relationship to plants. Plants are commonly observed, cultivated, eaten, and appreciated in the real world, which gives them *intuitiveness* and *affordances*. When people think of plants, a *single mental image* emerges - a collection of leaves and flowers. The use of plants as metaphor satisfy the three criteria of basic-level concept, and are therefore close to reality by metaphorical distance.

3.3.3 *Close to Both Reality and Data*

A smaller number of data sculptures use *imitations* of the subject or the meaning of the data as the metaphorical core, which places them close to data and reality. Live Wire (Figure 7 & 8, left) best illustrates this correlation by using *movement* (i.e. vibration of the wire itself) as a metaphor in the representation of network activities through an Ethernet network cable. Movement is a living organism's basic characteristic of being *alive*, it unambiguously stands as a basic-level concept (Section 2.3.2). Movement is generally observed when some kind of activity is taking place - making it a conceptually related metaphor for the traveling signals in a network cable.

3.3.4 *Critique*

We should note that the following factors have not been explicitly specified in the proposed model, but might be nonetheless relevant or influential in the analysis of existing data sculptures for other purposes.

Changing social context. In general, a metaphor is dependent on how well the audience can relate the source concept with the target concept. However, this relationship is not static and changes over time. For instance, as our society moves towards a more technology-oriented culture, it is expected that the general public will become more familiar with abstract computing concepts or novel interaction interfaces. Therefore, it should be noted that the positions of data sculptures in the model will shift along the vertical axis (metaphorical distance from reality) because the changing social context will always redefine what is regarded as reality.

Interaction allows an audience to become more aware of the embodiment between the digital data and the physical representation by way of direct exploration and discovery. Therefore, a different perspective on embodiment could potentially be gained by investigating the interactive aspects of a data sculpture.

Subjectivity. The proposed embodiment model was derived by the subjective weighting of a set of existing data sculptures by the first author of this paper. Therefore, it should be considered by its direct numerical measurement of the 2 characteristics captured along the axes. However, useful knowledge can be gained by the careful analysis of the relative position of emerging groups of data sculptures, as described in Section 3.3.1 to 3.3.3.

4. DISCUSSION AND CONCLUSION

This paper investigates the concept of *data sculpture* as a potentially useful physical representation of abstract data, which also possesses both artistic and functional qualities. Together, these qualities can help to capture the attention of a lay mass audience by sufficiently engaging their interests and curiosity. How much understanding and insight a particular data sculpture is able to convey, also determines how "informative" and useful it is. *Embodiment* has been identified as a major influential factor to a data sculpture's informative value. In addition, the concept of *metaphorical distance* has been introduced to provide a relative scale with which to measure one particular aspect of embodiment: the use of data mapping *metaphor* in the physical representation. As a result, a *model of embodiment in data sculpture* was developed to capture the influence of metaphorical distance on a collection of 43 real-world examples of existing data sculptures.

The model is unique in its focus on metaphor as the degree of embodiment in a specific data sculpture. More specifically, using metaphorical distance as a scale, our model analyzes the connection between data and representation, and the connection between representation and the audience's knowledge and experience. The analysis of the model also reveals closely related groups that share one common type of metaphor, including information graphics, spatial arrangement, natural phenomena, imitations, and movement. Within these groups, the metaphorical distances may vary significantly on one or both axes. More detailed user studies to assess the influence of metaphorical distances and metaphor type form future work. The proposed model could also provide an initial framework for a more complete understanding of embodiment in the data mapping metaphors of existing information visualization applications, and their influence on effectiveness, efficiency and user satisfaction considerations.

This paper demonstrates how data sculptures can offer an alternative approach in using physical objects as a medium for communication, and that different methods of physically representing abstract data exist in terms of their metaphorical distance from both data and reality. This cross-disciplinary study should therefore be considered as the first step towards supporting researchers develop design guidelines for the physical representation of information that can be effective in social, artistic and commercial contexts.

5. REFERENCES

[1] Card, S. K., Mackinlay, J. D. and Shneiderman, B. 1999.Using vision to think. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA.579--581

[2] Dourish, P., Adler, A., Bellotti, V. and Henderson, A. 1996. Your place or mine? Learning from long-term use of Audio-Video communication. *Computer Supported Cooperative Work (CSCW)*, 5, 1 1996), 33-62.

[3] Brave, S., Ishii, H. and Dahley, A. 1998. Tangible interfaces for remote collaboration and communication. *Proceedings of the 1998 ACM conference on Computer supported cooperative work*1998), 169-178.

[4] Vande Moere, A. 2008. Beyond the Tyranny of the Pixel: Exploring the Physicality of Information Visualization. In *Proceedings of the IEEE International Conference on Information Visualisation (IV'08)* (London, UK, 2008). Accepted for publication

[5] Viegas, F. B., Wattenberg, M., van Ham, F., Kriss, J. and McKeon, M. 2007. ManyEyes: a Site for Visualization at Internet Scale. *IEEE Transactions on Visualization and Computer Graphics*, 13, 6 (November/December 2007), 1121-1128.

[6] Swivel http://www.swivel.com, accessed: May 2007

[7] Data360, http://www.data360.org, accessed: 07/05/2008

[8] Keynes, M. 2008. Field of Rememberance_5781, http://flickr.com/photos/kitlogan/303120059/, accessed: May 2008

[9] Cheng, A. 2008. A Year in Iraq, http://www.nytimes.com/2008/01/06/opinion/06chart.html, accessed: May 2008

[10] Clarkson, T. 1808. Diagram of the slave ship Brooks, http://www.garstangfairtrade.org.uk/johns_images/slave_ship.jpg, accessed: May 2008

[11] Chen, C. 2005. Top 10 Unsolved Information Visualization Problems. *IEEE Computer Graphics and Applications*, 25, 4 (July/August 2005), 12-16.

[12] Lau, A. and Vande Moere, A. 2007. Towards a Model of Information Aesthetics in Information Visualization. In Proceedings of the The 11th International Conference Information Visualization (Zürich, Switzerland). IEEE Computer Society. 87-92

[13] Viegas, F. and Wattenberg, M. 2007. Artistic Data Visualization: Beyond Visual Analytics. In Proceedings of the Proceedings of HCII 2007 (in press).

[14] Pousman, Z., Stasko, J. T. and Mateas, M. 2007. Casual Information Visualization: Depictions of Data in Everyday Life. *IEEE Transactions on Visualization and Computer Graphics*, 13, 6 (November/December 2007), 1145-1152.

[15] Wisneski, C., Ishii, H., Dahley, A., Gorbet, M., Brave, S., Ullmer, B. and Yarin, P. 1998. Ambient Displays: Turning Architectural Space into an Interface between People and Digital Information. In Proceedings of the The First International Workshop on Cooperative Buildings, Integrating Information, Organization, and Architecture (London, UK). Springer-Verlag London, UK. 22-32

[16] Ishii, H. and Ullmer, B. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In Proceedings of the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (Atlanta, Georgia, United States, March 22 - 27). ACM New York, NY, USA. 234-241

[17] Ullmer, B. and Ishii, H. 2000. Emerging frameworks for tangible user interfaces. *IBM Systems Journal*, 39, 3 (July 2000), 915-931.

[18] Hornecker, E. 2005. A Design Theme for Tangible Interaction: Embodied Facilitation. In *Proceedings of the Conference on Computer-Supported Cooperative Work* (Paris, France, 18-22 September, 2005). Springer

[19] Holmquist, L. E., Redstrom, J. and Ljungstrand, P. 1999. Token-Based Access to Digital Information. In Proceedings of the Handheld and Ubiquitous Computing: First International Symposium, HUC'99 (Karlsruhe, Germany, September). Springer. 234-245

[20] Koleva, B., Benford, S., Ng, K. H. and Rodden, T. 2003. A Framework for Tangible User Interfaces. In *Proceedings of the Physical Interaction (PI03) Workshop on Real World User Interfaces* (Udine, Italy, September 8, 2003)

[21] Soanes, C. and Stevenson, A. 2003.*Oxford dictionary of English*. Oxford University Press New York.

[22] Bilda, Z. 2007. An embodied cognition framework for interactive experience. *CoDesign*, 3, 2 (June 2007), 123-137.

[23] Ziemke, T. 2003. What's that Thing Called Embodiment? In Proceedings of the Proceedings of the 25th Annual Conference of the Cognitive Science Society (Boston, Massachusetts, USA). Cognitive Science Society. 1134-1139

[24] Fishkin, K. P., Gujar, A., Harrison, B. L., Moran, T. P. and Want, R. 2000. Embodied user interfaces for really direct manipulation. *Communications of the ACM*, 43, 9 (September 2000), 74-80.

[25] Djajadiningrat, T., Wensveen, S., Frens, J. and Overbeeke, K. 2004. Tangible products: redressing the balance between appearance and action. *Personal and Ubiquitous Computing*, 8, 5 (September 2004), 294-309.

[26] Dourish, P. 2001.Where the Action Is: The Foundations of Embodied Interaction. MIT Press, Cambridge.

[27] Lakoff, G. and Johnson, M. 1980.*Metaphors We Live By*. University of Chicago Press, Chicago.

[28] Stan's Café 2006. Of All the People In the World (Photograph by Ben Hockman), http://www.flickr.com/photos/hockman/, accessed: May 2008

[29] Chandler, D. 2002.*Semiotics for Beginners*. Daniel Chandler (University of Wales), Aberystwyth.

[30] Saussure, F., Bally, C., Sechehaye, A. and Riedlinger, A. 1966.*Course in general linguistics*. McGraw-Hill New York.

[31] Wozny, L. A. 1989. The Application of Metaphor, Analogy, and Conceptual Models in Computer Systems. *Interacting with Computers*, 1, 3 (December 1989), 273--283.

[32] Waterkeyn, A. 1954. Atomium, Photographed by Miel Van Opstal: http://micromiel.com/images/atomium.jpg, accessed: May 2008

[33] Rinaldo, K. E. 1998. The Flock. *Leonardo*, 31, 5 (October 1998), 405-407.

[34] Patten, J., Ishii, H., Hines, J. and Pangaro, G. 2001. Sensetable: a wireless object tracking platform for tangible user interfaces. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (Seattle, Washington, United States, 31 March-5 April). ACM Press New York, NY, USA. 253 - 260

[35] Bloch, M., Carter, S., Cox, A. and NYT 2008. All of Inflation's Little Parts - An Average Consumer's Spending, http://www.nytimes.com/interactive/2008/05/03/business/20080403_SPENDING_GRAPHIC.html, accessed: May 2008

[36] Salavon, J. 2006. Studies for American Varietal (US Population, by County, 1790-2000), http://salavon.com/AmVar/AmVarStudy_Stills.php, accessed: May 2008

[37] Mensvoort, K. v. 2004. DataFountain: Money Currency Rates Displayed with a Water Fountain, http://www.koert.com/work/datafountain/, accessed: May 2008

[38] Jeremijenko, N. 1995. LiveWire, http://www.nyu.edu/projects/xdesign/mainmenu/archive_livewire.html, accessed: May 2008

[39] Olsson, K. 2005-2006. Memorial to Time Well Spent, accessed:

[40] Baecker, R. 2006. NOWHERE DATENFRÄSMASCHINE, , http://www.no-surprises.de/nowhere/, accessed: May 2008

[41] Nestler, G. and Eckermann, S. 2006. Plastic-trade-off, http://www.we-make-money-not-art.com/archives/2006/05/plastic-trade-o.php, accessed: May 2008

[42] Sugimoto, H. 2004. Mathematical Form: Surface 0006 Kuen's Surface: a surface with constant negative curvature, http://www.kunstsammlung.de/en/exhibitions/2007/k20-hiroshi-sugimoto.html, accessed: May 2008

[43] PhysicalInteractionLab 2007. Wable, http://www.physicalinteractionlab.com/projects/wable, accessed: May 2008

[44] Cliquet, E. 2006. Internet Statistics, http://www.ordigami.net/internet-stats, accessed: May 2008

[45] ART+COM 2005. The New Austria - "Crisis and Wealth", http://www.artcom.de/, accessed: May 2008

[46] Fischer, A. N. 2008. A week in the life, http://dasautomat.com/, accessed: May 2008

[47] Plummer-Fernandez, m. 2007. Sound Chair, http://www.plummerfernandez.com/, accessed: May 2008

[48] Lobo, N. 2006. EMF Displacement, http://www.nickdlobo.com/wordpress/nicolas-lobo/emf-displacement/, accessed: May 2008

[49] Antifakos, S. and Schiele, B. 2003. LaughingLily: Using a flower as a real-world information display. *Proceedings of Ubicomp*, 32003), 161-162.

[50] Kuribayashi, S. and Wakita, A. 2006. PlantDisplay: turning houseplants into ambient display. In Proceedings of the The 2006 ACM SIGCHI international conference on Advances in computer entertainment technology (Hollywood, United States, 14 - 16 June). ACM Computers.

[51] Oh, J. H. 2006. GORI. Node Garden. In Proceedings of the Proceedings of the 14th annual ACM international conference on Multimedia (Santa Barbara, CA, 23-27 October 2006). ACM New York, NY, USA. 1039-1040

[52] Holstius, D., Kembel, J., Hurst, A., Wan, P. H. and Forlizzi, J. 2004. Infotropism: living and robotic plants as interactive displays. In Proceedings of the The 2004 Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques (Cambridge, MA, USA, August 1-4, 2004). ACM Press New York, NY, USA. 215--221