Embodying virtual space to enhance the understanding of information

Lisa Susan Strausfeld

Bachelor of Art in Art History,
Brown University, 1986
Master of Architecture,
Harvard University Graduate School of Design, 1991

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of
Master of Science in Media Arts and Sciences at the
Massachusetts Institute of Technology

September 1995

Author
Lisa Strausfeld
Program in Media Arts and Sciences
August 11, 1995

Certified by
William J. Mitchell
Dean, School of Architecture and Planning
Thesis Advisor

Accepted by
Stephen A. Benton
Chair, Department Committee for Graduate Students
Program in Media Arts and Sciences

Embodying virtual space to enhance the understanding of information

Lisa Susan Strausfeld

Abstract

With current advancements in real-time 3D computer graphics and animation hardware, it is now possible to create virtual information spaces through which users can move and interact. The move into virtual space, while providing greater possibilities for interaction with information, introduces a new challenge for information designers: How can we use *space* to enhance the understanding of *information*?

This thesis presents *embodied virtual space*, a two-part theoretical framework that addresses this problem of interactive 3D information design, as well as *The Millennium Project*, prototype software that exhibits the theory in practice. *Embodied virtual space* is based on two areas of research that view both our experience in virtual space and our understanding of information as *embodied* activities. In this thesis, the *body* provides the connection between space, on the one hand, and information, on the other. Part 1 of the theoretical framework reveals the role of *the body in space* through an empirical analysis of 3D virtual space (supported by theories of perception that emphasize embodiment.) Part 2 of the theoretical approach reveals the role of *the body in information* through a study of embodied cognitive models based on linguistic metaphor theory. The result of this work is a footing in the foundation of *spatial literacy*, a way for designers to think about and talk about information in space.

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning on August 18, 1995, in partial fulfillment of the requirements for the degree of Master of Science in Media Arts and Sciences.

Thesis Advisor:
William J.Mitchell
Dean, School of Architecture and Planning
Massachusetts Institute of Technology

This work was performed at the Visible Language Workshop of the MIT Media Laboratory. Support for this work was provided by JNIDS. The views expressed within do not necessarily reflect the views of the supporting sponsors.

Thesis Committee

Thesis Advisor
William J. Mitchell
Dean, School of Architecture and Planning
Massachusetts Institute of Technology

Reader
Ron MacNeil
Principal Research Associate
Visible Language Workshop, MIT Media Laboratory

Reader
Michael Benedikt
Professor and Director of the Center for American Architecture and Design
School of Architecture, University of Texas at Austin

Acknowledgments

I am grateful for the intellectual, technical, logistical and emotional support I have received from advisors, colleagues, faculty, staff, friends and family. I would especially like to thank the following people for their contribution to this thesis:

- My thesis advisors, Muriel Cooper and William Mitchell, and readers, Michael Benedikt and Ron MacNeil, for their specific insights and general support of this research. I am also grateful to each one of them for their unprecedented commitment to the creation of academic environments and texts that have inspired students like myself to further explore the connections between design and technology.
- Earl Rennison, a fellow Masters student in the Visible Language Workshop, whose complimentary skills and way of thinking made for a truly enlightening collaboration in The Millennium Project.
- Suguru Ishizaki, a Ph.D. student in the Visible Language Workshop, who was an unofficial advisor and motivator of this research. Suguru's gifts for design and thinking are surpassed only by his gift for teaching.
- Laura Strausfeld, my twin sister, for introducing me to metaphor theory (in particular, the work of George Lakoff) and for always helping me to keep things in perspective.
- David Small, whose many years of research innovation and maintenance of the Visible Language Workshop has had a significant influence on my work over the past two years.
- My exceptional colleagues in (and around) the Visible Language Workshop: David Allport, Maia Engeli, Suguru Ishizaki, Robin Kulberg, Ishantha Lokuge, Earl Rennison, Robert Silvers, David Small, Jeffrey Ventrella, Louie Weitzman, Yin Yin Wong, and Xiaoyang Yang. I have learned a great deal from each of them.
- Media Lab faculty for their support of my work and design research, in general: Glorianna Davenport, Michael Hawley, Ken Haase, Henry Lieberman, Pattie Maes, and especially Tod Machover for inviting me to work on interesting projects.
- My UROPs, Amy Schneider and Vivek Palan for their committed work on the Millennium Project database.
- Members of the Media Lab staff, especially Nancy Young, Linda Peterson, and Santina Tonelli, for their organization and efficiency coupled with understanding and patience.
- My friends, in particular Martha Cassell, Nancy Kleppel, and Angela Shen Hsieh who gave me motivation to get out of the lab every once in a while.
- Gong Szeto, who initially inspired me to come to the Media Lab.
- My family, especially my parents, for their unconditional love, faith and support.

This thesis is dedicated to a designer who could see into the future: my past advisor and present mentor, Muriel Cooper.

Contents

1

Introduction

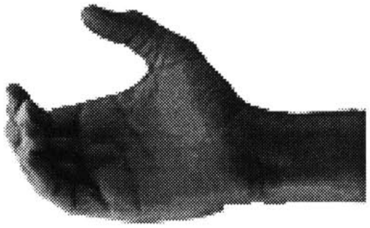
1.1 Overview

Imagine yourself without size or weight. You are in a zero-gravity space and you see an object in the distance. As you fly towards it, you are able to recognize the object as your financial portfolio. From this distance, the form of the object conveys that your portfolio is doing well. You move closer. As you near the object, you pass through an atmosphere of information about your net assets and overall return statistics. You continue moving closer. Suddenly you stop and look around. Your financial portfolio is no longer an object, but a space that you now inhabit. Information surrounds you. From this view you can see all of your mutual funds and how they're faring. You turn around and get a view of your real estate investments. Something looks awry on a Cambridge property, so you move towards this new object to investigate....

This scenario is a potential experience of future explorers of virtual information worlds. Until recently, information design was restricted to the 2D printed or electronic page. With current advancements in real-time 3D computer graphics and animation hardware, it is now possible to create 3D virtual information environments through which users can move and interact. The move into virtual space, while providing greater possibilities for interaction with information, introduces a new challenge for information designers: How can we use *space* to enhance the understanding of *information*?

This thesis presents *embodied virtual space*, a two-part theoretical framework that addresses this problem of interactive 3D information design, as well as *The Millennium Project*, prototype software that exhibits the theory in practice. *Embodied virtual space* is based on two areas of research that view both our experience in virtual space and our understanding of information as *embodied* activities. In this thesis, the body provides the connection between space, on the one hand, and information, on the other. Part 1 of the theoretical framework reveals the role of *the body in space* through an empirical analysis of 3D virtual space (supported by theories of perception that emphasize embodiment.) Part 2 of the theoretical approach reveals the role of *the body in information* through a study of embodied cognitive models based on linguistic metaphor theory. The result of this work is a footing in the foundation of *spatial literacy*, a way for designers to think about and talk about information in space.

Embodied Virtual Space



Embodied virtual space is a theoretical framework built with the intention of helping designers better understand and talk about issues of interactive 3D information design. This framework was inspired by two initially independent observations that exposed the significance of the role of the body in perceiving virtual space, on the one hand, and in understanding information, on the other. The first observation relates to virtual space: Our natural intuition about 3D navigation reflects a strong subconscious tendency we have to project our bodies into virtual space. The second observation relates to the understanding of information: When we talk about understanding, we subconsciously refer to our eyes, our hands, and the movement of our bodies in space. We say things like: "I *see*", "I *grasp* it", or "I'm *approaching* an understanding."

A hypothesis was developed, based on these two observations: The ability to identify the embodied features of both virtual space and the understanding of information may enable designers to create more effective virtual information spaces. Specifically, the embodied features of virtual space can be used to *represent* the embodied features of information.

The Millennium Project[1]

n 1912 the S.S. "Titanic" sank on it's maiden voyage, Woodrow Wilson won the U.S. presidential election, Sun Yat-sen founded Kuomintang (the Chinese National Party), C.G. Jung published "The Theory of Psychoanalysis," Edwin

---

[1] The Millennium Project was developed jointly with Media Lab graduate student, Earl Rennison.

Bradenburger invented a process for manufacturing cellophane, and Marcel Duchamp painted "Nude descending a Staircase." How, if at all, do these events relate to one another? Where, when and what were the confluences of ideas and people that influenced the outcome of these events? How do we acquire the knowledge to understand the complex associations between people and ideas, across time and place, based on the artifacts and events they created?

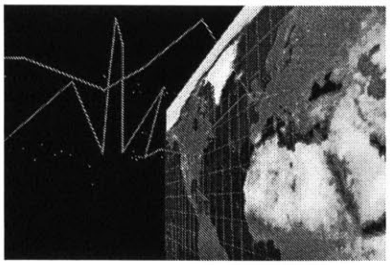


Figure 1.1 *View of the Geographical-Temporal context of the MILLENNIUM PROJECT.*

The *Millennium Project* represents a computational approach for enhancing the understanding of a large, multidimensional set of information based on *embodied virtual space,* the theoretical framework presented in this thesis and *visual discourse,* the thesis work of Earl Rennison [Rennison, 95]. The goal of the project is to provide a knowledge seeker the ability to move through virtual time and space to explore and discover the connections between artifacts of philosophy, painting, music, literature, science, and political events of a pivotal time in world history: the years from 1906 to 1918. This virtual space continually constructs and reconstructs itself based on the knowledge seeker's movements through and within it, much like the process of moving through the conceptual spaces of our minds as we construct meaning.

1.2 Problem

What's the connection between space and information? Before we can expect virtual space to *enhance* the understanding of information, we need to understand just how space and information are related: How does the experience of moving through space resemble the understanding of today's business news? How does the experience of holding an object in one's hand resemble the understanding of mutual funds? The connection between space and information is the subject of this section. First, I will clarify the question by defining some terms.

Definitions

I have been speaking around words that are central to this research: *space, information, and embodiment.* Their definitions follow.

Space: *Space,* which comes from the Latin verb *spatiari,* to wander, has a wide range of definitions. It can refer both to a distance extending without limit in all directions, or an expanse within which things are contained.

Space can refer to an interval of time, such as an open place between lines of a staff of music, or an area of thought, such as a set of points in mathematics satisfying a given set of postulates [Webster, 83]. The ambiguity of the word *space*, which also means something particular to astronauts, typographers, philosophers, and car parkers, is the key to its suitability for representing information.

For the sake of clarity, however, only two types of space will be referred to in this thesis: *physical space* and *virtual space*. Physical space refers to the space we live in and understand through bodily interaction. We distinguish two types of physical space: *gravity space* and *zero-gravity space*. Gravity space is the space we inhabit on earth or imagine we could inhabit on other planets in our solar system. Zero-gravity space, or galactical space is a space most of us have seen (thanks to NASA and Hollywood) but never inhabited. Nevertheless, it is still a space for which we can imagine some degree of bodily intuition.

Virtual space refers to the artificial space created by real-time 3D computer graphics and animation. Virtual space either resembles physical space or it does not. When virtual space resembles gravity space or zero-gravity space, we say that it is *concrete*. When virtual space resembles neither, we say that it is *abstract*. Virtual space may also occasionally be both *concrete* and *abstract*.

Information: Information is not like physical space. It is abstract rather than concrete. Any text, numbers, images, sounds, video segments or 2D and 3D forms that convey meaning will be referred to as *information*. In the paradigm of *form and content*, we usually think of information as content. The word information, however, relates to form. It derives from the French verb *informare* which means "to give form to". According to Richard Saul Wurman, the difference between information and data, is that data has no form. [Wurman, 90] It is form that gives meaning and value to data; form allows data to *inform*.

Space and information : This thesis investigates the use of virtual space to give form to data. Virtual space will be used, in other words, to represent information.

Recent work conducted at the Visible Language Workshop supports the hypothesis that virtual space is a compelling medium for the representation of information.[1] [Abrams 94; Owen 94; Rennison 94; Small 94] But as Muriel Cooper acknowledged, we have great difficulty articulating what it means to put information in 3D virtual space. [Abrams, 94] A central objective of this thesis is to find a way to talk about information in space, to frame the issues and develop a vocabulary of terms that will be useful for designers.

The problem this research addresses is methodological: how can designers use virtual space to enable understanding of information? We can frame the problem like this: we have virtual space, on one hand, and information on the other. We need to find some way to conceptually map between the two domains. Specifically, we need to correlate parameters particular to the information *content* to parameters particular to a computer graphics *display.* Figure 1.2 diagrams this mapping process for news information.

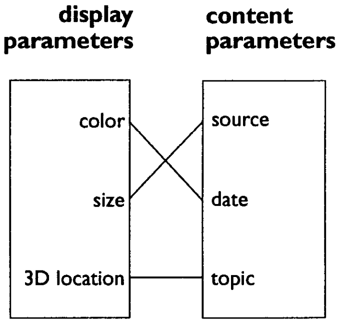


Figure 1.2 *Display and content parameters of information should have some meaningful association.*

For most types of information, the mapping between information content and spatial organization is a challenging problem for designers.[2] Information is abstract while virtual space is concrete. Although we can design virtual spaces that are more abstract (i.e., less referential to physical space), the drawing requirements of 3D graphics are unavoidably concrete – we need to think in terms of objects that have 3D coordinates.

Abstraction will be discussed as a design strategy in Chapter 4, but it is important to emphasize here the advantages of *concrete virtual space*, virtual space that references physical space. Recent virtual reality applications show that navigation through virtual space is natural and intuitive when the virtual space resembles physical space. The ability for natural and intuitive interaction is one of the most important design criteria for the representation of complex information.

Embodiment: Embodiment, which is the state of anything that refers to the body, is how this thesis proposes to bridge the gap between space and information.

---

[1] Representation, in this context, includes all of the features of interaction.

[2] Geographical or spatial information (such as architecture) is not as challenging a problem because it clearly lends itself to virtual space representation.

I argue that virtual space is *embodied* because my research indicates that our analogous experience in physical space creates an inevitable tendency for us to project our own bodies into virtual space. My argument for embodied understanding is based on work in metaphor theory. In *The Body in the Mind*, Mark Johnson introduces *embodiment* as "the key to dealing adequately with meaning and reason [Johnson, 92]."

The notion of the user's "body", of course, is figurative in virtual space. "We are all cyborgs now," writes Mitchell in *City of Bits* [Mitchell, 95]. We can fly through time, change scale, and see through objects. One of the great advantages of virtual space, in fact, appears to be *disembodiment*, the ability to move through space without the constraints of the size and weight of a *body.*

Nevertheless, the research conducted for this thesis (in particular with respect to 3D navigation) strongly suggests the presence of a "body" in the mind of the user as she interacts in virtual space. The user need not even see it (she cannot see her own body without reflection), or "use" it directly for navigation (a mouse or keyboard can replace feet and hands), yet it is still somehow "there," guiding movement and generating expectations.

"Your gaze scans the streets as if they were written pages: the city says everything you must think, makes you repeat her discourse, and while you believe you are visiting Tamara you are only recording the names with which she defines herself and all her parts."

– Italo Calvino, *Invisible Cities*

"The design of cyberspace is, after all, the design of another life-world, a parallel universe, offering the intoxicating prospect of actually fulfilling - with a technology very nearly achieved - a dream thousands of years old: the dream of transcending the physical world, fully alive, at will, to dwell in some Beyond - to be empowered or enlightened there, alone or with others, and to return."

– Michael Benedikt, *Cyberspace*

"[T]he most crucial task before us is not one of putting in place the digital plumbing of broadband communications links and associated electronic appliances (which we will certainly get anyway), nor even of producing electronically deliverable "content," but rather one of imagining and creating digitally mediated environments for the kinds of lives that we will want to lead and the sorts of communities that we will want to have."

-- William J. Mitchell, *City of Bits*

1.3 Motivation: Information, Architecture, and Cyberspace

While metaphor theory provides a basis, Architecture and Cyberspace are the inspirations for this research. The following section describes one idea (of many) that this thesis borrows from architecture.

Architecture

When architects work on a building project, there are many different types of information that have to be coordinated. Before well designed architecture software existed (such as Sonata™ or Speedikon™) these types of information had to be handled separately (in models and drawings for presentation and construction, which are drawn either by hand or in different software packages). Now they can coexist in a single project model or database. These project models contain the following:

- a 3D model, typically a building,
- plans and sections, which are 2D horizontal and vertical slices of the 3D model[1]
- a walk-through feature which simulates the experience of moving through the full-scale building, and

---

[1] These drawings are still the standard for construction documentation.

- a database, which contains non-spatial, non-visual information such as component specifications, material quantities, and cost estimation.

This single 3D CAD model helps architects manage the complex information associated with a building project in the following ways:

- It provides information at many **scales,** from the massing of the building to the hinges of the doors, all in a single, continuous environment.
- It provides information from many **perspectives** and **points of view.**
- It provides a holistic view of the information that can be examined and **analyzed** like an object one might hold in one's hand.
- It provides information in **context.** It is clear where plans and sections slice through the model (or building).
- Because we can interact with and **experience** the model directly, it provides coherent context shifts, such as that between the object you hold in your hand and the space through which you move your body.
- The 3D CAD model allows for multiple representations of the information in one environment.

Cyberspace

What if, instead of the information associated with a building, a 3D model like the one above represented today's news, a financial portfolio, or the history of modern art? What would it mean to hold this model in your hand, see it from all sides, or move around inside it?

Cyberspace brings information and space together. The word comes from William Gibson's 1984 novel *Neuromancer,* and has become almost synonymous with the internet and World Wide Web. As Michael Benedikt describes it, cyberspace is "the realm of pure information." It is a "parallel universe created and sustained by the world's computers and communication lines", a "mental geography", a "collective memory or hallucination", yet "free from the bounds of physical space and time [Benedikt, 91]."

Cyberspace is invisible, but has many visible representations. On the internet it is text, on the World Wide Web, with the help of browsers such as *Netscape,* it is pages of text, images, sound, and video - and most recently *Webspace* - virtual spaces inhabited by 3D objects. Despite the diversity of its visible forms, the function and purpose of cyberspace is consistent: it is what connects people across the globe to one another, and to vast resources of information, from business to entertainment.

The experience of cyberspace via the internet or World Wide Web belies its current visible representations. A Netscape "surf session" for modern art images, for example, could easily take us across the country, the ocean, the globe, and back again, with several "search stops" inside vast databases of images collected by museums, universities, or individuals around the world. Each web site, currently, is represented by an electronic page (or pages) of text and images, revealing nothing of the site's geographical context, individual characteristics, or categorical relationship to other sites.

Benedikt maintains that cyberspace "is premised upon the desirability of spatialization per se for the understanding of information [Benedikt, 91]." Despite its overwhelmingly spatial features, however, the representation of cyberspace today is still flat, and predominantly unspatial.

The future vision for this research is the spatialization of cyberspace, at the very least in the form of 3D multi-user web spaces. While this thesis is motivated by this vision, it does not assume its desirability; the role of this research is *not* to defend 3D over 2D representations of information. This thesis is intended, rather, to explore the *potential* for 3D virtual space to represent information. It will do so by identifying design opportunities *and* problems from both theoretical and computational perspectives.

1.4 Related Work: 3 Strategies

I have observed three strategies for dealing with the problem of representing information with virtual space. In this section, related research in the context of these three strategies will be discussed.

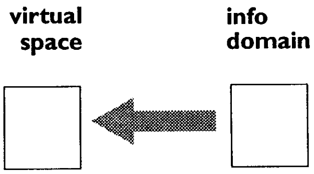


Figure 1.3 *Strategy 1.*

Strategy 1: *Identify organizational structure of information and find appropriate spatial representation.* [Figure 1.3]

This strategy ignores space, initially, and focuses on information. The approach is to identify, first, an organizational structure that already exists in information and, second, find an appropriate spatial representation for this organizational structure.

Researchers at Xerox PARC identified hierarchical and linear organizational structures in information to generate *Cone Trees* and *Perspective Wall,* respectively. [Robertson, 91] [Mackinlay, 91] *Cone Trees* is a representation of hierarchical information such as Unix directories and company organization charts. *Perspective Wall* is a representation of linear information such as documents of projects over long periods of time. Both applications use 3D visualization and interactive animation techniques.

While both projects support Xerox PARC's hypothesis that visualizing information in the context of its overall structure enables understanding and stimulates recognition of patterns, I argue that they are too constrained by the organizational information structures they represent and cannot take advantage of the possibilities of virtual space. To illustrate: What if we could see the hierarchical structure of *Cone Trees* from a distance or *Perspective Wall* from a different point of view?

In sum, because the organizational structures derive from information rather than space, this strategy does not allow 3D information environments to exploit enough of the possibilities that virtual space affords.

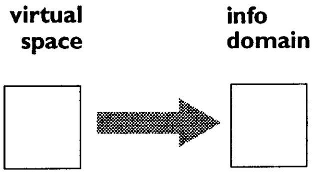


Figure 1.4 *Strategy 2.*

Strategy 2: *Identify organizational structure of physical space and find appropriate information representation.* [Figure 1.4]

Strategy 2 is the opposite of Strategy 1. This strategy ignores information, initially, and focuses on physical space. The approach is to identify, first, an organizational structure that already exists in physical space (such as a city or a building) and, second, find an appropriate representation of information to insert into this organizational structure.

Silicon Graphics' *3D File System Navigator* uses a quasi-urban space structure to organize Unix directories. Although they are appear more suburban than city-like, the results do succeed in revealing patterns of organization, excessively large files and overloaded directories.

The *3D/Rooms* project, also from Xerox PARC, uses the spatial structure of a building to organize information. [Card, 91] This strategy works well if the information has some spatial attributes (like a company personnel browser), but becomes limiting when applied to more abstract information such as news and finance.[1].

---

[1] More interesting is to use the 3D/Rooms approach for personnel browsers for companies like Chiat Day, who no longer have a fixed physical spatial organization.

Because the organizational structures derive from space rather than information, this strategy also does not allow 3D information environments to represent enough of the multi-dimensional complexity of information.

Strategy 3: *Find organizational structures common to both information and physical space.* [Figure 1.5]

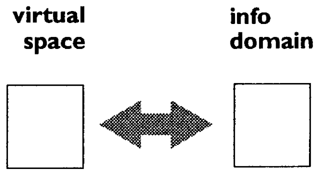


Figure 1.5 *Strategy 3.*

The 3rd strategy is to find organizational structures common to both information and virtual/physical space. These have been further categorized into *scale, transparency,* and *point-of-view.*

Scale is an organizational structure common to both information and physical space, and therefore one of the focuses of this thesis. Other researchers have successfully used scale to represent large sets of information. Among these are the Ken Perlin's *Pad* interface, Benjamin Bederson's *PA3D* system, Earl Rennison's *Galaxy of News* system, and David Small's current research in visualizing large quantities of text [Perlin 93; Bederson 93; Rennison 94; Small 95]. All of these projects employ "semantic zoom" which labels our intuitive spatial and abstract understanding that *closer* means *more detail.* While these projects are spatial, they still operate primarily in either a 2D or orthogonal mode. Steve Feiner's *Worlds within Worlds* project visualizes multi-scale financial information in 3D [Feiner, 90].

Work by Grace Colby and Laura Scholl, Ishantha Lokuge and Suguru Ishizaki of the Visible Language Workshop relates to the ideas of layering and transparency, which could loosely be considered structures common to both information and physical space [Colby, 92; Lokuge, 94]. This approach has been useful for 2D multi-layered geographic information but may have applications for more abstract information in 3D.

Yin Yin Wong and I have explored the use of point-of-view as an organizational structure common to space and information in the context of news and finance [Wong, 94; Strausfeld, 94]. My work with *Financial Viewpoints* is discussed below.

On a more conceptual level, Michael Benedikt and his students have done visualizations of databases such as architecture library slide archives, virtual sales conventions, and sonar submarine data, that more directly address issues of scale and the body in virtual space [Benedikt, 91].

2

Background
Financial Viewpoints

2.1 Overview

This chapter describes *Financial Viewpoints*, a prototype interactive 3D information space that represents seven mutual funds. I present the project here as *background* because its successes and failures became the starting point for the research of this thesis.

The project is an example of the 3rd strategy described in the previous chapter for representing information with space: *Find organizational structures common to both information and physical space.* The approach for this project, in retrospect, was motivated by a training in 3D design from a background in architecture. It was inspired both by the affordances of the 3D CAD model for architecture, described in the Motivation section above, as well as a desire to take full advantage of 3D.

For the sake of discussion, if we reduce the design process to the manipulation of elements like text, images, and geometry, in both 2D and 3D design we can manipulate position, scale, color, transparency, and rotation of these elements. In Financial Viewpoints, there was an interest in exploiting the additional manipulations possible in 3D, namely Z position and 2 additional axes of rotation.

Figure 2.1 shows views of an early version of *Financial Viewpoints*, before financial data was inserted. They show the basic formal structure of the model, which is a planar one. Each plane represents an information *context*. Parallel planes (like the vertical planes shown here) are categorically equivalent. Orthogonal planes extract like information across parallel planes to

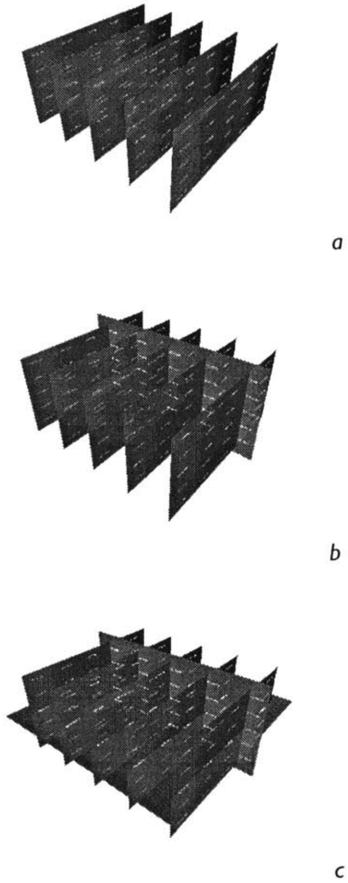


Figure 2.1 *Early views of Financial Viewpoints show the basic formal structure of the model, which is planar.*

form a new context. The horizontal plane defines a 3rd type of context which formally and conceptually intersects the vertical planes.

Visualizing Complex Data

3D visualization has the potential to allow us to better understand complex information. Any single 2D representation of a complex data set constrains its complexity in a particular way and generates a specific meaning. Tables, bar charts, and graphs produce specific meanings or force particular interpretations of data. These sorts of representations (graphical or tabular) allow us to simplify what may be too complex to comprehend all at once. It may be possible, however, to grasp the full complexity of a data set by aggregating a series of these "simplified" and coherent representations. The goal of this project was to create an environment that can sustain a multitude of representations of a single data set. The hope is that such an environment will enable us to more rapidly and intuitively analyze and understand complex information.

Formal Strategy

In general, it is the *relationships* between pieces of data that are of interest or value to us. The piece of data representing the percentage of a mutual fund's holdings in technology stocks tells us very little until it is associated with annual returns of that fund and then compared to the same data on other mutual funds. *Data visualization* is an approach to allow us to extract *information* from a set of data through visual means. The objective of data visualization is to expose relationships among pieces of data in a visually coherent way. The more complex the relationships, the more challenging it is for a designer to construct a meaningful visualization and the more potentially difficult it is for the user to read the relationships from the visualization.

In the design of this project, I was faced with the challenge of spatially and visually organizing about 350 pieces of data (50 pieces of data for each of seven funds). Each one of these pieces of data has several contexts within which it can be viewed and understood. For example, the piece of data which represents the percentage of CGM's holdings in consumer durables belongs to several different categories or *contexts* which include: 1) the mutual fund it belongs to (CGM), 2) a grouping of data representing the present holdings in other areas (sector weightings), and 3) the group consisting of the percentage of consumer durables for all seven funds. In each one of these contexts, this single piece of data may have a different meaning.

Figure 2.2 *A grid of numbers representing seven mutual funds.*

Principles of Spatial Representation

A central objective of the design of the spatial/visual representation of this information was the integrity of the pieces of data. It was important, in other words, that each piece of data have just one instantiation in the space, that there be no redundancy or repetition of data despite the fact that each piece of data may be relevant to several different contexts.

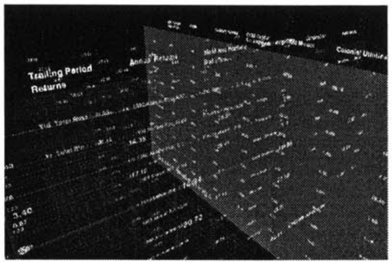


Figure 2.3 *Sliding planes along the X and Y axes highlight data in different contexts.*

Structure and Organization of Data

The information for this project is financial data on seven Mutual Funds. The information is distributed on a 3-dimensional grid. (Figure 2.2) The grid is not neutral, but is an organizing device employed with the intention of reducing the complexity of the data.

For the purposes of this project, information about each Mutual Fund was displayed in 7 columns in the following categories: Rating Statistics, Trailing Period Returns, Annual Returns, Yield and Portfolio Statistics, Sector Weightings, Composition, and Operations. The data grid was conceptualized as a volume that can be sectioned by sliding planes along the X and Y axes. (Figure 2.3) A plane that slides along the X-axis serves as a template for each Mutual Fund. As it intersects with the data for each fund, it highlights and labels the numbers. A plane that slides along the Y-axis cuts a section through all 7 Mutual Funds for each column of data. When viewing this Y reference plane head on (i.e., when the eye aligns with the normal of the plane), the X reference plane is viewed from its side. Because it is only a pixel wide, it essentially disappears in this view. Ideally, the user should be able to focus on the highlighted data without distraction from foreground or background information. Perceptually, the data space should appear to be constantly conforming to the user's focus of attention while maintaining its integrity as a coherent structure.

Cutting in the Z dimension: In an earlier version of this project, a plane cut the data volume uniformly in the Z dimension. The distribution of the data in this current version does not make it meaningful to do so. This problem led to a more graphical solution about how to handle the Z dimension. Rather than a 2D plane, lines are employed to slice the data in Z. The text/numbers highlight and orient themselves for top viewing, and a bar chart is generated showing relative values for each data item, for all 7 Mutual Funds. The user can move these bars/lines and intersect each data item. Multiple bar charts allow for some quick visual comparisons of values that may or may not appear to have some relation. Figure 2.4 shows a view of 3 year risk to annual return for 1991.

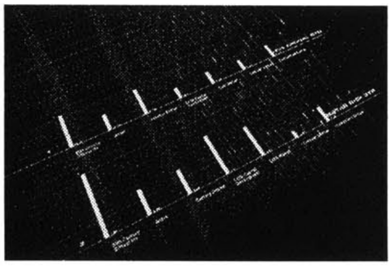


Figure 2.4 *Bar charts comparing three year risk to annual return in 1991 for each of the seven funds.*

Other modes of viewing in Z: In the case of annual returns, movement in the Z dimension is meaningful because it represents movement through time in one-year increments. A graph was plotted for each fund showing annual return over 10 years' time. Here we have the possibility of tabular numerical data synchronized with graphical data. When we highlight the annual return data with our Y reference plane, the result is a 3-dimensional spreadsheet. (Figure 2.5) Negative values pierce through the plane. If we connect the annual returns for each year for each fund, across all funds, the result is a 3D surface. (Figure 2.6) Perhaps this could represent the behavior of a portfolio of funds. The meaning of the order and spacing of the funds needs to be explored for this representation.

Figure 2.5 *Combination of numerical and graphical data: negative values of graphs pierce through plane of annual returns.*

Images: Photos of Mutual Fund managers for the "Operations" category add another medium of communication to the space. Video and audio objects could be added to "inhabit" the space. When approached by the user, these video and audio clips could provide more background information on each fund. (Figure 2.7)

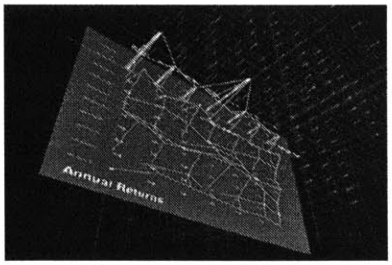


Figure 2.6 *A 3D surface of annual returns that could represent the behavior of a portfolio of funds.*

2.2 Discussion

This space was built as a primarily "retrospective" analytical tool of financial information. It illustrates the benefits of 3D visualization of abstract information which has the potential to enhance users' understanding of complex information. A future version of this work would further the pursuit of these visualization techniques and would explore the dynamic and time critical nature of real time financial information.

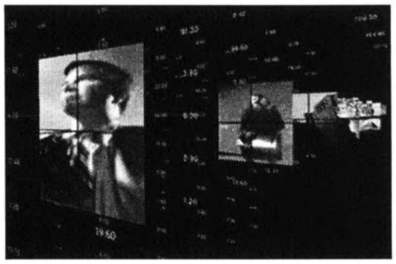


Figure 2.7 *Images of managers of all seven mutual funds.*

Questions

While *Financial Viewpoints* provides some solutions to the problem of visualizing information in 3D, it also raises some the following questions:

- The grid. How does it scale? What if there are not 7 but 20 funds, or 50 or 100?
- Although it is useful for disambiguating distance and scale, what does the grid mean? What do adjacencies and distances between different funds mean? Can the grid become a meaningful icon for itself from a distance?
- The walk-through/fly-through experience. What does it mean to move through numbers? How does this experience enhance our understanding of the information?
- The navigation. Navigation problems revealed that there is a conceptual confusion about whether this thing is an object we can grasp and move, or a space that is fixed that we move our bodies through. (It can be both, but the transitions must be very clear.)

Summary

There are many issues that *Financial Viewpoints* raises relative to design, interaction, and navigation in 3D. The research on perception in virtual space (chapter 3) and linguistic metaphor theory (chapter 4) has significantly improved my understanding of the conceptual models at work in this project and in other 3D information environments.

3

Theoretical Framework Part I: The Body in Space

"It is to the three-dimensional world that our organism is attuned, where it learns to test its anticipations against the flow of incoming stimuli, weeding out or confirming the predictable melodies of transformation that result from movement."

- E.H. Gombrich, *Art and Illusion*

3.1 Overview

This chapter presents an empirical analysis of virtual space through a number of illustrated studies categorized by *3D scale* and *point-of-view.* The purpose of these studies is to raise awareness about the presence of the body in space. The studies are intended to be neither exhaustive nor definitive. Their role is, rather, to map out the range of decisions "available" in 3D design, to better understand the phenomenological effect of these decisions on the viewer and, most importantly, to elucidate a process of observation and analysis that can be applied to specific problems of 3D design.

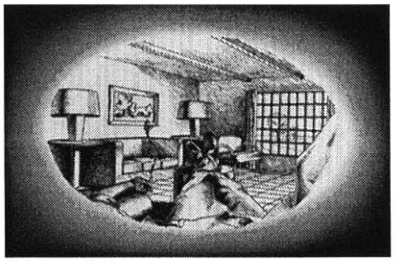


Figure 3.1 *"The ego as seen by the left eye," taken from Gibson's book* The Ecological Approach to Visual Perception.

My analysis is empirical, but it is supported by theories of perception that emphasize embodiment, in particular the work of J.J. Gibson on visual perception. Gibson's revision of earlier theories of visual perception was based on their emphasis on the connection solely between the eye and the brain. Alternatively, Gibson felt that "natural vision depends on the eyes in the head on a body supported by the ground, the brain being only the central organ of a complete visual system [Gibson, 79]." Figure 3.1, an image taken from *The Ecological Approach to Visual Perception*, illustrates the embodied nature of visual perception.

3.2 Introduction

To introduce this chapter, I will use an example from *Financial Viewpoints* and Yin Yin Wong's *NewsViews* that inspired much of this research. Both projects possessed the same curious navigation problem: at different distances from the information "object," the user's expectations about the navigation controls (e.g. rotate left, rotate right, rotate up, rotate down) *invert*. Specifically, if the user is far enough away from the object to perceive it as detached, or contained, the expectation for the ROTATE LEFT control, for example, is that the *object* will *rotate left*. (Figure 3.2) Conversely, if the user is close enough to the object to perceive it as a *space*, the expectation for the ROTATE LEFT control is that the *user* will *rotate left*, hence the space, or *object* will *rotate right*.(Figure 3.3)

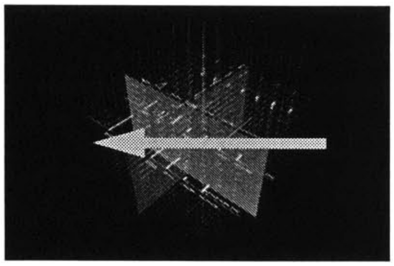


Figure 3.2 *"Object" view of Financial Viewpoints. The user's expectation for the control to ROTATE LEFT is that the* ***object will move left.***

Figure 3.3 *"Space" view of Financial Viewpoints. The user's expectation for the control to ROTATE LEFT is that the* ***object will move right****, and the user will move left.*

The significance of this observation was the fact that, although none of us had ever experienced, first-hand, an abstract news or financial space, we possessed expectations about how to navigate through such a space. These expectations were so strong, in fact, that although the programmed navigation controls remained *consistent* throughout the space, our expectations for their effect *altered* with our perceived position in the space.

This example highlights the simultaneous power and challenge of designing in 3D: our analogous experience in *physical space* affords us particular intuitions and expectations about how to perceive and navigate through *virtual space*. This thesis proposes to exploit our tendency to project our own bodies into virtual space in order to take advantage of the intuitions about navigation that accompany embodiment, and to use our understanding of the role of the body in space to make informed design decisions.

3.3 Navigation in 3D

A clearer understanding of 3D navigation provides an explanation for the inverted navigation control expectations identified in the example above. I have observed three basic types of navigation in 3D space that correspond to Gibson's three types of movement: "head turning relative to the body, limb movement relative to the body, and locomotion relative to the environment [Gibson, 79]." They are:

- point-of-view rotation,
- manipulation, and
- locomotion

With point-of-view rotation, the user imagines that she is moving her head up, down, left and right to get different views of the space. With manipulation, the user perceives she is moving an object in space, with her own hand or a tool that has become an extension of her hand. With locomotion navigation, the user perceives she is moving herself via her body (i.e. feet or imagined wings) or via some sort of mediating vehicle (i.e. a car, plane, spaceship, or magic carpet).

The example above illustrates that when we perceive ourselves to be *inside* an object in virtual space (i.e., when the boundaries of the object are no longer completely in view), it is most natural for the navigation controls to control our movements in the space (i.e., locomotion or point-of-view rotation mode). When we perceive ourselves to be *outside* of an object, however (i.e., when the boundaries of the object are completely in view), it is most natural for the navigation controls to control the movements of the object in the space, much like the idea of "direct manipulation" (i.e., manipulation mode). David Allport, Earl Rennison and I have done some experimentation with a gesture input device (developed by Allport) that automatically transitions between these locomotion and manipulation navigation modes based on a continuous evaluation of the user's position relative to other objects in the virtual space. (Figure 3.4) For more details on that work, refer to [Allport, 95].

Figure 3.4 *A view of Allport "flying" through virtual space with his "wings" gesture input device.*

3.4 Scale Studies

An interesting feature about the body in virtual space, is that its perceived size is not fixed. Furthermore, perceived size of the body appears to be dependent upon the perceived size of the environment. (Conversely, the perceived size of the environment appears to be dependent upon the perceived size of the body.) Mitchell writes, "For cyborgs, then, the border between interiority and exteriority is destabilized. Distinctions between self and other are open to reconstruction. Difference becomes provisional [Mitchell, 95]." The images in Table 1 illustrate this point. To the user, the size of the environment is related to her perception of the scale of objects in her visual field.

Table 1 shows the effect of a variety of scale relationships between one object and a viewer. The images are organized in 4 rows of objects and 4 columns of object-viewer relationships. The differences between the objects presented are scale-related. In the first row a cube is used to illustrate the

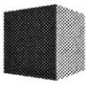
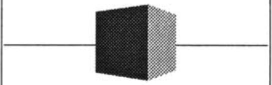
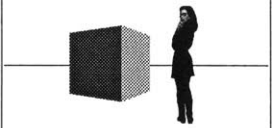
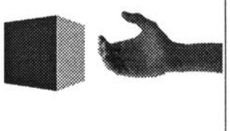
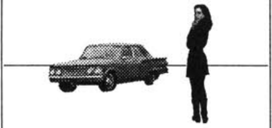
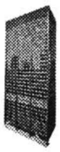
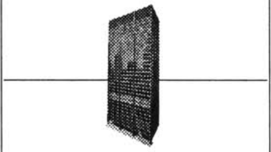
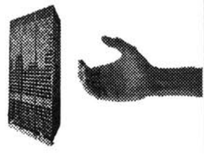
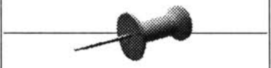
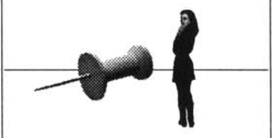
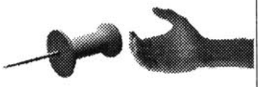
Object		Object with horizon	Object with horizon and scale figure	Object with hand
1 Abstract geometrical object	1.a 	1.b 	1.c 	1.d 
2 Human scaled object	2.a 	2.b 	2.c 	2.d 
3 Larger than human scaled object	3.a 	3.b 	3.c 	3.d 
4 Smaller than human scaled object	4.a 	4.b 	4.c 	4.d 

Table 1: Studies of scale of 1 object with respect to viewer

ambiguity of the scale of abstract geometrical forms. The objects in the other rows are less ambiguous in scale because they refer to objects we encounter in the physical world: cars, skyscrapers, and push pins.The 4 columns show the effect of a horizon, a scale figure and a hand on the perception of scale of these objects relative to the viewer.

Table 1 reveals some key issues about the perception of the scale of objects relative to our "bodies" in virtual space, as well as the perception of the scale of our "bodies" relative to objects in virtual space. For example, the effect of the scale figure in column 3 is that we tend to identify with (rather than objectify) images of the body in space (especially if they are images of our own body). The scales of the body images and the objects shown in images **I.c** and **2.c** appear consistent with our experience of the physical world, but what if they are not? How do we reconcile the two scales? The tendency in images **3.c** and **4.c** is to scale one object (here I refer to the body image as an object) up or down to match the scale of the other (i.e., the push pin is perceived to be very large or I, the viewer, am perceived to be very small).

Navigation and Scale

There is an interesting connection between navigation and scale. User expectations about 3D navigation controls appear to be dependent upon the perceived scale of the object/space in view with respect to the user. Specifically, I have observed that the user subconsciously generates her own expectations about the current mode of navigation based on her perceptions of the *scale* of what she sees on the computer screen relative to her own "body". If an object measures larger or even, perhaps, "heavier" than the user's body, the user tends to imagine that the object is *fixed* in space and, hence, *space defining* like a large piece of furniture, a wall partition, or a building from a distance. Interestingly enough, an object can be perceived in this way even if it references something very small and light in physical space. The horizon view of the pushpin and scale figure in image **4.c** makes the pushpin look as massive as a grand piano. The effect on navigation is that the user will tend to *move around* the object rather than tend to *pick it up* (i.e., the user will expect to use the *locomotion* rather than *manipulation* mode of navigation.) This effect also works in the reverse: in image I, the user will expect to pick up the skyscraper rather than move around it because the user's identity with the hand causes her to imagine herself to be much larger than the skyscraper.

These studies suggest some significant opportunities for the design of computational tools for navigation. For example, scale cues in an interactive 3D application can be evaluated to afford automatic transitions between different navigation modes. Current 3D applications and development environments (e.g., OpenGL and Inventor) only support one model of navigation at a time. Transitions between, for example, locomotion and manipulation have to be made manually by the user. Another useful navigation tool could be the automatic application and release of rotational constraints. When the user is in locomotion mode, in some 3D spaces it is desirable to constrain rotational movement in order to maintain the near horizontality of the "ground "plane. When the user is in manipulation mode, these rotational constraints could be released to reflect the complete freedom of movement associated with an object one holds in one's hand.

Figure 3.5.a *Two pieces of text with ambiguous scale relationship.*

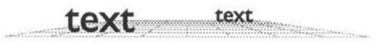


Figure 3.5.b *Two pieces of text of the same size placed on a 3D grid.*

Scale of objects relative to our bodies also has a communicative power that presents a great opportunity for designers of 3D spaces. We attach particular emotions to objects larger than us, such as intimidation and awe, and to objects smaller than us, such as empathy or unimportance. The spatial experience of the Vietnam Veterans Memorial in Washington, D.C. creates an emotional narrative that moves from insignificance to consequence, as the granite wall of dead soldiers' names moves from the height of our ankles to well above our heads.

Figure 3.5.c *Two pieces of text of different scales next to two figures scaled proportional to the text.*

Text and Scale

There are some 3D design issues specific to text and scale. Text possesses many of the abstract properties of geometry. Figures 3.5.b through 3.5.d reveal the ambiguity of the scale relationship between the two pieces of text shown in Figure 3.5.a. Differences in scale can be explained by differences in distance (Figure 3.5.b), differences in absolute size (Figure 3.5.d), or some combination of the two.

Figure 3.5.d *Two pieces of text of different scales next to two figures of the same scale.*

Text also has properties quite apart from geometry that relate to legibility. That is, text has a particular size range that can be viewed and read comfortable by the eye. Viewed outside of this range, text cannot be "read" in the conventional sense. It is either so large or so small that it is read as abstract forms.

Our relationship to text in the physical environment also has an effect on our reading of text in virtual space. Particular points of view on text can evoke "billboard-sized" text or "fine-print" text. I discuss points of view on text below.

3.5 Designing in 3D

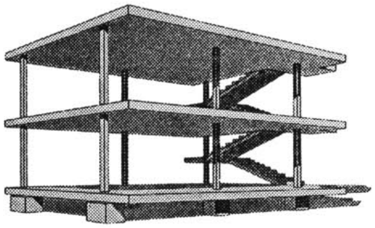


Figure 3.6 *Lines and planes as columns and slabs in Le Corbusier's 1914 design for the Domino House.*

Although the possible representations of 3D spaces using computer graphics are limitless, the number of graphical primitives and operations are fairly limited. Specifically, graphical information objects are made up of one or more of the following primitives:

- points
- lines
- planes (includes planar polygons)
- volumes (cubes, spheres, or other 3D models)
- text and textures (which are essentially planar)

Possible operations or attributes are:

- position (XYZ)
- orientation
- scale
- color (HSV or RGB)
- transparency
- lighting
- font type, if text

The studies documented in this chapter analyze the phenomenological effects of position, orientation, and scale on the view of simple graphical objects. Although significant, the effect of continuous movement and dynamic behavior of objects is not included in these studies.

3.6 Point of View Studies

These studies explore some of the significant effects of rotation (in perspective) on a plane or a piece of text (which is a particular kind of plane) relative to the viewer.

The chart on the following page is divided into three columns. Each of these

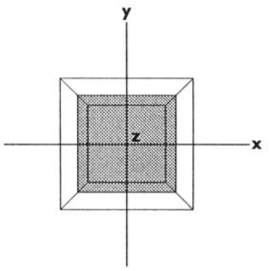
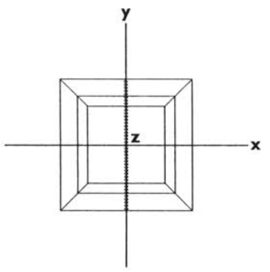
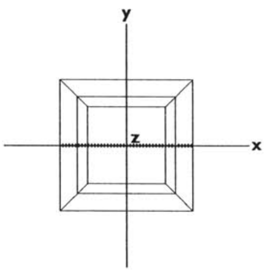
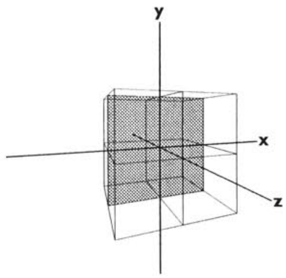
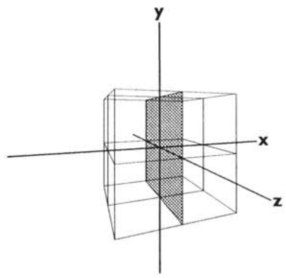
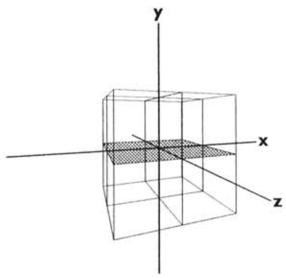
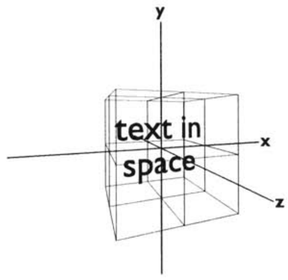
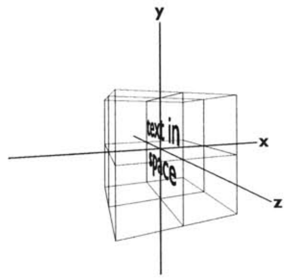
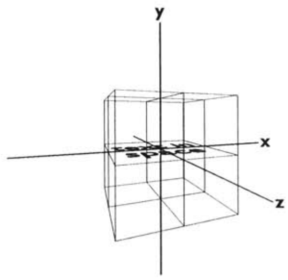
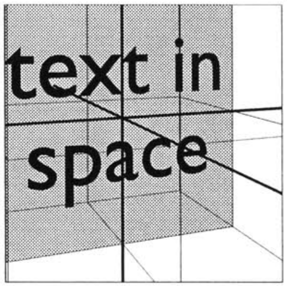
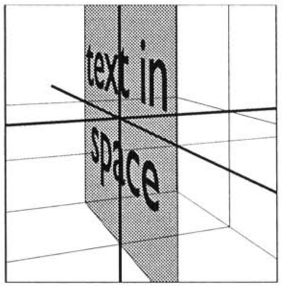
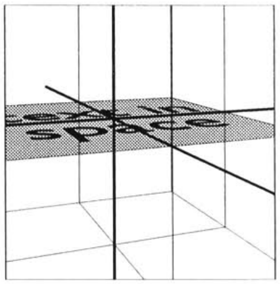
view	XY plane	YZ plane	XZ plane
1 viewer's gaze perpendicular to **XY** plane	1.a 	1.b 	1.c 
2 viewer's gaze almost perpendicular to **XY** plane and slightly above origin	2.a 	2.b 	2.c 
3 same view as above, with text	3.a 	3.b 	3.c 
4 same view as above, larger or nearer	4.a 	4.b 	4.c 

Table 2: Studies of 3 orientations of a 3D plane relative to a viewer

columns corresponds to a planar orientation parallel to one of the three Cartesian planes: the XY plane, the YZ plane, and the XZ plane. Rows **1** and **2** of the chart show perspective views of a plane parallel to the three Cartesian planes. In rows **2** through **4**, the viewer is positioned nearly perpendicular to the XY plane, and slightly above the origin.

Planes and Point of View

The first row of Table 2 represents a special position and orientation of the viewer with respect to the object. In this view, the viewer is facing exactly perpendicular to the XY plane, gazing along the Z axis and aligned with the origin.

Observe that without the bounding box, diagram **1.a** is spatially ambiguous. Because the plane is orthogonal to the frame, it could be read as both a plane in space, "orthogonal" to the viewer, or as a square on a 2D page. Diagrams **1.b** and **1.c** further illustrate the significance of the viewer's position relative to the object in row **1**. When the plane is parallel to both the YZ plane and the XZ plane, it becomes a line as wide as the plane is thick. The phenomenon of one shape suddenly becoming another shape, like a rectangle becoming a line, tends to be confusing in 2D, and demonstrates a key feature of 3D: the ability for the identity of an object to be maintained (in the mind of the viewer) despite significant changes in its visual form. This is possible because of the ability, in 3D, to view an object from multiple points of view.

The potential for a plane to become a line (of optional thickness) when viewed on its side was exploited in *Financial Viewpoints.* Because each of the template planes are only a pixel thick, they become nearly invisible at 90 degrees, allowing the viewer to see only one template plane, head-on, at a time.

Text and Point of View

Text in 3D (with no thickness) is essentially a plane with a biased orientation and scale. The diagrams in row **3** show text from the same view as the planes in row **2**. In 3D, a graphical text object is a special case of a plane. Diagram **3.a** shows text in its biased, or preferred, orientation: perpendicular to the gaze of the viewer. In this view, the biased orientation of the text plane is nearly parallel to the XY plane. Diagrams **3.b** and **3.c** show text oriented parallel to the YZ and XZ planes, respectively. The text is more difficult to read in these views because its biased orientation is nearly perpendicular, rather than parallel, to the gaze of the viewer.

3D text in virtual space has multiple "readings" that can express something unique to the viewer from different distances and different points of view. Specifically, if we assign a normal vector to each text plane, then the dot product of this normal with the (inverse) vector aligned with the gaze of the viewer can be used as a *measure of legibility.*

When the viewer's gaze is aligned with the normal of the text, legibility of the text is at its highest, and the dot product of the vectors is equal to 1. When the viewer's gaze is perpendicular to the normal of the text, legibility of the text is at its lowest, and the dot product of the vectors is equal to 0. A dot product of -1 occurs when the text appears reversed to the viewer. Negative dot products indicate that the viewer is *behind* the text.

$$M = \vec{A} \bullet -\vec{B}$$

where M is the measure of legibility, and A and B are normalized vectors

To address the relationship between legibility of text and scale, the dot product above can be scaled by a value that expresses the size of the text relative to the size of the display. (This value must take into account both font size and distance of the text from the viewer.)

$$M = F_V(S, F, D) \times (\vec{A} \bullet -\vec{B})$$

where F_V is a function of screen size (S), font size (F), and distance of text (D) from viewer

A measure of legibility between 0 and 1 expresses that the text can be "read" to some degree, either as text or as form. Albeit challenging, the opportunity exists for designers to make use of these viewpoint-dependent multiple readings of text.

Enclosure and Point of View

The orthogonal frame of the viewport represents a threshold across which an object can shift its perceived status from detached *object* to surrounding *space*. Diagrams **4.a, 4.b,** and **4.c** of Table 2 are "close-up" views of the planes and text shown in rows **2** and **3**. These views could be generated either by moving the viewer's position closer to the object, by increasing the scale of the object, or both. Regardless, the phenomenological effect of these views is suggestive of "enclosure". The orthogonal frame of the view (or computer display) represents a threshold across which the plane can shift perceived roles from *object* to *space*. When the edges of the plane are entirely in view, the plane reads as an object. When the edges of the plane are partially cut off by the frame, the plane appears *spatial*. Specifically, when the plane is rotated perpendicular to the XZ plane (90 degrees around either the X axis or the Z axis, as shown in diagrams **4.a** and **4.b**), the viewer tends to read it as a *wall*. When the plane is parallel to the XZ plane, the viewer tends to read it as a *floor* or *ceiling*, depending on the viewer's eye-level.The *scale* of this horizontal XZ plane also effects the viewer's perception of it. If it is much larger than the framed view, its reading shifts from *floor* to *ground*. If it is contained within the framed view, but neither far enough beneath the viewer's eye-level to be read as a floor, nor high enough above the viewer's eye-level to be read as a ceiling, this plane could be perceived as any type of horizontal surface one might encounter in the physical environment, such as a table, a step, or a shelf.

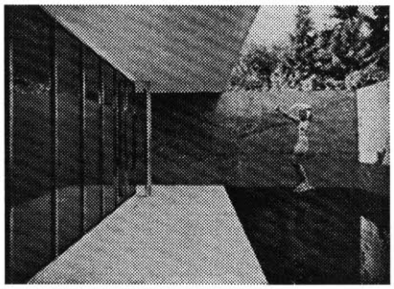


Figure 3.7 *In Mies van der Rohe's Barcelona Pavilion, floors, walls, ceilings, and even pools of water are treated similarly, as abstract geometrical planes.*

The ability of a 3D object (even one composed of abstract elements like text) to be inhabited like a space, and the ability of a space to be manipulated analytically like an object opens up novel possibilities for information design and interpretation. What could it mean, for example, for a viewer or user to feel she is *inside* an information object, or *outside*, *left*[1], *right*, *above*, or *below* it?

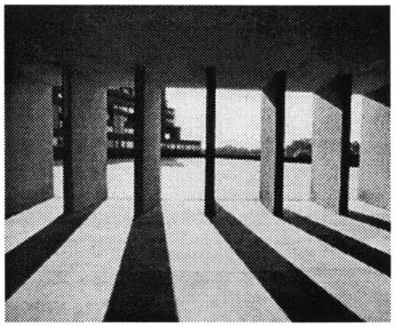


Figure 3.8 *The arcade of Aldo Rossi's Gallaratese housing complex is made up of a series of parallel planes.*

The effect of the physical environment on human thoughts, emotions, and actions is considerable (and the subject of Winifred Gallagher's book *The Power of Place*) [Gallagher, 94]. Physical space has a communicative power that has long been exploited by architects. Architects use 3D form (e.g. solid and transparent planes) to guide people through space (Figure 3.7); they create patterns of movement and stasis as well as direct views with the use of light and shadow. (Figure 3.8)

If virtual space has the potential, like physical space, to guide movement and

---

[1] The Russian Tea Room restaurant in New York City advertises that it is "to the *left* of Carnegie Hall."

direct views, how can we use our understanding of these spatial cues to design information environments?

3.7 Summary

This chapter presented an empirical analysis of virtual space through a number of illustrated studies categorized by *3D scale* and *point-of-view*. A general process of observation and analysis was demonstrated that can be applied to specific problems of 3D design.

4

Theoretical Framework Part 2
The Body in Information

4.1 Introduction

The purpose of the previous chapter was to show, by example, how an understanding of the presence of the body in virtual space can empower us as designers of interactive 3D information spaces.

An understanding of the effects of scale and point of view, however, can only solve part of the puzzle. How are we to determine, for example, whether a piece of demographic information is wall-like or floor-like? the size of an elevator or an electron? How, in other words, are we to make and evaluate design decisions in 3D space that relate to *specific* information?

The purpose of this chapter is to complete the puzzle of information in space. I will show how *metaphor theory* enables us to locate the body in a place more unexpected than virtual space: in the realm of information.

Metaphor

Understanding financial information does not appear to be similar to understanding the physical world. We understand the physical world by experiencing it: we look, we touch, we move around, and we relate things to our bodies [Johnson, 92].

Financial information, however, is abstract. We cannot literally see it, touch it, move though it, or relate it to our bodies.Yet we are able to somehow structure abstract ideas in such a way that we understand them and can store them in our minds. Linguistic metaphor theory claims that the way we experience the physical world through our bodies makes its way into the cognitive models we use to structure abstract ideas. Understanding is *embodied* in that our bodily experience directly influences the way we structure thought [Johnson, 92].

Metaphor is how we map the concrete cognitive structures or models in our minds to an abstract domain, like information. The problem of representing the abstract with the concrete is the problem of language. We encounter this problem every time we attempt to express ideas outside the realm of the physical world. In *Metaphors We Live By*, Lakoff and Johnson expose the way language allows us implicitly (and often sub-consciously) to refer to our physical and cultural experience in the world in order to express or understand abstract concepts or ideas. Lakoff and Johnson show that language is based on a conceptual system that is metaphorical in nature. They write: *"The essence of metaphor is understanding and experiencing one kind of thing in terms of another* [Lakoff, 80]."

Metaphor has been a popular source of inspiration for interface designers. The value of metaphor in the context of electronic media is to orient users in an initially new and characteristically abstract domain. Applying the concrete metaphor of the desktop, for example, to the relatively abstract operating system of the MacIntosh creates expectations and understanding for the user based on tangible concepts such as folders and documents.

Interface designers, however, have long relied upon a limited range of metaphors. Microsoft's *Windows* and Apple's *Desktop* are perhaps the most widely recognized interface metaphors in use today. While the application of metaphors like these in interface design has proven to be beneficial, most of the benefits are enjoyed early on in the life of the application. Typically once the user learns the conceptual mapping between the source and the target domains (i.e., the metaphor and the application), the value of the metaphor decreases. Furthermore, once the user is comfortable with the new domain (the application), the metaphor is often perceived as unnecessarily forcing a particular organization or structure on the information environment.

This research focuses on metaphors based on embodied cognitive models for the following reasons:

1. Body-related metaphors have a strong connection to *understanding*. Language provides evidence that understanding is structured by our bodily

experience in the physical world.

2. Body-related metaphors, because they refer to our ongoing experience in the physical world, can be extended and combined. Other metaphors (like the desktop metaphor) have limiting structures that inhibit extension and combination.
3. Body-related metaphors are inherently spatial because they relate to the way we interact in physical space. Our daily experience in physical space provides us with good intuitions about virtual space interaction via movement and object manipulation.

4.2 Embodied Cognitive Models

In the next five subsections I present a number of kinesthetic cognitive models that support a five-part approach to enabling understanding of information.These cognitive models encapsulate ideas put forth on metaphor theory by George Lakoff and Mark Johnson [Lakoff, 80; Lakoff, 87; Johnson, 92]. According to Lakoff, there are four types of cognitive models around which thought is structured:

1. Propositional
2. Image schematic
3. Metaphoric
4. Metonymic

Propositional models specify elements, their properties, and the relations among them (like the *desktop* and its relationship to *file folders*). Image schematic models specify schematic images that operate on a more conceptual level such as *trajectories* or *containers.* Metaphoric models are mappings from a propositional or image-schematic model in a source domain to an analogous structure in a target domain (like the mapping of the desktop model to a graphical user interface). Metonymic models involve the substitution of a part of a one of the above model types for the whole, or for another part of the model (e.g. "The White House refused to comment on the issue.") The first two cognitive models, propositional and image schematic, characterize concrete thought structures while the second two models characterize mental mappings of these concrete structures onto abstract thoughts.

The models and metaphors explicated in the following sections were used to make and evaluate design decisions in the *Millennium Project* which is discussed in chapter 5. My use of the pronouns *we* and *us* in the following sections refers to my collaboration with Earl Rennison on this project.

In Table 3, I have categorized a set of kinesthetic cognitive models. The first column of this table, labeled "body", identifies the body parts or features that I have associated with a group of cognitive models. Column 2 lists two to three cognitive models, each one in one of the four categories described above. Columns 3 and 4 provide language examples and a visual example to show the relationship between the group of cognitive models and the body.

Context

"I can figure it *out*."
"How did you get *into* computers?"
"Let's get to the *heart* of the matter."
"What are the *central* points?"

Context relates to body location. We experience our bodies both as containers of objects (e.g., internal organs) and as objects in containers (e.g., buildings). We experience our bodies as having centers (internal organs) and peripheries (skin, fingers and toes). We generally view the centers as more important than the peripheries.

The container schema models a fundamental and inescapable logic of 3D space: everything is either inside a container or out of it – P or not P. The process of categorization relies on image schemas that use the body as a reference. Categorization is central to understanding and plays a significant role in the information environment we created in the *Millennium Project.*

Understanding the different roles of objects in 3D virtual space has influenced our research in both the design of 3D information environments as well as the navigation and object manipulation within these environments. In the *Millennium Project* we introduced the idea of *context containers.* A context container encloses a collection of information objects from our database and gives meaning to the spatial relationships of objects with respect to the container, and with respect to other contained objects. An example context container could contain information objects on philosophy, painting, music, and architecture from Europe between 1909 and 1911. The information objects in this context are automatically assigned meaningful locations and

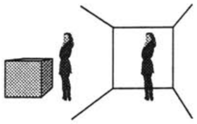
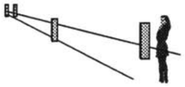
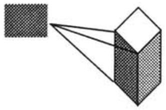
Body	Cognitive Models	Language Examples	Visual Examples	Explanations
Body Location [Context]	the CONTAINER image schema the CENTER-PERIPHERY image schema the IMPORTANT IS CENTRAL metaphor	"I can figure it *out*." "How did you get *into* computers?" "Let's get to the *heart* of the matter." "What are the *central* points?"		We experience our bodies both as containers of objects (e.g., internal organs) and as objects in containers (e.g., buildings). We experience our bodies as having centers (internal organs) and peripheries (fingers and toes). We generally view the centers as more important than the peripheries.
Body Movement [Experience]	the SOURCE-PATH-GOAL image schema the MIND IS A BODY MOVING IN SPACE metaphor	"I'm *approaching* an understanding of the situation." "We've got *a long way to go* in our studies." "*Follow the path* of the argument."		Our movement through space takes us from starting points (sources) to ending points (goals) along paths. There may be obstacles along the paths or diversions that may take us on new paths.
Body Size [Scale Relations]	the SCALE image schema the IMPORTANT IS BIG metaphor	"I'm feeling *up* today." "The chances are *higher* today that there will be *low* humidity." "This is a *big* opportunity for me."		We experience our world in terms of qualitative and quantitative relationships between objects and events (e.g., more, less, and the same).
Eyes [Perception]	the SEEING AS UNDERSTANDING metaphor the MIND'S EYE metaphor	"I *see* what you mean." "It's *clear* to me now." "I need to get a new *point of view* on this issue and *focus* on what is essential." "Let's keep things in *perspective*."		Vision, our primary source of information about the world, plays a crucial role in our acquisition of knowledge. Mental attention is typically connected to the gaze of the viewer.
Hands [Analysis]	the GRASPING AS UNDERSTANDING metaphor the TOUCHING AS THINKING ABOUT metaphor	"I *get* it." "I've *reached* an understanding." "Let's *examine* the issue further." "*Let go* of the past."		We use our hands to examine physical objects, to turn them around in order to see all of their sides. We allow that our eyes may sometimes fool us, but if we can touch things, we feel confident in our ability to understand them.

Table 3: Kinesthetic Cognitive Models

sizes based on geographical location, time, and categorical similarity. We can move through this container of philosophy, painting, music, and architecture objects as we might move through a museum gallery. We are able to pick up objects to analyze and examine from different points of view. If we want to explore an object further, we can enter the object as a container of new and more detailed information objects. Conversely, if we move well outside of the original container of objects (from Europe between 1909 and 1911), we can pick up the container itself to examine the distribution of objects within it over time, category, and location.

Experience

"I'm *approaching* an understanding of the situation."
"We've got *a long way to go* in our studies."
"Follow the *path* of the argument."

Experience relates to body movement. Our movement through space takes us from starting points (*sources*) to ending points (*goals*), along *paths*. There may be obstacles along the paths or diversions that may take us on new paths.

Movement between different contexts is characteristic of the understanding process. In the *Millennium Project* we explored the idea of *transitional spaces*, spaces that literally transition us from one context container (a source context) to another (a target context). Transitional spaces are like corridors between rooms, or narrow urban streets between piazzas. These pathways reveal structural connections between contexts and avoid the disorienting context shifts of hypertext environments. In addition to maintaining context by smooth transitions, transitional spaces allow us to fork off the path to our target context. Transitional spaces invite us to pursue other paths, doorways, or narrow streets, to other contexts [Lynch, 60].

Scale Relations

"I'm feeling *up* today."
"The chances are *higher* today that there will be *low* humidity."
"This is a *big* opportunity for me."

We understand our world in terms of qualitative and quantitative relationships between objects and events (e.g. *more*, *less*, and *the same*). The scale schema has helped us make design decisions about the relative sizes and locations of information objects in our virtual spaces.

We understand scale most readily when we relate things to our bodies. It is much easier for us to comprehend the scale difference between X and Y as roughly equivalent to the height difference between a 12-story building and a paper clip, than as a roughly 2000-to-1 ratio. Most of the objects in our physical environment are familiar to us and have identifiable human scales that help us understand new and unfamiliar objects that we encounter. We know (or at least think we know) the size of a chair, for example, from any distance but do not know the size of a cube from any distance. Further, we can deduce the distance of a chair because we know its size.

Graphical scale is used to represent multi-level categorical information in the *Millennium Project.* As a user moves through different categories, new contexts are generated of a size that reflects the *scale* of the category. In the *Millennium Project*, for example, the context enclosing Wittgenstein is contained within and much smaller than the context enclosing Philosophy.

Perception

"I see what you mean."
"It's *clear* to me now."
"I need to get a new *point of view* on this issue and *focus* on what is essential."
"Let's keep things in *perspective*."

Vision, our primary source of information about the world, plays a crucial role in our acquisition of knowledge. Mental attention is metaphorically connected to the gaze of the viewer. [Lakoff, 87]

In the *Millennium Project*, we make use of transparency, perspective, and 3D point of view. Spatial perception, of course, is integrally tied to movement [Arnheim, 54]. As we move around a space, or within a container, we see objects from different perspectives. When we pick up an object, we rotate it in different directions in order to view all of its sides. Both activities, which involve movement of ourselves within a space, or movement of an object, enable us to gain a more thorough understanding of our environment and the objects within it. Information objects in the Millennium Project are designed to be viewed from several points of view and against several context container backgrounds. The use of 3D point of view in my previous work is described in chapter 2 and [Strausfeld, 95b].

Analysis

"I *get* it."
"I've *reached* an understanding."
"Let's *examine* the issue further."
"*Let go* of the past."

We use our hands to examine physical objects, to turn them around in order to see all of their sides. We allow that our eyes may sometimes fool us, but if we can touch things, we feel confident in our ability to understand them.

In addition to flying through information environments, we allow for direct manipulation of information objects as well as context containers in the Millennium Project. Movement through space alone is not sufficient for understanding spatialized information. In our context containers, we are able to pick up objects to examine as well as alter the container itself in order to redistribute the objects contained within it. For example, if we are inside a context container of "philosophy in Vienna between 1909 and 1911", we can pick up a Loos object to analyze, or we can stretch the timeline wall of the container to broaden the time span we are examining.

4.3 Abstraction

Muriel Cooper emphasized the "power of abstraction" as an alternative to metaphor in a 1994 interview [Abrams, 94]. Abstraction can also be used as an effective tool for visual communication or expression because it provides the viewer a freedom of interpretation that metaphor does not. Abstraction is the opposite of metaphor in that it is about defying reference to anything concrete. Abstract artists since Kandinsky have attempted to achieve complete non-referentiality through abstraction. Although many would argue that total non-referentiality is impossible, many artists were successful in achieving such a high degree of abstraction that their work has multiple references or possible interpretations.

Ambiguity is the by-product of abstraction and the reason why abstraction is appealing to many artists. Ambiguity requires the viewer's active "reading" of the image; it makes the experience of art interactive. Ambiguity (via abstraction) in information design is a double edged sword. Interaction is desirable, but lack of clarity is not.

4.4 Montage

Montage is a pictorial technique that lies in between abstraction and metaphor. Photographic fragments that reference the physical world and a modernist layout style make montage an *embodied form of abstraction.*

Montage makes it possible for the 2D space of the page to appear inhabitable, as if by the body of the viewer. Images of the body, or parts of the body with which the viewer can identify, work to pull the viewer into the space of the page. The reading of the page oscillates between a flat surface and a deep void. (Figure 4.1)

The power of montage, it seems, is its ability to engender a continuous spatial reading of fragmented elements. Orthogonally cropped photographs arranged on a page are perceived as openings, like windows, into separate realities or spaces. Masked photographs (photographs with the backgrounds clipped out) arranged on a page appear to occupy a singular reality or space. (The image in Figure 4.2 is from Voyager's CD-ROM of *The Society of Mind* shows Marvin Minsky (thanks to blue screen video) occupying the same space as his text and diagrams.

Figure 4.1 *An example of montage that shows the combination of photographic fragments and a modernist layout style.*

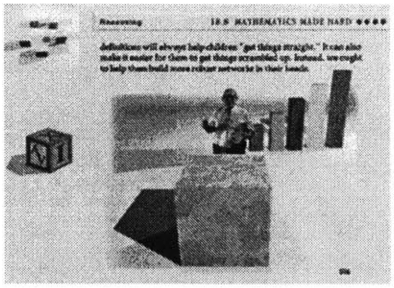


Figure 4.2 *Montage is used in this SOCIETY OF MIND CD-ROM to pull readers into the space of the book.*

5

Application
The Millennium Project

5.1 Background

The *Millennium Project* was done jointly with fellow Visible Language Workshop graduate student, Earl Rennison. The idea for the project was the result of a conversation between Earl and myself about the year 1912 that took place in front of the painting *Nude Descending the Staircase* in the Duchamp gallery of the Philadelphia Museum of Art. The essence of that conversation was that there was a shared interest in how the events (political, philosophical, scientific, musical, literary, as well as art historical) leading up to the birth of abstract painting in France (Cubism), Italy (Futurism), Germany (Die Brucke,) the Netherlands (De Stijl,) and Russia (Rayonism and Suprematism) related to one another.

Reflection on turn-of-the-century world events from nearly one hundred years ago inspired projection on our upcoming turn-of-the-millennium. The *Millennium Project* was conceived as an attempt for us to understand, in a new way, the connections between events from our past that we have previously learned about primarily in isolation.

5.2 Introduction

This chapter describes a conceptual and computational approach for enabling understanding of a large, multidimensional set of information. The goal of the *Millennium Project* is to provide a knowledge seeker the ability to move through virtual time and space to explore and discover the connections between artifacts of philosophy, painting, music, literature, science, and political events of a pivotal time in world history: the years from 1906 to 1918. This virtual space continually constructs and reconstructs itself based on the knowledge seeker's movements through and within it, much like the process of moving through the conceptual spaces of our minds as we construct meaning.

In this chapter I describe a computational process that Earl Rennison and I have developed to enable dynamic exploration of information based on the theoretical framework described in the previous section, and on the approach explored for structuring information in Earl's *Galaxy of News* system [Rennison, 94]. There are two primary objectives of our computational process: 1) to compute conceptual structures that describe information relationships automatically, and 2) to present the conceptual structures to a user dynamically in such as way that enhances the user's understanding of the information.

Although my research has focused primarily on the second objective, I will discuss the project as a whole, summarizing aspects of the project done by Earl, and describing my contribution in more detail.

In the *Millennium Project*, we have developed a system that automatically analyzes a corpus of information to derive conceptual structures that aid us in understanding the relationships between information objects that represent concepts spanning both space and time. These conceptual structures include categorical structures, hierarchical structures, relational structures, radial structures, linear quantity scales, and foreground-background structures. Each of these structures helps us understand the relationships between information elements. Table 4 presents an overview of a conceptual and computational framework we use to project information organized in conceptual structures into virtual information spaces. This table shows how conceptual structures relate to the five information categories proposed by Richard Saul Wurman [Wurman, 89]. These include:

- Location
- Alphabet position
- Time
- Category
- Hierarchy[1].

In addition, Table 4 shows the correspondence between conceptual struc-

---

[1] Wurman refers to hierarchy as the relative size and position of things. This differs from categorical hierarchies.

Conceptual Structure	Information Organization Structure	Computational Structure	Corresponding Image Schema	Metaphorical Mapping	Virtual Space Mapping
Categorical Structure	Categorical Temporal (i.e. periods)	ARN/Graph	CONTAINER	CONTEXTUAL as INSIDE	Graphical objects as containers that either define space or occupy space
Hierarchical Structure	Hierarchical	Acyclic directed graph	PART-WHOLE UP-DOWN SCALE	GENERAL as WHOLE ABSTRACT as HIGHER IMPORTANT as BIG	Graphical objects as containers inside other containers Graphical objects scaled relative to importance
Relational Structure	Categorical Temporal (cause-effect) Location (geographical)	ARN TARN LARN	LINK	RELATED as CONNECTED SIMILAR as CLOSE	Graphical objects attached Graphical objects positioned relative to one another (as using MDS)
Radial Structure	Categorical (fuzzy)	Fuzzy cluster graphs	CENTER-PERIPHERY	IMPORTANT as CENTRAL	Spherical, axial and hyperbolic spaces
Linear Quantity Scales	Hierarchical Alphabetical	Sorted list	UP-DOWN LINEAR ORDER	MORE as UP	Graphical objects viewed sequentially
Foreground-background Structure	Temporal Alphabetical	Sorted list	FRONT-BACK	FUTURE as IN FRONT	Graphical objects viewed sequentially

Table 4: Projection from Conceptual Structures into Virtual Information Spaces

tures and image schemas (as introduced in the previous chapter), between conceptual structures and metaphorical mappings, and presents the computational structures we use to represent the conceptual structures.

We have also developed methods for presenting the information to the user dynamically through "visual discourse", a process that interactively unfolds over time [Rennison, 95]. There are two important aspects of visual discourse: 1) how the conceptual structures are mapped to virtual space such that they convey meaning, and 2) how the computer interprets user interaction.

5.3 Overview of Computational Process

Our computational process consists of the following steps:

1. Analyzing the information-base to construct a representation of the relationships between the information objects, namely analyzing the underlying *structure* of the information-base
2. Presenting the information relationships in a 3D virtual space that provides a particular contextual view on the information, and
3. Interpreting user movements and actions in the 3D virtual space as continuous queries for additional information, and reconstructing the virtual space to show the relationships between the objects returned from the query. The relationships between these steps and important subprocesses are illustrated in Figure 5.1. This chapter is divided into three sections which correspond to the diagram below: information structuring, space construction, and user interaction interpretation.

5.4 Information Structuring

This section is divided into the following sections which correspond to the diagram above: database, structure, information object filtering, extracting key features, constructing relationship representation, and computing conceptual structures. Earl Rennison developed this aspect of the project so the reader should consult his Masters Thesis for algorithms and more specific descriptions of the techniques. I present summaries of Earl's work here to maintain the context of the project as a whole and because the design of the projection from conceptual structures to virtual information spaces (as presented in Table 2) was done collaboratively.

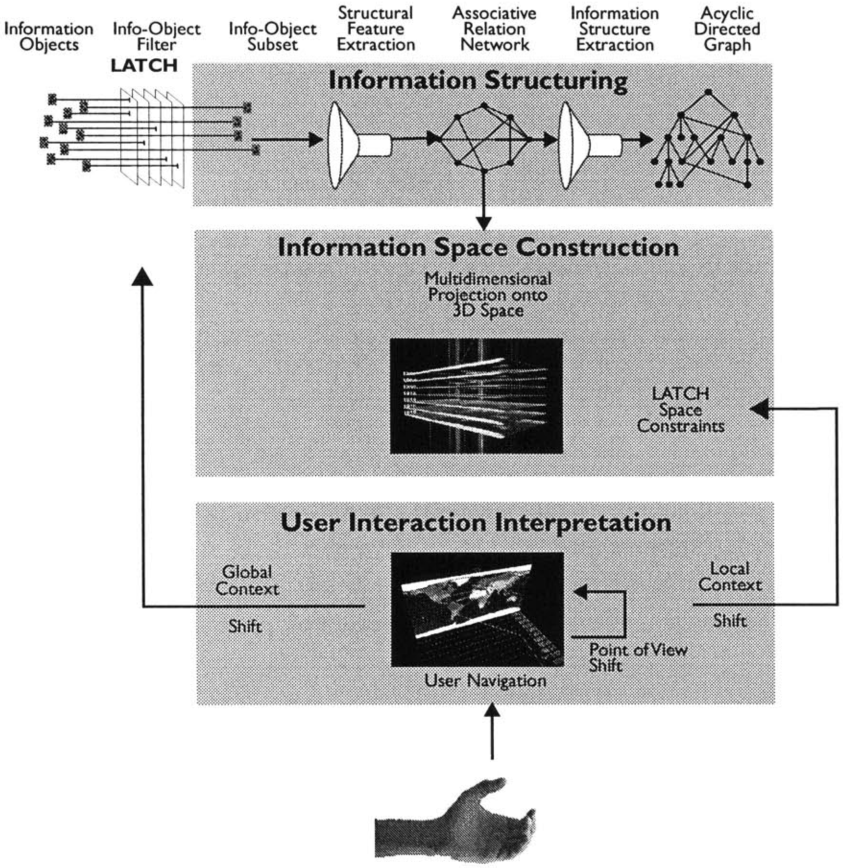


Figure 5.1 The Computational Process of Visual Discourse.

Database[1]

Our database consists of a set information objects in the form of text files that describe events, artifacts, people and ideas pertaining to the years 1906-1918. They are displayed as 3D text objects that sometimes include images, video clips, or sounds. Each information object contains annotations that describe its properties. These basic properties include:

1. Date
2. Location
3. Associations (keywords and other information objects), and
4. Cause-effect relationships.

Information object files also contain display information. Some artifact

---

[1] The database for the Millennium Project was compiled by Amy Schneider and Vivek Palan from both printed and on-line sources.

objects, such as those describing paintings, contain links to image files and size information of the actual artifacts. People objects also contain links to image files of portraits (with clipping paths to separate the figure from the background), and (estimated) heights so that all portraits can be scaled consistently. A sample information object file is shown in. Figure 5.2.

Structure

This section describes our approach to structuring our information-base to enable people to understand the complex relationships among information objects. We use a process for analyzing information objects and deriving structures that convey relationships between the information elements derived by Earl and described in detail in his thesis. Information elements in this definition include the original information objects as well as features that are extracted from the information objects (such as keywords). We use the extracted features to analyze the structure of the information objects (we describe this process below). The structure analysis process yields structures that correlate to cognitive structures such as categories, hierarchical structures, relational structures, and radial structures [Lakoff, 87]. These structures will in turn be used in the process of mapping the structural relations onto a visual space that is presented to the user (as described in the space construction section below). In addition, these conceptual structures aid the user in navigating through the virtual information spaces and enable understanding of the relationships between information objects describing events and artifacts that span place and time.

As illustrated in Figure 5.1, the conceptual structures are derived through the following process:

1. Filtering the original set of information objects to a reduced subset (via a LATCH filter, optional)
2. Extracting key features from the reduced set of information objects (e.g. keywords)
3. Constructing a computational representation that captures the structural relationships between extracted features and the underlying information objects (e.g. Associative Relation Network, referred to as ARN)
4. Processing the structural relationship representation to extract computational structures that correspond to conceptual structures (e.g. Acyclic

```
<ODFile 0.9>
<ObjType people>
<ObjName `alma-mahler.html'>
<Annotator (Lisa Strausfeld, Earl Rennison)>
<Author `'>
<Location (`Vienna, Austria', `New York, New York, USA')>
<Date (`Aug. 31, 1879', `Dec. 11, 1964')>
<Source `Britannica Online'>
<ImageFile ‘alma-mahler.rgb’>
<PersonHeight ‘5-5’>
<!-- Association Sets that describe this object -->
<AssociationSet Subjects ((music, art, piano, writer),
   (woman, marriage, wife, divorce, relationships, affairs, love),
   (Mahler Symphony No. 6, Mahler Symphony No. 8, The Tempest
   Wozzeck,And the Bridge Is Love),
   (Gustav Mahler, Oskar Kokoschka, Gustav Klimt, Walter Gropius,
   Franz Werfel, Arnold Schoenberg, Gerhart Hauptmann,
   Enrico Caruso, Alban Berg)) >
<AssociationSet Influenced (Gustav Mahler, Oskar Kokoschka,
   Gustav Klimt, Walter Gropius, Franz Werfel) >
<TITLE>Alma Mahler</TITLE>
<H1> Alma Mahler </H1>
(b. Aug. 31, 1879, Vienna, Austria-Hungary--d. Dec. 11, 1964, New
York, N.Y.,U.S.) <p>
Alma Mahler (also known as Alma Maria Schindler, Alma Gropius,
and Alma Werfel) was wife of Gustav Mahler, known for her
relationships with celebrated men. <p>
The daughter of the painter Emil Schindler, Alma grew up
surrounded by art and artists. She studied art and became friends
with the painter Gustav Klimt, who made several portraits of her.
Her primary interest, however, was in music: she was a gifted
pianist and studied musical composition with Alexander von
Zemlinsky. <p>
In 1902 she married Gustav Mahler, who at first discouraged her
from composing; he is said to have changed his mind after hearing
her songs. Mahler left a musical portrait of her in the first
movement of his Symphony No. 6, and he dedicated Symphony No. 8
to her. After his death in 1911 Alma had an affair with Oskar
Kokoschka, who painted her many times, most notably in "The
Tempest" (1914; "Die Windsbraut"). In 1915 she married the
architect Walter Gropius; they were divorced after World War I.
She married the writer Franz Werfel in 1929. In the late 1930s
the Werfels left Nazi Germany, eventually settling in the United
States. <p>
During her lifetime Alma Mahler became friends with numerous
celebrated artists, including the composer Arnold Schoenberg, the
writer Gerhart Hauptmann, and the singer Enrico Caruso. The
composer Alban Berg dedicated his opera Wozzeck (1921) to her. <p>
Alma Mahler published two collections of Gustav Mahler's letters
as well as her memoirs, And the Bridge Is Love (1958). She also
published a number of songs. <p>
```

Figure 5.2 Example Information Object File.

Directed Graph).

We describe each of these steps in the following subsections.

Information Object Filtering

The first step of the structure analysis process is to filter the original set of objects to a reduced set. This essentially establishes the initial or global context for a discourse. This filtering process is based on an initial condition specified by the user. For example, "Let's start will information that pertains to the geographical location of Vienna, Austria, during the period from 1911 to 1912, that falls into the categories of painting and abstraction." This sentence formulates a query or filter that screens information objects to derive a subset of objects. Queries for information objects are either made explicitly, via a text entry mechanism such as a dialog box, or through implicit interaction within an information space. Implicit information queries, which are based on users' movements in the information space, are described in more detail in the *User Interaction Interpretation* section below.

In the *Millennium Project*, we have defined a filtering process based on Richard Wurman's five methods for organizing information, as described above. We call our initial filter a "LATCH Filter." In this initial stage, objects are passed through a LATCH filter to establish the initial set of information objects.

It is also important to note that this filtering stage is optional. If the user does not specify an initial condition, the entire database is used as an initial context and the following process continues from there.

Extracting Key Features

The second stage of the analysis process is to extract key features from the information objects. These features include such information as the dates/duration that an event occurred, location an event occurred, and sets of symbols that describe the information object (refer to Figure 4.4). The symbols in this case refer to elements such as nouns, noun phrases, verbs, and verb phrases that describe the subjects, actions, and objects of the information context. They may also include constructs such as Universal Record Locators (URLs) and names.

The features fall into two categories: general properties and structural relations. General properties include information such as size, date/time, location, and so forth. The general properties of the information objects vary according to the type of object. For example, information objects that pertain to artifacts may contain a size of the artifact, date produced, location produced, and who created it. Information objects that pertain to events would not include a size (unless some conceptual size can be specified), the date may be specified as a duration, the location may be specified as a region that may change over time, etc. Structural information consists of sets of symbols that indirectly bind an information object to other related objects.

For details on symbol extraction techniques, please refer to Earl's thesis.

Constructing Relationship Representation

Once we have extracted important features from the documents, we use these features to construct a representation that captures the *emergent relationships* between the information objects. A key element of our research is to find emergent structural properties that are not globally or explicitly defined, but rather emerge from the amalgamated properties of the individual objects. Hence, we do not impose a global structure on the information spaces; they are derived automatically from the contents of the information-bases through this bottom-up structuring process.

In the *Millennium Project*, we specifically use associative relations that define co-occurrences of symbols as the basis for our structural representation [Rennison, 94]. In addition, we also use temporal-causal relationships, and geographical and absolute temporal parameters (as specified by the authors of the information objects) to build a representation of the underlying structure. As described above, each information object can contain a set of dates, a set of locations, and associated sets of symbols (Association-Sets). When these sets of symbols, dates, and locations are inserted into the core representation they strengthen weights between the symbols, dates and locations.

The main element of our representation is an Associative Relation Network (ARN) [Rennison, 94]. An ARN captures the relationships between symbols contained within information objects. The relationships between symbols contained in an ARN define the relationships between information objects. An ARN maintains weighted relationships between symbols contained in the network, as well as the relationships between symbols and the information objects with which they are associated.

Each symbol in the representation has a reference to all the locations and times that the symbol occurred as defined by an information object. Likewise, each location and time has a reference to associated symbols, and back to the information objects that contain the location or time. The locations are also stored in a geographic database that facilitates quick filtering and searching of either symbols or information objects. Times are stored in a temporal database that facilitates quick filtering and searching for related symbols and information objects.

The primary utility of this representation is the ability to compute probability, similarity, and distance measures between symbols and information objects. These measures are used in computing categorical classifications, fuzzy clusters, hierarchical structures and sorted lists as described in Table 4. The complex representations described above are dynamically processed to extract these structural relationships that are implicitly maintained by the representation. This process is discussed in the next section.

Computing Conceptual Structures

The most important step of the structuring process is deriving computational structures that correspond to conceptual structures and implicitly define structural relationships between information elements. We specifically compute the following computational structures:

- *graph* where each node in the graph corresponds to a category[1] and linked nodes correspond to related symbolic categories
- *acyclic directed graphs* where each node in the graph corresponds to a symbolic category and linked nodes correspond to symbolic sub-categories
- *fuzzy cluster graphs* where each node in the graph corresponds to a symbolic category and linked nodes correspond to related symbolic categories such that the node is the central theme (as in a conceptual radial structure)
- *sorted lists* where each node represents a place in some linearly ordered

---

[1] Note that in some cases the nodes may correspond to times, locations or the information objects depending upon the type of conceptual or information structure we are generating.

sequence or scale.

For descriptions of how these structures are computed, refer to Earl's thesis.

The information hierarchy resulting from this process is used to aid the user in navigating through information structures. The result of the computational processes described above is a set of computational structures that map to conceptual structures. In the next section, we describe how these computational structures are used to construct spaces that reflect the underlying conceptual meaning.

5.5 Information Space Construction

The presentation aspect of the Visual Discourse process consists of projecting the multi-dimensional structural model into a three dimensional visualization. Because of the high dimensionality of the underlying space (a direct correlation to the number of features extracted from the information objects), it is not possible, or at least not meaningfully intelligible, to project the entire underlying space directly into a 3D representation. The construction of the projection, therefore, must be carefully considered. The projection should be a direct representation of the cognitive structures derived from the information objects. Our objective is to generate dynamic virtual spaces that correspond to the mental spaces we continually construct during natural language exchanges.

The next three sections describe how we construct *contexts*, *objects*, and paths through the information called *threads*.

Contexts

We have defined a model and process for projecting the structural information into a 3D space. The process is dependent upon the type of view, or the conceptual viewpoint, on the information for a given space. Currently, we have parameterized the types of spaces that can be generated according to location, alphabetical position (though the use of this constraint is limited), time (*absolute*, e.g. at time T, and *relative*, e.g. before, after), category, and hierarchy, or as Wurman terms LATCH [Wurman, 89]. These parameters may be specified individually, or by combinations. For example, a space can be generated to illustrate the temporal relationships between information elements (which may include combinations of the original information objects, and features extracted from the information objects). Or, a temporal relationship may be combined with a geographical relationship. Specification of these parameters essentially define the *context* in which the information elements are positioned in space. Some particularly meaningful contexts include the following:

1. Geographical
2. Temporal
3. Categorical
4. Geographical-Temporal
5. Categorical-Temporal (absolute)
6. Categorical-Temporal (relative)[1]
7. Categorical-Geographical
8. Categorical-Geographical-Temporal

Context	**Geographical**	**Temporal**	**Categorical**	**Geographical-Temporal**
Container shape	sphere	line	radial fractal tree	box
Landmarks	locations	dates	symbols [e.g. *painting* or *flight*]	significant objects [to this context]
Edges	the limits of the earth (represented as a sphere)	earliest and latest dates of this context	unbounded	-180 Lat, -90 Lon, 180 Lat, 90 Lon and earliest and latest dates of context
Scale range	fixed	fixed	defined by depth of symbols in current context	fixed
Object XYZ position	X = R sin(Lon) • cos(Lat) Y = R cos(Lon) • cos(lLat) Z = R sin(Lat)	X = 0 Y = 0 Z = date	X and Y determined by Multi-dimensional Scaling (MDS) Z variable	X = Lon Y = Lat Z = date
Paths/Threads	symbol date	symbol location	?	symbol date location

Table 5: Contexts

The multidimensional structural representation of our information-base

---

[1] This in effect shows causal relationships.

allows our system to dynamically generate meaningful sets of information objects that adapt to our continuous queries, as expressed by our continuous movements in the information space. In order to explore and interact with these information sets dynamically, we have to display them in such a way that invites investigation and allows for intuitive interaction. To this end, a 3D space builder automatically constructs information *contexts* from a list of information objects and a list of extracted features (such as keywords) which are also displayed as graphical objects. An information context is displayed as an enclosure that contains the set of information and feature objects.

Table 5 presents four of the contexts we have built: Geographical, Temporal, Categorical, and Geographical-Temporal. (These contexts and others are described in the subsections that follow.) For each context, Table 5 shows the following: *container shape*, *landmarks*, *edges*, *scale range*, *object XYZ position*, and paths or *threads*. *Landmarks* are significant orientation objects for navigation, and *edges* define the limits of the context container. The method for assigning 3D positions to the objects contained in each context is expressed by the *object XYZ position*. More information about how objects are displayed is provided below in the *Objects* section. *Threads* are particular pathways through the context that connect a list of information objects. They are also described in more detail below in the *Threads* section.

Geographical Context: Figure 5.3 shows context 1: Geographical. This context allows the viewer to query by geographic location through the manipulation of a globe. Locations, such as city and country names provide the primary entry points, or *landmarks*, for this context. Once the desired location is centered, the viewer can move in to access all information objects from that particular location.

Temporal Context: The Temporal context of the *Millennium Project* is organized as a simple timeline where dates provide the primary entry points, or *landmarks*, to the information. The representation for this context is based on the TIME is a PATH metaphor, where the PAST is BEHIND and the FUTURE is FORWARD. Robin Kulberg has explored other representations of timelines in 3D in [Kulberg, 95].

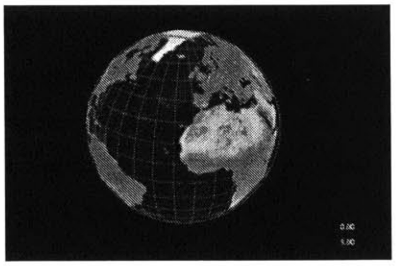


Figure 5.3 *The first context of the Millennium Project presented to the user is GEOGRAPHICAL, represented by a globe.*

Categorical Context: Most of the work on categorical contexts in the *Mil-*

lennium Project was done by Earl Rennison. A categorical context represents a category (expressed computationally as a *symbol*), its subcategories and the information objects associated with the category. The design of categorical spaces is more challenging than geographical or temporal spaces because they are typically higher in dimension. (The entire database of the *Millennium Project* is about 1500 dimensions.) Michael Benedikt has proposed the "round-robin" approach for swapping these higher dimensions among the 5 (or so) dimensions we can represent with 3D graphics [Benedikt, 91]. In the *Millennium Project*, we use a projection technique developed by Earl Rennison in *Galaxy of News*. In that project, about 1000 dimensions or categories of news were projected into 52 at the highest or most abstract level and displayed as navigable keywords. As the user approaches one of these keywords, the space unfolds and more lower level keywords are revealed. This process continues until the information objects themselves (news articles) are revealed.

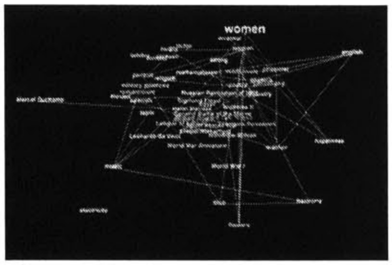


Figure 5.4 *View of a CATEGORICAL context. from a distance. Keywords provide landmarks to the information.*

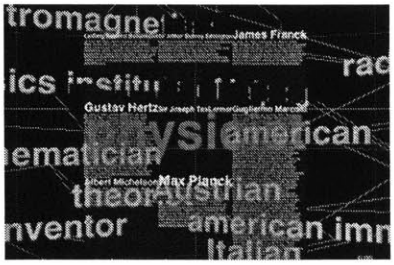


Figure 5.5 *View of a CATEGORICAL context of information pertaining to PHYSICS.*

The *acyclic directed graph* described in the previous section on Information Structuring is the computational representation of the space we represent as a categorical context. The difference between the categorical context of the *Millennium Project* and the space of the *Galaxy of News* is that our space is unbounded, fully 3-dimensional, and has a shape that can be viewed when the viewer moves outside of it. Figure 5.4 and Figure 5.5 show views of categorical contexts generated by Rennison.

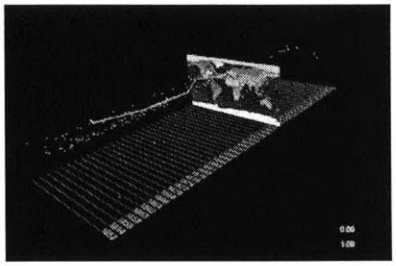


Figure 5.6 *The GEOGRAPHCIAL-TEMPORAL context container is a box with Longitude, Latitude, and time as its XYZ dimensions, respectively.*

Geographical-Temporal Context: In this context, the X-axis corresponds to Longitude, the Y-axis to Latitude, and the Z-axis to time. The result is a box-shaped container as shown in Figure 5.6. The world map can be scrolled forwards and backwards along the Z-axis (i.e. in time) to adjust its position as a background reference to the information objects. When the user is outside of the container of this context, the distribution of the objects in the database (represented by points) is visible. The representation of the objects and threads in this context will be discussed in the next sections.

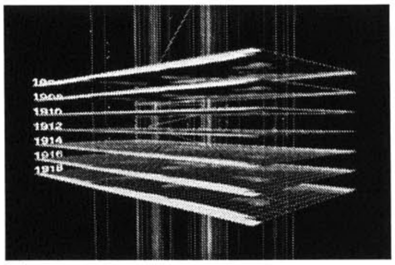


Figure 5.7 *The GEOGRAPHICAL LAYERS OF TIME context from 1910 to 1918.*

Geographical Layers of Time Context: This context is similar to the Geographical-Temporal context described above, but represents a period of time as parallel geographical planes. Figure 5.7 shows an examples of this context from 1910 to 1918. Movement inside of this context occurs perpendicular to the movement in the Geographical-Temporal context. The spatial experience is more enclosed, and somewhat like a large multi-floor interior space. This quasi-human-scaled space is still experimental, but the intention here is to provide a more visceral (i.e embodied on a familiar human scale) experience of the information. (Figure 5.8)

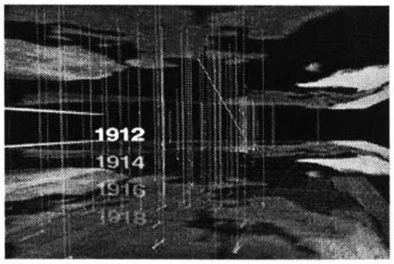


Figure 5.8 *The inside of this version of the GEOGRAPHICAL-TEMPORAL context resembles a building interior.*

People Context: Another experimental context presents only people objects in any of the context containers described above. People objects are represented a bit differently from the event and artifact objects in our database. People objects are represented by uniformly scaled portraits that have been clipped to mask out their backgrounds. (See Figure 5.9) In addition, people objects in the Geographical-Temporal contexts are displayed from a distance not as single points but as lines between two or more points that represent significant milestones in the lives of the people. This enables the viewer to see intersections, parallels, phase shifts or other patterns among the peoples' lives in our database.

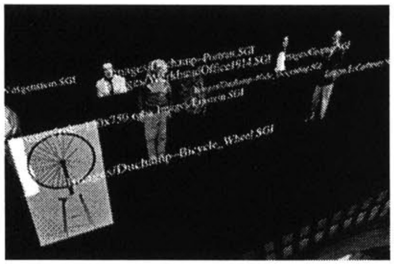


Figure 5.9 *A view of a group of PEOPLE OBJECTS in the Millennium Project database.*

Objects

All information objects contained in a 3D information context are assigned a context-specific XYZ location, XYZ axial rotation, scale, color, and transparency based on a mapping of each one of these display attributes to an appropriate information content attribute. In addition, each information object displays different representations of itself relative to the viewer's (the camera's) position and orientation in space. Because of the importance of maintaining the identity of objects in a context space where the viewer can move freely, we are careful to fix location, scale, and color of objects for each context. Axial rotation, transparency, and level of detail, however, are free to vary with the position and point of view of the user.

Table 5 shows the position assignments or, as Benedikt calls them, "extrinsic dimensions" for objects in four of our contexts [Benedikt, 91]. "Intrinsic dimensions" represented by other display attributes will be discussed relative to objects contained in the Geographical-Temporal context. As shown in Objects in this context are represented from a distance as dots. As the viewer gets closer to an object, a title appears. As the viewer gets closer still, the body text of the object "unfolds" or fades in. (See Figure 5.10 and Figure 5.11)

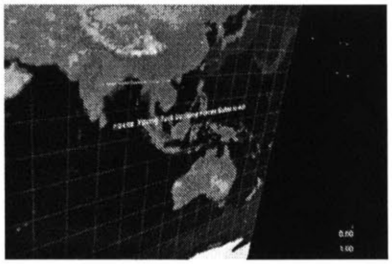
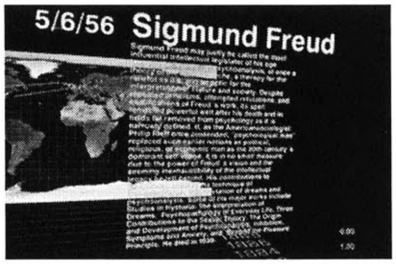


Figure 5.10 *From a distance, a graphical information object is represented as a headline only.*



5/6/56 Sigmund Freud

Figure 5.11 *From closer up, a graphical information object is displayed with both headline and body text.*

Changes in the representations of graphical objects occur because the objects are "reactable". That is, they have built-in functions which continually evaluate their position and orientation with respect to the user. Table 4 illustrates how we decide which object representation to display based on our interpretation of user interaction. User interaction interpretation is described in more detail below.

Threads

Threads are dynamically generated chronological pathways through time and geographic space along categorically connected information objects. A thread is defined computationally as a camera path, a graphical object (a line set, specifically) and a symbol. The camera path and line set are automatically generated by a chronologically sorted list of information objects associated with the symbol. When a user approaches a graphical symbol in the space (displayed as text), the symbol becomes activated, the thread is created, and the user is taken along a guided categorical tour through the information base. Figure 5.12 through Figure 5.15 show views of a thread connecting information objects in the database that relate to *flight*.

The graphical representation of threads as multi-segmented bending lines in a geographical-temporal space provides some potentially useful meta-level information about the information base. For example, the thread representing *flight* in our Millennium information base begins in Kitty Hawk in 1903. Between 1906 and 1912, the thread moves back and forth across the Atlantic, as inventors in Europe and the U.S. break early flight time and distance records. By 1914, all flight-related events in our information base are located in Europe and relate to World War I air combat. (see Figure 5.13)

Multiple threads in the geographical-temporal space can also reveal complex relationships between categories. Future work would explore the ability of multiple graphical threads to express parallel, intersecting, and phase shifting relationships between symbols (i.e. categories). A view of the 3 threads: LANGUAGE, PHILOSOPHY, and, VIENNA is shown in Figure 5.16. The intersection of these threads is shown in Figure 5.17.

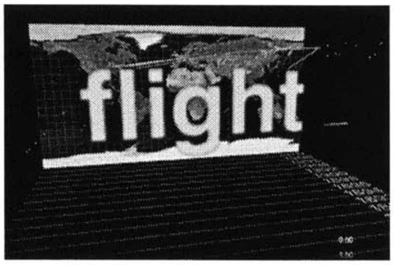


Figure 5.12 *As the viewer approaches the symbol FLIGHT, a THREAD will be activated that takes the user along a chronological path of information objects that relate to flight.*

Figure 5.13 *The first stop on the FLIGHT THREAD guided tour is in Kitty Hawk in 1903.*

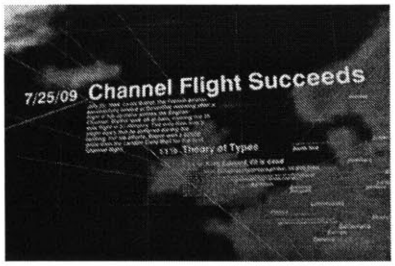


Figure 5.14 *A view of another stop on the FLIGHT THREAD.*

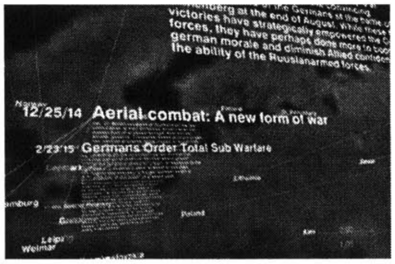


Figure 5.15 *A view of a stop on the FLIGHT THREAD during WW1.*

5.6 User Interaction Interpretation.

An important aspect of meaning communication, and hence understanding of information-bases, is the dynamic process of shifting point-of-view and shifting context. For Fauconnier, a central theme in meaning construction is access through conceptual connections that define mappings between source and target domains [Fauconnier, 94]. In our computational environment we define a context to be a set of information objects and the relationships among them. A context is represented and presented to the knowledge seeker as a container and a set of contained objects, where the container defines the relationship between the objects. We define a context shift to be either global or local. Establishing a global context implies *filtering* or refiltering the original information objects into a working subset of information objects. For example, we may wish to establish a global context to be all objects "in the geographic area of 'France' during the period of 1911 to 1912." Local context shifts imply a change in *conceptual viewpoint* on the subset of information objects and *illustrate* a new set of relationships between the context of objects. For example, we can shift between a CATEGORICAL view, to a CATEGORICAL-TEMPORAL view, to a GEOGRAPHICAL-TEMPORAL view. Key questions that arise from this process are: How does the user indicate these context shifts? How are these context shifts executed?

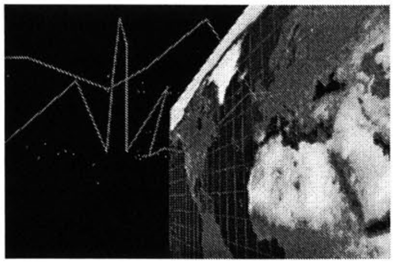


Figure 5.16 *A view of the 3 threads: LANGUAGE, PHILOSOPHY and VIENNA.*

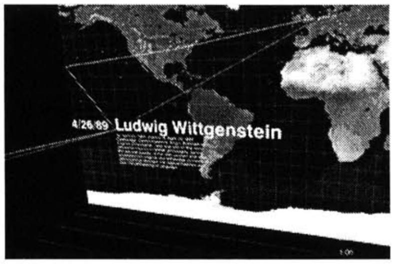


Figure 5.17 *A view of the intersection of the threads: LANGUAGE, PHILOSOPHY, and VIENNA..*

Table 6, *Interpretation of User Interaction*, outlines our approach to these questions. It lists the possible user interactions and their effect on the display of objects and contexts as well as the underlying information representation. An information object will display more detailed information up close than it will from far away, for example, and will foreground and background different information from different points of view. The left column lists possible user interactions which consist of movement of self and manipulation of objects. The middle column describes how we interpret user actions based on the cognitive models outlined in Chapter 4. The right column describes what changes are made to the current context based on our interpretation of the user's actions.

Context transitions

Another task of our 3D space builder is the generation of *transitional spaces.* Transitional spaces are connectors from one context container to another. A transition between a context that is contained inside another (i.e. the infor-

.T

User Interaction		Action Interpretation	Computational Operation
Movement of Self	WITHIN a container	User wants to explore current context	Different views generated within current context
	INTO an object	User wants the object to establish a new context container	NEW SUB-CONTEXT New space constructed Transition performed between old and new spaces
	TOWARDS object(s)	User wants more detail about the object	NEW OBJECT REPRESENTATION by adding detail
	AWAY (BACKING-UP) from object(s)	User wants less detail/more abstraction	NEW OBJECT REPRESENTATION by removing detail When outside container, NEW CONTEXT, original objects replaced with abstracted representations
	THROUGH an object	User wants next in a sequence	NEW SUB-CONTEXT with next in sequence computed
	OVER, UNDER, AROUND object(s)	User wants to see object(s) from different points of view	Different views generated within current context
Manipulation of Object(s)	Translate: MOVE, PUSH, PULL or DRAG	User wants to see object(s) in different relation to other objects in space	Currently, no operation. (Future work may use object manipulation to generate a new context that user "builds" interactively.)
	Rotate: TURN	User wants to see object(s) from different points of view	CHANGING OBJECT REPRESENTATION based on view angle with respect to context container
	Scale: STRETCH or COMPRESS	If scaling container, user wants to extend or contract context constraints (e.g. time)	NEW CONTEXT generated by extending or contracting constraints mapped to the XY, or Z axes
Movement of Self and Object	UNFOLDING of object into a space	User wants to enter a new context based on current object	NEW SUB-CONTEXT Transition of object into space performed

Key:

NEW CONTEXT: Context generated by establishing new filtering constraints and refiltering the original set of information objects

NEW SUB-CONTEXT: Context generated by adding additional constraints and refiltering the information objects in the current context to generate a new set of information objects

NEW OBJECT REPRESENTATION: Space is restructured by adding or removing related- and/or sub-structures that correspond to the object

Table 6: Interpretation of User Interaction

mation object list of the new context is a subset of the old information object list) is experienced like a power-of-ten shift or an infinite zoom [Morrison, 94]. In the transition from a GEOGRAPHICAL context into the GEOGRAPHICAL-TEMPORAL context, the spherical globe grid morphs into a planar grid and the timeline is extruded along the Z-axis.

Navigation

The Millennium Project supports the three types of navigation discussed in Chapter 3: head rotation, manipulation, and locomotion, plus a fourth type that allows the user to lock onto an object in a context and move around it with a fixed radius. Currently the user can manually switch navigation modes. Future work will explore optional automated mode switching based on our ability to interpret the meaning of user position relative to context containers or objects.

Controlling speed of locomotion (not rotational manipulation or head rotation), we discovered, becomes a problem in spaces of varying density and scale. In larger or less dense spaces, we often want to move faster, while in smaller and denser spaces we often want to slow down. Benedikt noted this phenomenon in his *Principle of Scale: "the maximum (space) velocity of user motion in cyberspace is an inverse monotonic function of the complexity of the world visible to him* [Benedikt, 91]." To address this problem, we designed a *scalable* camera. Currently, the maximum velocity of this camera is adjusted to the scale of each context. In the future, we would like this camera to adjust automatically to the information density *within* contexts as well.

5.7 Summary

This chapter described the Millennium Project, a research effort to construct a dynamic 3+D virtual environment for exploring and discovering connections between artifacts of philosophy, painting, music, literature, science, and political events of world history from the years 1906 to 1918. We have shown how *embodied cognitive models* and *visual discourse,* our conceptual framework based on linguistics and cognitive science, supports our approach to enabling understanding of information by:

- building structural representations of sets of information objects in our information-base that correspond to appropriate conceptual structures,
- automatically displaying meaningful 3D information contexts with spatial structures that correspond to these conceptual structures, and
- interpreting user interaction to enable continuous querying and processing of the information-base through spatial movement and object manipulation rather than mouse clicking.

Lastly, this project has been motivated by a desire to create a unique virtual experience not possible in the physical world. We have aimed to create virtual spaces as rich, dynamic, and compelling as the spaces of our minds as we understand, create, and dream.

6

Conclusion

6.1 Summary

In this thesis I have presented *embodied virtual space* and the *Millennium Project*. *Embodied virtual space* is a two-part theoretical framework that addresses the problem of representing information with space by exploiting the embodied qualities of both virtual space and the understanding of information. The *Millennium Project* is a prototype application of the theory in practice.

The first area of research was presented as a process-oriented analytical study of the role of the body in our perception and understanding of virtual space. This research was empirical, but supported by embodied theories of visual perception.

The second area of research presented was based on work in metaphor theory that uses language to evidence the role of the body in structuring our understanding of abstract ideas. A set of embodied cognitive models was organized that show the connection between the body, space, and the understanding of information.

The Millennium Project was presented as the first application of the theory to a specific set of information.

6.2 Results and Future Work

The most significant result of this research is evidenced by the document before you: a way to speak about issues of interactive 3D information design. The issues presented here are not exhaustive, the design concepts are not prescriptive, and the perceptual and cognitive explanations are not definitive. The key contribution of this thesis is a way of thinking that can be continually expanded and revised by designers.

User Testing

User testing is the first priority for future work. The theoretical approach I have presented here would stand on much firmer ground if evaluated by user testing. Experiments need to be designed to test out the claims I have made about virtual space and navigation, and about the ability for embodied virtual space to enhance the understanding of information.

The theoretical approach I have presented enabled me to make some of my own observations about design issues associated with interactive 3D information spaces. I regard these observations as useful "discoveries" that now have a strong influence on my design approach.

Navigation: The Body in Space

The most significant and, for me, the most unexpected results of this research involved navigation. Navigation is something assumed in physical space. Architects, designers of physical space, *consider* navigation but they do not *design* it; they design static objects that anticipate movement.

Navigation needs to be designed in virtual space. Directions for movement need to be assigned meaningfully to input device controls. The following are key observations about navigation that resulted from an understanding of virtual space as embodied:

1. The three types of navigation: point of view rotation, manipulation, and locomotion, relate directly to head rotation, hands, and body movement.
2. When navigating in 3D, users tend to project their bodies into the virtual space.
3. User expectations about navigation controls are directly tied to their perception of their virtual bodies with respect to the environment. Specifically:
    - When the user perceives that she is contained inside a space she will expect the navigation controls to move her virtual body (i.e., rotation and locomotion).
    - When the user perceives that she is outside of a self-contained object,

and when the object is roughly centered in her view, she will expect the navigation controls to move the object (i.e., manipulation).

- When the user perceives that she is smaller in scale than the objects in her environment, she will expect the navigation controls to move her virtual body (i.e., rotation and locomotion).
- When the user perceives that she is larger in scale than an object in her environment, and when the object is roughly centered in her view, she will expect the navigation controls to move the object (i.e., manipulation).

These observations about navigation clearly lend themselves to computational description and many of them were implemented in the *Millennium Project*. "Automated intelligent navigation mode switching" would be an interesting and important area for future research. In addition, if user testing reveals that users have different thresholds for navigation mode switching, a customized navigation system would be desirable.

Navigation needs to be designed in ways other than the meaningful assignment of navigation controls to input device controls. A significant amount of effort in the *Millennium Project* went into the design of the *movement* of the camera in space: how fast should it be, how much acceleration should it have, and how should it reflect the different navigation modes. A discussion with Earl about movement in the Millennium Project resulted in the decision to remove deceleration from point of view rotation. We found it hard to control and reasoned that the movement without deceleration was a closer match to head rotation. Future work in this area would do well to enlist the help of people experienced in the design of movement, such as filmmakers and choreographers.

Metaphor:The Body in Information

Another significant outcome of this research has been the ability to look to language for solutions to problems of information design. By examining how we use language to talk about information, we are likely to uncover a model or a metaphor suggestive of a graphical or spatial design solution. Lakoff thinks of metaphor as a *tool*. The fact that metaphor is "an integral part of our ordinary everyday thought and language" makes it a tool accessible to everyone [Lakoff, 89].

After understanding the "tool,", I found that I was able to identify metaphors on my own without digging into linguistic sources. The idea for*threads* in the *Millennium Project*, for example, came from my own verbal description of the connections between specific historical events in the database. Thinking about *threads* as part of the metaphor of *sewing* or *weaving* connections suggested new directions for design that I would not have otherwise considered.

The following are some general metaphor-related observations about information in space:

1. Geographical information already lends itself to at least two dimensions of space.
2. Temporal information lends itself to linear spatial structures. (TIME is a PATH.)
3. Categorical information is the most difficult to represent spatially because of it multi-dimensionality. There are some useful metaphors for categorical information, however, which include:
   - Scale
   - Point of view, and
   - Context (as a container)

Language of Space

Fifty years ago, Gyorgy Kepes wrote *Language of Vision* to help people see what goes into visual experience. The visual literacy advocated by that work and others (Arnheim and Gombrich) became a tool for artists, designers, and critics to create and evaluate abstract art.

Today we need a *Language of Space* to help people grasp what goes into spatial experience. Spatial literacy has the promise of laying the foundation for truly interactive cyber-spatial experiences of information. This thesis has set some footings.

References

[Abrams, 94] Abrams, Janet. “Muriel Cooper’s Visible Wisdom”*J.D. The International Design Magazine*, September October 1994, pp. 48-55, 96-97.

[Allport, 95] Allport, D., E. Rennison, L. Strausfeld, Issues of Gestural Navigation in Abstract Information Spaces, *Proceedings of CHI 95, Conference Companion.*Denver, Colorado.

[Arnheim, 54] Arnheim, Rudolf. *Art and Visual Thinking.* London: University of California Press, 1954.

[Arnheim, 69] Arnheim, Rudolf. *Visual Thinking.* Berkeley: University of California Press, 1969.

[Bachelard, 69] Bachelard, Gaston. *The Poetics of Space.* Boston: Beacon Press, 1969.

[Bederson, 93] Bederson, Benjamin, and Hollan, James. PA3D: A Multiscale Hierarchical Sketchpad. *Proceedings of UIST.* 1993.

[Benedikt, 91] Benedikt, Michael. “Cyberspace: Some Proposals”, *Cyberspace: First Steps.* Cambridge: MIT Press, 1991.

[Bylinsky, 93] Bylinsky, Gene. The Payoff From 3-D Computing. *Fortune,* Autumn 1993, pp. 32-40.

[Calvino, 74] Calvino, Italo. Invisible Cities. New York: Harcourt Brace & Company, 1974.

[Colby, 92] Colby, Grace, and Laura Scholl. Transparency and Blur as Selective Cues for Complex Information. *Proceedings of SPIE.* 1992.

[Cooper, 89] Cooper, Muriel. *Design Quarterly* 142. Cambridge: MIT Press, 1989.

[Fauconnier, 94] Fauconnier, Gilles. *Mental Spaces: Aspects of Meaning Construction in Natural Language.* Cambridge, UK: Cambridge University Press, 1994.

[Feiner, 90] Feiner, Steven, and Clifford Beshers. “Worlds within Worlds: Metaphors for Exploring n-Dimensional Virtual Worlds”. *Proceedings of UIST.* 1990. Snowbird, Utah: ACM.

[Gibson, 79] Gibson, James J. *The Ecological Approach to Visual Perception.* Boston: Houghton Mifflin Co., 1979.

[Heidegger, 75] Heidegger, Martin. *Poetry, Language, Thought.* New York: Harper & Row, 1975.

[Hillier, 73] Hillier, Bill and Leaman, Adrian. How is Design Possible? A Sketch For a Theory. *The Design Activity International Conference,* August 1973.

[Holtzman, 94] Holtzman, Steven. *Digital Mantras: The Languages of Abstract and Virtual Worlds.* Cambridge: MIT Press, 1994.

[Jackendoff, 83] Jackendoff, R. *Semantics and Cognition.* Cambridge, MA: MIT Press, 1983.

[Johnson, 92] Johnson, Mark. *The Body in the Mind.* Chicago: The University of Chicago Press, 1992.

[Kepes, 44] Kepes, Gyorgy. *Language of Vision.* Chicago: Hillison & Etten Company, 1944.

[Kulberg, 95] Kulberg, Robin. Dynamic Timelines: Visualizing Historical Information in Three Dimensions, M.S. Thesis, Massachusetts Institute of Technology, 1995.

[Lakoff, 80] Lakoff, George and Johnson, Mark. *Metaphors We Lie By.* Chicago: University of Chicago Press, 1980.

[Lakoff, 89] Lakoff, George and Turner, Mark, *More than Cool Reason: A Field Guide to Poetic Metaphor.* University of Chicago Press, 1989.

[Lakoff, 87] Lakoff, George. *Women, Fire, and Dangerous Things.* Chicago: University of Chicago Press, 1987.

[Lynch, 60] Lynch, Kevin. *The Image Of The City.* Cambridge, MA: MIT Press, 1960.

[Mackinlay, 91] Mackinlay, Jock, Robertson, George, and Card, Stuart. The Perspective Wall: Detail and Context Smoothly Integrated. *Proceedings of Chi '91.* ACM.

[Mitchell, 95] Mitchell, William J. *City of Bits: Space, Place, and the Infobahn.* Cambridge: MIT Press, 1995.

[Morrison, 94] Morrison, Philip & Phyllis, and the Office of Charles and Ray Eames. *Powers of Ten: About the Relative Size of Things in the Universe.* New York: Scientific American Library, 1994.

[Ortony, 93] Ortony, Andrew (Ed.). *Metaphor and Thought.* Cambridge, England: Cambridge University Press, 1993.

[Owen, 94] Owen, William. Design in the Age of Digital Reproduction. *EYE*, 14/94, 1994, pp. 26-40.

[Perlin, 93] Perlin, Ken, and Fox, David. Pad: An Alternative Approach to the Computer Interface. *Computer Graphics Proceedings.* 1993.

[Rao, 94] Rao, Ramana, and Card, Stuart. The Table Lens: Merging Graphical and Symbolic Representations in an Interactive Focus+Context Visualization for Tabular Information. *Chi '94 Conference Companion.* Boston, Massachusetts: ACM.

[Rennison, 94] Rennison, Earl. Galaxy of News: An Approach to Visualizing and Understanding Expansive News Landscapes. *Proceedings of UIST*, 1994, Marina Del Ray, California.

[Rennison, 95] Rennison, E. *The Mind's Eye: An Approach to Understanding Large Complex Information-Bases through Visual Discourse.* MS Thesis. Massachusetts Institute of Technology. Cambridge, MA. August, 1995.

[Robertson, 91] Robertson, George G., Jock D. Mackinlay, and Stuart K. Card. Cone Trees: Animated 3D Visualizations of

Hierarchical Information. *Proceedings of UIST.* 1991. Hilton Head, South Carolina: ACM.

[Robertson, 93] Robertson, George G., Card, Stuart K., and Mackinlay, Jock D. Information Visualization Using 3D Interactive Animation. *Communications of the ACM*, April 1993, Vol.36, No. 4.

[Rowe, 76] Rowe, Colin. *The Mathematics of the Ideal Villa, and Other Essays.* Cambridge: MIT Press, 1976.

[Small, 94] Small, David, Suguru Ishizaki, and Muriel Cooper. Typographic Space. *CHI '94 Conference Companion.* Boston, Massachusetts: ACM.

[Strausfeld, 95a] Strausfeld, L. and Rennison, E. *The Millennium Project: Constructing a Dynamic 3+D Virtual Environment for Exploring Geographically, Temporally and Categorically Organized Historical Information.* Proceedings of COSIT, Vienna, 1995.

[Strausfeld, 95b] Strausfeld, L. Financial Viewpoints. *Proceedings of CHI 95, Conference Companion.* Denver, Colorado.

[Teitelbaum, 92] Teitelbaum, Matthew (Ed.). *Montage and Modern Life: 1919-1942.* MIT Press, 1992.

[Tufte, 83] Tufte, Edward. *The Visual Display of Quantitative Information.* Cheshire, CT: Graphics Press, 1983.

[Tufte, 90] Tufte, Edward. *Envisioning Information.* Cheshire, CT: Graphics Press, 1990.

[Venturi, 89] Venturi, R., Scott Brown, D., and Izenour, S. *Learning From Las Vegas.* Cambridge: The MIT Press, 1989.

[Weitzman, 94] Weitzman, Louis and Wittenburg, Kent. Automatic Presentation of Multimedia Documents Using Relational Grammars, In *ACM Multimedia' 94*, San Francisco, Ca. October 15-20, 1994.

[Wong, 94] Wong, Yin. *NewsViews.* Class project for Computer Graphics Workshop, Visible Language Workshop, MIT Media Lab, 1994.

[Wurman, 89] Wurman, Richard Saul. *Information Anxiety.* New York: Bantam Books, 1989.