Handbook of Virtual Environments (Second Edition)

Information Visualization in Virtual Environments:

Tradeoffs and Guidelines

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Introduction

> Imagine yourself a hyper-intelligent being from another galaxy. You are a luminous egg. You are exploring the universe in search of molecular resources and other life. As you warp into the Milky Way, your dashboard alights, detailing the presence of numerous electro-magnetic signals and valuable atomic elements in the Sol system. Turning your ship toward a small yellow star, you consider the attributes of each planet in the system: size, mass, chemical compositions and environmental qualities. Patterns in these attributes generate hypotheses about the history and habitability of the planets in this system. Of the top planets you examine closer, you find the third stone from the sun is a 'Blue Marble' – a rare gem in this entropic universe. You fly in to take a closer look…

There are several reasons to motivate our current chapter with this thought experiment. The first is to examine our assumptions about other minds. The second is that this narrative includes some technology that augments the cognition of our alien pilot to help them make sense of the situation, evaluate alternatives, and arrive at an actionable decision. Third, it illustrates the prototypical cycle of information visualization activities: overview, filter/zoom, details-on-demand.

If you were able to 'suspend your disbelief' and go with the story, you created your own virtual reality. It is indeed amazing that this rich process of mental activation was achieved with only 127 words! No doubt, each of you readers filled in some unique details in your own mind, and these will vary widely. When presented with explicit visuals (about your alien race, the look of the dashboard, the ship), the variance is reduced and we are closer to a shared understanding in our minds. A picture tells a thousand words (Larkin 1987) and an experience can explain a lifetime. But how does this happen? How do our minds makes sense out of the noisy and incomplete data fed to them by the senses?

Certainly things like biological survival, reproduction, and quality-of-life occupy most of our time; however many have argued that an understanding of the nature of our minds is our greatest quest. Religion, Philosophy and Anthropology have been the historic proving grounds for a deeper understanding of our understanding. More recently however, cognitive psychology and neuroscience are providing startling discoveries and discussions from the mechanics of perception and action to the nature of emotion, knowledge, and cognition.

We believe the brain to be the seat of our consciousness, though there is no one locus of control. Once upon a time, when Descartes' 'Dualist' philosophies held sway, the Pineal Gland was thought to be the controller (metaphorical joystick) of the homunculus driving our actions on the physical plane. This has proven an inadequate explanation. Similarly, we cannot say that the Periaqueductal Grey is the locus of transcendental bliss or euphoria. In addition, there is no one cell in your brain who activates when you recognize your grandmother – memories and associations are distributed throughout the vast network of brain. While amazingly complex, we are beginning to understand the computational processes embodied by these vast networks of neurons; this is especially true in the visual system.

The Observer and the Observed

The visual system accounts for approximately three out of eight pounds in the human brain. We know that our visual system has evolved sensitivities specific to attributes of the environment that impact our survival: high resolution sensing of luminance for nighttime activities, color sensitivity to distinguish food from poison and to break camouflage, stereo vision to judge trajectories and distances, retino-topically varied sensitivities (such as different sub-systems for focus and periphery) to label objects and locate them in space.

We also know that the mind fills in details with that it expects to see: optical and Gestalt illusions, prototypical qualities of an object or event, L3++3rs is a word. So clearly, our perception is not just a bottom-up process constricted purely from our sensory data. Our minds use abstractions and assumptions to get by.

The mind is adaptable and plastic. It is reconfigurable by culture and technology – those imperatives that move too fast for biological evolution. It is a good thing too, since the emergent properties of the variety of societies around our global village would challenge the most advanced protocol droid. While each of us inhabit a unique and personal reality, we engage in linguistic communication and collective hallucination effortlessly everyday. We can also recover some mental functions after damage such as stroke or trauma when our brains successfully re-map processing functions from the damaged area to new areas and networks.

We may be brains in a vat. We may be butterflies in Hawaii dreaming we are men or imagining a perfect storm. We have serious reasons to be skeptical of our sensory inputs, and this is not new news. Indeed, Plato's Analogy of the Cave was an original inspiration for Virtual Reality; this analogy explored the nature of perception and knowledge and reality and asked the fundamental question of: "Why do you believe your senses?" Two millennia later, the philosophers Hume and Kant pushed the limits of this reasoning. Hume's skepticism and problems with inductive inferences and epistemology has infected generations of philosophers. Kant's metaphysical challenge with knowledge existing independent of experience (famously explored in Critique of Pure Reason) point to this same quandary of existence for *a priori* or dis-embodied concepts.

For our purposes, we will adopt a pragmatic stance by considering our mind as an embodied organism, which is the product of eons of biological evolution on this earth. As such, its sensory system and physical musculature are tuned to function in *this* electro-magnetic spectrum, *this* gravity field, *this* atmosphere. Because the mind is embodied, we have the possibility for immersive technologies to substitute and supplement the senses. All sorts of creative gadgets and systems for sensory substitution have been invented and developed (Bowman 2004); for a historical and particularly expansive vision, readers should consult the book Virtual Reality (Pimentel and Teixeira 1993). Through the present day, this equipment is built with the goal of improving the 'Immersion' of the user – the objective degree of sensory substitution provided. This should not be confused with the concept of 'Presence', which is the subjective rating of the user to 'being there' in the virtual environment. Now, more than ever in history, we have the can deliver synthetic sensory stimuli that is interactive and of high-fidelity.

The Media and the Message

The Cognitive Scientist looks not just on the nature of the sensory transducers and actuators, but also at the representations and information processing required to get from stimulus to response. Cognitive Psychology takes a computational perspective on mental representations and their processing - it attempts to understand mental activity in terms of the computational work required to encode an input, transform and manipulate that representation and create an output or behavior. Thus, Cognitive Psychology considers the complexity, kinds, components and scale of processing between stimulus and response. Beginning with the nervous system of worms and Planaria, scientists have worked their way up the evolutionary ladder mapping more and more of the complex neural circuits that build our reality.

Considering the human observer and the evolutionary development of its perceptual and cognitive systems, we can examine the qualities of stimuli that communicate information. Information about the state of the environment can be received through several sensory modalities of course, and humans are demonstrably 'tuned' to certain visual wavelengths, audio frequencies, chemicals (taste and smell) and physical contacts (haptics). These are all prime candidates to offload information rendering to. However each has limitations in terms of the information types, ranges and dynamics of the values they can accurately represent. For example, in both haptics and sonification, humans have different sensitivities to frequency and amplitude making quantitative values difficult to portray. In addition, these sensory modalities are quickly habituated, meaning that over time they become less sensitive to signal (what does it take for you to feel your clothes?).

Perhaps not explicitly stated, much of this work is concerned with understanding how we humans can solve such difficult problems on a daily basis when our working memory is so limited (Miller 1956) . Visualization can amplify cognition i.e. (Card 1999) in several ways, but especially by providing an external data store and processing service for costly mental operations i.e. (Zhang 1994). Visual displays provide key input to visual working memory (Baddeley and Logie 1999; Baddeley 2003) (Logie 1995). Thus, we can optimize our stimuli for pre-attentive processing and still establish the crucial, shared representational correspondence between the concepts in the mind and the evidence in the data.

This approach has born much fruit, which feeds our understanding in areas from mental rotation (Sheppard 2004), line graph reading (Lohse 1991), robotics, to expert systems in chess, medical diagnosis and Jeopardy. Taken in full, the experimental literature shows that there are clear patterns in human abilities and competencies: spatial visualization (Sorby 2009), chunking strategies and the art of memory are all skills that can be learned and improved. There are also clear biases in human reasoning including confirmation bias, fundamental attribution error, blind-spot bias, anchoring bias, projection bias and representativeness bias (Kahneman and Tversky 1979). Interactive, decision-making tools can help mitigate and alleviate common mistakes due to these biases i.e. (Evans 1989). Similarly, our alien explorer uses an information display dashboard to augment their reasoning and decision making.

Background

Readers should be aware of a notional distinction between 'scientific visualization' and 'information visualization'. Traditionally, scientific visualization refers to a situation where there is some natural spatial mapping for the data (i.e. an airplane wing, a globe). In contrast, information visualizations can be map data values into any spatial domain (i.e. a scatterplot, a pie chart). However, many of the same perceptual and cognitive challenges exist between these fields. In addition, when scientists are concerned with gene expression data or high-dimensional patterns in a nuclear reaction, this distinction is less useful. 'Visual Analytics' i.e. (Thomas 2006) gets around this distinction by focusing on the inclusion of interactions and statistical tools to augment the user's reasoning and sense-making process. As we will see in this chapter, Virtual Environments can be used with advantage for all these brands of visualization.

Graphical Information

Primary factors in visualization design, which we will describe below, concern both the data (its dimensionality, type, scale, range, and attributes of interest) and human factors (the user's purpose and expertise). Different data types and tasks require different representation and interaction techniques. How users construct knowledge about what a graphic 'means' is also of inherent interest to visualization applications. For users to understand and interpret images, higher-level cognitive processes are usually needed. A number of authors have enumerated design strategies and representation parameters for rendering signifieds in graphics ((Bertin 1983), (Tufte 1983; Tufte 1990)) and there are effects from both the kind of data and the kind of task (Shneiderman 1996).

Card, Mackinlay, and Scheiderman (Card 1999) have examined a variety of graphical forms and critically compared visual cues in: scatter-plot, cone-trees, hyperbolic trees, tree maps, point-of-interest, and perspective wall renderings. As we shall see, their work is important since any of these 2D visualizations may be embedded inside, or manifested as, a virtual environment. Interactive computer graphics present another level of complication for designers to convey meaning as they are responsive, dynamic and may take diverse forms. There are challenges both on the input medium to the user and the action medium for the user. These are known as the Gulf of Evaluation and the Gulf of Execution respectively (Norman 1986). Typically in the literature, visualizations are described and categorized per-user-task such as exploring, finding, comparing, and recognizing (patterns). These tasks are common in interactive 3D worlds as well. Information objects may need to be depicted with affordances for such actions (see below).

Visual Markers

The nature of visual perception is obviously a crucial factor in the design of effective graphics. The challenge is to understand human perceptual dimensions and map data to its display in order that dependent variables can be instantly perceived and processed pre-consciously and in parallel (Friedhoff 2000). Such properties of the visual system have been described (ie sensitivity to texture, color, motion, depth) and graphical presentation models have been formulated to exploit these properties, such as pre-attentive processing ((Pickett 1995), (Treisman 1988) and visual cues and perception (Keller 1993).

General types of data can be described as: Quantitative (numerical), Ordinal, and Nominal (or categorical). Visualization design requires the mapping of data attributes to 'visual markers' (the graphical representations of those attributes). Information mappings to visualizations must be computable (they must be able to be generated by a computer), and they must be comprehensible by the user (the user must understand the rules that govern the mapping in order to interpret the visualization). The employment of various visual markers can be defined by the visualization designer or defined by the user.

Tools such as Spotfire (Ahlberg 1995) and Snap (North 2000) are good examples of expanding this interactive user control over the mapping, display and coordination of views. Open source tools such as Paraview (Squillacote and Ahrens 2006) provide capable user control over virtually every aspect of the pipeline through a GUI and a Python-scriptable interface. In addition, a set of 'modes' of interaction have been proposed for exploratory data visualizations which attempt to account for user feedback and control in a runtime display (Hibbard 1995). For the publishing of interactive 3D information visualizations, Polys described several paradigms for mapping data attributes to the scene graph through Extensible Markup Language (XML) and Extensible 3D (X3D) (Polys 2003; Polys 2005b). Table 1 summarizes the ordering of visual markers by accuracy for the general data types. These rankings lay a foundation for identifying parameters that increase the information bandwidth between visual stimuli and user.

Data Type	**Quantitative**	**Ordinal**	**Nominal**
Graphical Representation	position length angle / slope area volume color / density (Cleveland and McGill 1984)	position density color texture connection containment length angle slope area volume (Mackinlay 1986)	position color texture connection containment density shape length angle slope area volume (Mackinlay 1986)

Table 1: Accuracy rankings for visual markers by general data type

Attention

When humans acquire a skill, they are typically learning to perform a complex behavior or set of behaviors. As they learn the skill, some aspects of performance can be automatized to require less cognitive and attentional resources. Automatized processes reduce cognitive overhead as they do not involve conscious control or attentional resources; as such, they can usually be performed in parallel with other tasks and are usually obligatory ((Eysenck 2000), pg 141). (Treisman 1988) noted that there may be extensive processing of unattended sources of information and articulated a robust theory called 'Pre-attentive Processing Theory'. **Pre-attentive perceptual processing** is involuntary, parallel and efficient.

The efficiency advantages of automatic processes make them a desirable target for certain aspects of visualization. By leveraging the pre-attentive processes of perception, we can make some tasks, such as outlier detection in visual search, much easier e.g. (Ware 2000; Ware 2003). However, some aspects of complex task performance should not be automatized in order to guarantee the user's sensitivity and flexibility to novel situations. These aspects of performance should remain controlled and receive proper attentional resources. In contrast to automatized processes, controlled processes can be characterized as declarative, serial, and explicitly managed by trainable conscious, or 'top-down', strategies (Gopher 1996).

Management of attentional resources can be determined by the environment but also by **user strategy**. The striking effects of the contrast between automatic attentional processes and those guided by top-down or instructional processes is clear in Simons work on attentional capture and inattentional blindness (Simmons 2000). When instructed or given one kind of kind of stimuli, another unexpected type may go unnoticed. In retrospect or under different instruction, the same unexpected stimuli is obvious. The perceptual system can be high-jacked by top-down control of attention, sometimes resulting in the phenomena described as 'attentional blink' (Rensink 2000). The human perceptual system can also be primed for detection of spatial and linguistic stimuli non-consciously (at a pre-semantic level) (Tulving 1990).

Gopher (1996) has also examined the role of a control system in attentional performance for variable priorities and variable degrees of theoretical understanding of the system in dealing with 'mishaps' in the system. He found that executive attentional control is a strategic behavior and that users can increase performance once they learn proper conceptual model. As Green & Bavelier have shown (Green 2003), a minimal **practice** period of 10 X 1 hour sessions on first person, 3D-action video games (e.g. Medal of Honor) can significantly improve user performance in attentional enumeration as measured by tests of "Useful Field Of View" (UFOV) and attentional blink. Interestingly, this effect was not observed in subjects trained with Tetris (an exocentric, 2D spatial puzzle game). Clearly, there are rich dynamics between bottom-up and top-down processing and these have a direct impact a user's experience and the usability of an application.

Scientific Visualization

The ScienceSpace Project showed that **conceptual learning** can be aided by features of immersive VEs such as: their spatial, 3-dimensional aspect, their support for users to change their frames of reference, and the inclusion of multi-sensory cues (Salzman 1999). The curriculum modules included learning about dynamics and interactions for the physics of Newton, Maxwell, and Pauling. It seems likely that this advantage would also transfer to desktop courseware and applications. Indeed, education researchers have shown improved student performance by augmenting science lectures with desktop virtual environments including the 'Virtual Cell' environment for teaching biology and the processes of cellular respiration (McClean 2001), (Saini-Eidukat 1999; White 1999).

This is compelling evidence for the value of VEs as learning tools and for concept acquisition during the development of a user's mental model. For example, the NYU School of Medicine (Bogart 2001) published a number of anatomy courseware modules in VRML that provide an information-rich interface to detailed models of the human head. The value and need for such tools have long been recognized (Farrell and Zappulla 1989; Kling-Petersen, Pascher et al. 1999). Recently, Google Inc. (Google 2010) presented an interactive anatomy virtual environment natively in the HTML 5 web browser using WebGL as the rendering engine.

In computational science and simulation, structure and function are often related over time; several visualization techniques are common. For example, mapping variable ranges to color scales, drawing isosurfaces (contours) at various thresholds in the data, tracing streamlines in the flow field and animating these properties over time. Figure 1 shows an example of a scientific visualization in a virtual environment using many of these techniques.

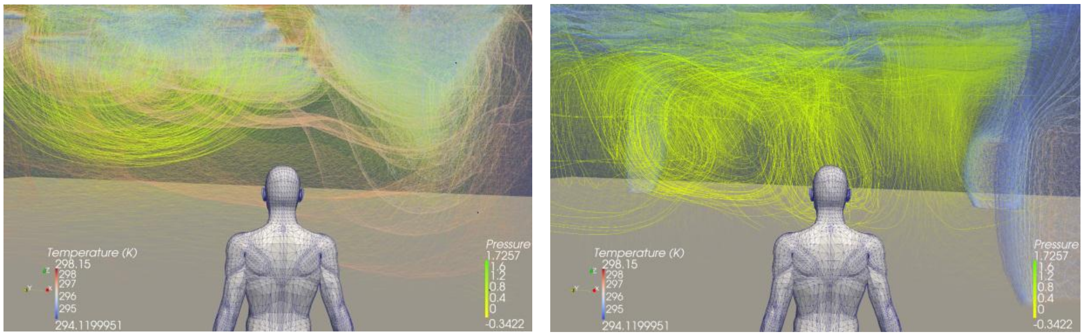

Figure 1: HVAC simulation for a green energy retrofit composed and rendered with Paraview (at t=15 and t=81). Image: Drs. Burns, Borggaard, Herdman, Cliff, Polys (2012); Courtesy US Department of Energy.

Glyphs are visual markers that can represent multiple variables as attributes on a single object. The pre-attentive power of Chernoff-face glyphs leverages human sensitivity to patterns in faces to show up to 27 separable attributes (Chernoff 1973). Glyphs as other shapes have been applied to high-dimensional data sets including tensors representing material properties (Hashash, Yao et al. 2003), brain activity circuits (Ropinski, Oeltze et al. 2011) or fluid properties such as pressure and velocity. Figure 2 shows a scientific visualization from the Paraview tutorial exported to X3D and rendered in the VT Visionarium VisCube.

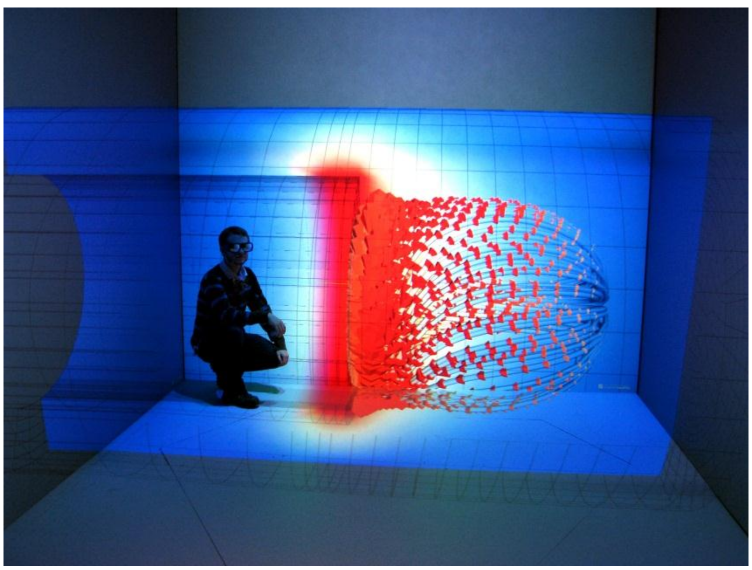

Figure 2: Cone Glyphs on streamlines representing fluid temperature and velocity; Image: Nicholas Polys & Patrick Shinpaugh (2010)

There has been much research into **volume** rendering techniques since the emergence of the field, most of which is outside of the scope of this chapter. For a general survey of volume rendering techniques, see Kaufman and Mueller (KAUFMAN 2004); for a perceptual evaluation approach, see (BOUCHENY 2009). Volume data is generated and used in several domains: geophysics, medical imaging, and non-invasive sensing of objects as varied as bridges, fossils, and luggage. There are a number of visualization techniques that can be applied to voxel data. For example, the ISO/IEC standard Extensible 3D (X3D) 3.3 specifies several 'render styles' that can be used to assign appearances to voxel data (Web3D 2012). These render styles define the mapping of values in the volume to their visual representation; mappings can be based on transfer functions, specific material definitions and lighting functions. Typically, volume data sets are segmented, meaning that voxels are marked as belonging to a specific group (a region of interest such as bone or kidney); groups can then be assigned different render styles (Figure 3). As an additional step, the values in the volume may be used to compute an explicit mesh or surface at a given threshold (for example, using algorithms such as Marching Tetrahedrons or Marching Cubes (Lorensen 1987)).

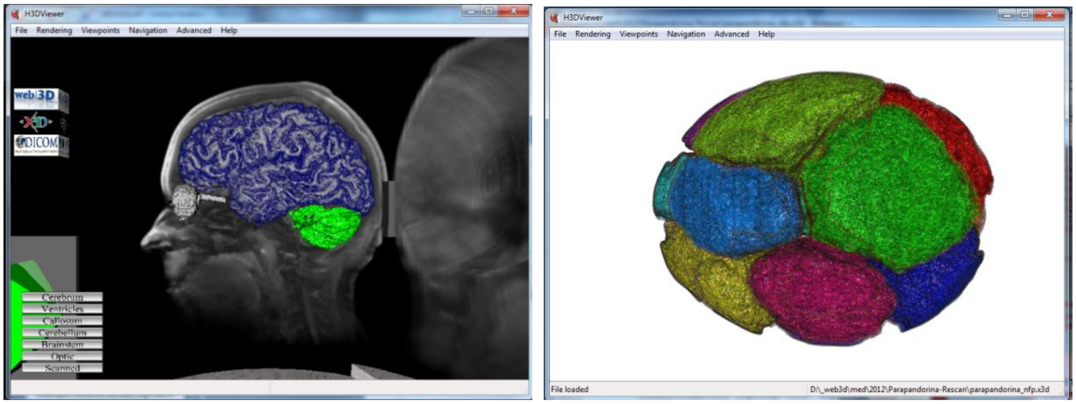

Figure 3: X3D Volume rendering: a) a brain MRI segmented into separate files and composed with an interactive interface; Image: Andy Wood, Nicholas Polys (2012). b) a segmented CT scan of the Parapandorina fossil; Image: Andy Wood, Nicholas Polys, Shuhai Xiao (2012)

Information Visualization

Card, Mackinlay, and Schneiderman have defined Information Visualization as "The use of computer-supported, interactive, visual representations of abstract data to amplify cognition" ((Card 1999), pg. 7). This definition provides us with a simple starting point to describe visualization techniques as it distinguishes abstract data from other types of data that directly describe physical reality or are inherently spatial (i.e. anatomy or molecular structure). Abstract data includes things like financial reports, collections of documents, web traffic records or derived statistics, such as the distribution of genetic features per category (e.g. Figure 4). Abstract data does not have obvious spatial mappings or natural visible forms; thus the challenge is to determine effective visual representations and interaction schemes for human analysis, decision-making, and discovery. For a good review of information visualization applications and techniques, see (Chen 2004) and (Spense 2007).

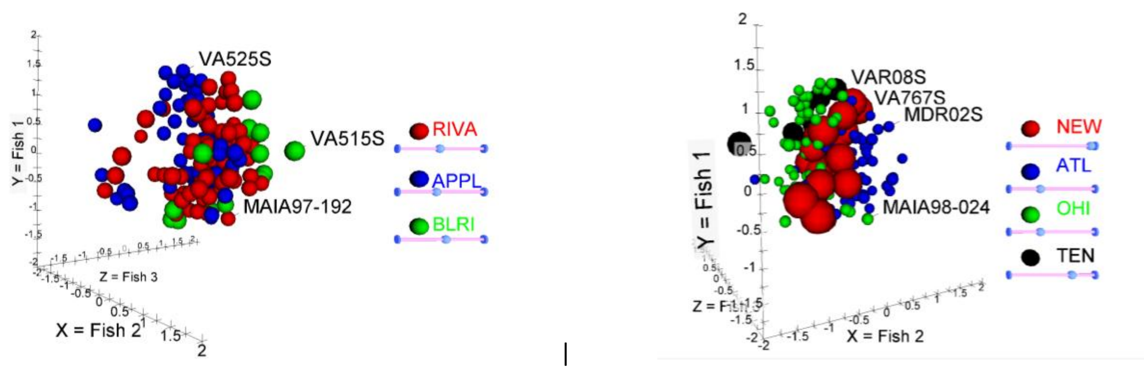

Figure 4: Two different interactive scatterplots of 3-dimensional data in X3D Examine mode: users manipulate HUD sliders to set the data point's radius; Image: Polys (2006)

The archetypical visualization pipeline has three important steps (see Figure 5). First, data is extracted and transformed from some raw sources into tables that contain the objects and attributes of interest. Second, these objects and attributes are mapped to some visual marker. Third, the resulting markers and structures are rendered to some camera or view. If the visualization is a high-resolution print, the process may stop there. In interactive visualization systems, the user may have control over any step in this pipeline.

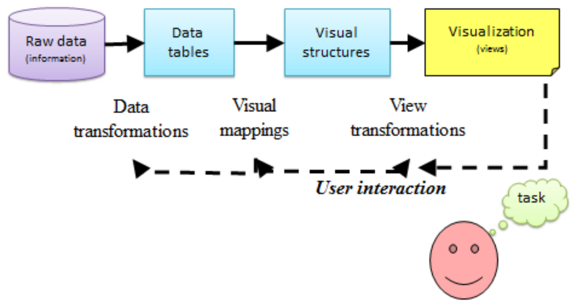

Figure 5: The archetypical visualization pipeline (adapted from (Card 1999))

Network data is a rich source for visualization challenges and breakthroughs. Nodes and edges can be used to represent the relationships and dynamics of many systems. Each kind of structure (hierarchical tree or graph), relationships (directed or un-directed, contains weighted or hyper edges, etc.) and task has a set of ***in-appropriate*** techniques. The challenge is to find appropriate visual mappings and layout techniques that make the topology understandable and avoid the notorious 'hair-ball' views. For example network security (Fink, Muessig et al. 2005) used a novel visualization tool to identify anomalies and patterns in router and server traffic. For hierarchies and trees, 3D cone trees (Robertson, Mackinlay et al. 1991), tree maps (Schneiderman 1992), and hyperbolic distortions (Lamping and Rao 1996) are now well-established techniques.

Chen (Chen 1999) showed that individual's spatial cognitive aptitudes significantly determined their performance when analyzing a semantic citation network where the network was 2D and search relevance was shown as a bar graph on each node (the StarWalker application). Later, (Geroimenko and Chen 2006) demonstrated several ontology visualization techniques with data from the semantic web. The unification of graph visualization and analysis tools into one user interface environment has also generated insightful analyses of cell-signaling pathways (Hossain, Akbar et al. 2009; Hossain, Akbar et al. 2012). Figure 6 shows some example views of graph data in a virtual environment (a constrained force-directed layout left, and a radial tree layout, right).

Figure 6: Network data presents special challenges since space is flexible, but topology is important:
(a) and (b) are STKE cell signaling data; Images from (Henry and Polys 2010). (c) a simple layout of an industrial product ontology; Radics & Polys (2011).

Geospatial data shares many properties with scientific data, in that the data attributes map natural to a spatial basis- they belong to a point or region in real 3D space. Geospatially-based data presents several unique cognitive and usability challenges (i.e.(Slocum, Blok et al. 2001). (Monmonier 1990) proposed some early strategies for the visualization of geographic time-series data. As web services and APIs become standardized for 3D geo-referenced content (for example, terrain, imagery, and other layers with features), we will see a rapid expansion of mirror worlds and 'mash-up' environments such as 3D Blacksburg (Tilden, Singh et al. 2011); see Figure 7.

Figure 7: X3D Blacksburg extent and immersion; Images: (a) and (b) Polys, Dickerson and Sforza (c) Virginia Tech

Multiple Views

A growing body of work is leveraging object-oriented software design to provide users with multiple linked views or renderings of data. (North 2000) showed that users can construct and operate their own coordinated multi-view layouts. (North 2001) has also described a taxonomy of tightly-coupled views and experimental evidence supporting user performance advantages with multiple coordinated views such as a significant speed up on overview + detail tasks. These visualizations are coordinated by simple events such as*:* 1. Selecting items <--> Selecting items, 2. Navigating views <--> Navigating views, and 3. Selecting items <--> Navigating views, for example. The 'Visualization Schema' approach allows users to easily and reliably their own coordinated visualizations (North 2002).

Such simple coordination events allow multiple views to be customized and composed in a structured way. (Roberts 1999) and (Boukhelifa 2003) have described additional models for coordinating multiple views for exploratory visualization including 2D and 3D views. In Roberts' Waltz system for example, multiform 2D and 3D visualizations of data are displayed and coordinated as users explore sets and subsets of the data. As we shall see, Virtual Environments can be coordinated with other views and this concept can be extended to visualizations embedded inside the environment. (Hochheiser 2004) developed and tested 'Timesearcher', an interactive visualization tool that allows analysts to examine abstract time-series data, such as stock market or census data, with advanced queries and filters.

Virtual Environments

A virtual environment (VE) is a synthetic, three or four-dimensional world rendered in real time in response to user input. The first three dimensions are spatial and typically described in Euclidean coordinates x, y, and z. The fourth dimension is time; objects in the VE may change properties over time for example animating position, size or color according to some clock or timeline. The data structure used to represent a virtual environment is called a ***scene graph*** and consists of two parts: the *transformation hierarchy*, which describes the spatial relationship of objects and groups, and the *behavior graph*, which describes the flow of events (connections) between nodes during runtime. At each time-step, the scene graph is traversed for rendering. The organization and semantics of a particular scene graph can have a direct effect on what is visible (rendered), what is interactive and how application logic is structured. For example, the application of lighting equations to geometric shapes in the scene is often scoped to only effect siblings and their children in the scene graph; similarly pointing and drag sensors are active over siblings and their children. Many flavors of scene graphs and their application programming interfaces (APIs) have come and gone over the years.

Figure 8: An architect's model of the Virginia Tech Center for the Arts, processed to X3D and published as persistent multi-user world; Image: Nicholas Polys, Dane Webster (2011).

Most notable for their durability, portability and inter-operability are the ISO/IEC standards of Virtual Reality Modeling Language (VRML)(Web3D 1997) and Extensible 3D (X3D) (Web3D 2012). These scene graphs are web-aware and platform-agnostic and have been used with a huge range applications over the years including multi-user persistent environments (i.e. Figure 8). Since the mid-nineties, ISO scene graphs have taken advantage of the exponential growth of graphics and rendering hardware – not only can they still be run by many software tools (at higher frame-rates than ever), they can also be run across a wide range of hardware platforms from mobile to immersive. This 'spectrum of immersion' is a reality for 3D user interface designers. X3D provides a powerful level of abstraction for the development and deployment of virtual worlds in a network-aware (web) environment (Polys, Brutzman et al. 2008) (BRUTZMAN 2007).

While both immersive and desktop platforms may render at different resolutions and may provide stereoscopy, the common setup is that desktops are mono-scopic and can support higher resolutions. There is a significant ongoing research thrust to understand the differences between VE platforms and to understand what design parameters should be changed when migrating content and applications (and why) (Bowman and McMahan 2007). In general, 3D User Interfaces (3DUIs) in VEs consists of three activities: Navigation, Selection, and Manipulation (Bowman 2001a) and desktop and immersive systems require different sets of interaction techniques (Bowman 2004). For example, desktop input devices (mice) are not tracked and have fewer degrees of freedom than those typically used in immersive settings. Without windows and icons and menus and pointers, designers have a new creative freedom to integrate the scene graph with novel display and input devices (i.e. (Behr and Reiners 2008)).

Design principles for interaction techniques in VEs have been described in terms of performance and naturalism [Bowman, 2002]. In spatial navigation for example, the travel technique should impose minimal cognitive load on the user and be learned easily so that it can be automatized and used 'second nature' [Bowman, 2004]. (Pierce 1997) first leveraged user perspective and proprioception in demonstrating image plane interaction techniques for selection, manipulation, and navigation in immersive environments. A number on combinations of 3DUI interaction techniques and levels of immersion can bring about the sensation of *presence* (the subjective feeling of "being there") in the user (Witmer and Singer 1998). In this chapter, we will dig deeper into the research on design principles for information and interaction techniques across desktop to immersive systems.

Information-Rich Virtual Environments

Information-Rich Virtual Environments (IRVEs) seek to unify the presentation of perceptual and abstract information displays in a natural way (i.e. (Bolter 1995)). In IRVEs, the virtual space serves as a context for the methods of Virtual Environments (VEs) and Information Visualization to be combined and so enables a unified interface for exploring the relationships between objects, space, and information. There was early evidence as to the value of enhancing perceptual / spatial information with visualizations of abstract and temporal data e.g. (Bowman 1998; Bowman 1999). The theory, tools and research agenda behind IRVEs was first formalized in (Bowman 2003a). Each spatial item, which we call a 'referent' (an object, a location, a group, people, and place) may have a variety of time-varying attributes or properties; that is, abstract and temporal information corresponding to it.

The challenge is to support users in analyzing such heterogeneous environments and understanding the relationships and patterns both *within* information types and *between* information types. IRVEs aim to render clear views of complex systems. The challenges and design space for IRVEs in desktop virtual environments were described in (Polys 2004b) and includes early techniques for: visual attributes, layout attributes and aggregation attributes that determine how abstract visualizations / annotations can be rendered with respect to their spatial referents. PathSim is an agent-based simulation to simulate the interaction of the immune system to Epstein-Barr virus (Thorley-Lawson, Hadinoto et al. 2007; Shapiro, Duca et al. 2008). In PathSim, agents travel and interact on a network approximating the physiology, thus a visualization service framework was devised to portray the time series simulation data in the context of the body (Polys 2004d; Polys 2007). PathSim Visualizer allows users to navigate a multi-scale 3D environment with (organs and tissue); users can view spatialized agent concentrations as: numeric counts, histograms for the current time, and line graphs showing agent concentrations over time.

Display: Sizes, Resolution

Both resolution and physical size of a display play an important role in determining how much information can or should be displayed on a screen (Wei 2000). Swaminathan & Sato (Swaminathan 1997) examined the advantages and disadvantages of large displays with various interface settings and found that for applications where information needs to be carefully studied or modified, 'desktop' settings are useful, but for collaborative, shared view and non-sustained and non-detailed work, a 'distance' setting is more useful. Tan et al (Tan 2003) found evidence that physically large displays aid user's performance due to increased visual immersion; Mackinlay & Heer (Mackinlay 2004) proposed seam-aware techniques to perceptually compensate for the bezels between tiled monitors.

While a number of studies have examined the hardware and the display's (physical) Field of View (e.g. Dsharp display (Czerwinski 2003)), less is known about the performance benefits related with the Software Field of View (SFOV) and virtual environments. However, Draper et al (Draper 2001) studied the effects of the horizontal field of view ratios and simulator sickness in head-coupled virtual environments and found that 1:1 ratios were less disruptive than those that were far off. There is also a good body of work on SFOV in the information visualization literature, typically with the goal of overcoming the limitations of small 2D display spaces. Furnas, for example, introduced generalized Fish-Eye views (Furnas 1981; Furnas 1986) as technique that allows users to navigate data sets with 'Focus-plus-Context'. Gutwin's recent study (Gutwin 2003) showed that fisheye views are better for large steering tasks even though they provide distortion at the periphery.

Activity Design

Ben Shneiderman (1996) outlined a task and data type taxonomy for interactive information visualization. Top-level tasks for navigating and comprehending abstract information are enumerated as: Overview, Zoom, Filter, Detail-on-demand, Relate, History, and Extract. Overview refers to a top-level or global view of the information space. Zoom, Filter, and Details-on-demand refer to the capability to 'drill down' to items of interest and inspect more details (of their attributes). History refers to the 'undo' capability (ie returning to a previous state or view) and Extract is visualizing sub-sets of the data. Enumerated data types are: 1-dimensional, 2-dimensional, 3-dimensional, Multidimensional, Temporal, Tree, and Network. Since each of these can be part of a VE, we will refer to these distinctions throughout the remainder of the proposal.

Generally, image information is best to display structure, detail, links of entities and groups; text is better for procedural information, logical conditions, abstract concepts (Ware 2000). From an activity design perspective, an tool in the design process is a 'Task-Knowledge Structure' analysis ((Diaper 1989; Sutcliffe 1994), (Sutcliffe 2003)), which concentrates on user tasks and the required information resource to formalize an entity-relationship model. This model enables the effective design of multimedia interfaces and information presentation by formalizing what media resources the user needs access to and when. This is an important technique for the design of information-rich virtual environments, as it intends to formally identify items that need user attention and to minimize perceptual overload and interference per task. Such an analysis can also help to identify familiar 'chunks' of information that can improve cognitive and task efficiency.

Munro et al (Munro 2002) outlined the cognitive processing issues in virtual environments by the type of information they convey (Table 2). In reviewing VE presentations and tutoring systems, the authors note that VEs are especially appropriate for: navigation and locomotion in complex environments, manipulation of complex objects and devices in 3D space, learning abstract concepts with spatial characteristics, complex data analysis, and decision making.

Location Knowledge	*Structural Knowledge*
Relative position Navigation 'How to view' (an object) 'How to use' (an object access & manipulation affordances e.g. a door)	Part-whole Support-depend (i.e. gravity) Containment
Behavioral Knowledge	*Procedural Knowledge*
Cause-and-effect Function Systemic behavior	Task prerequisite Goal hierarchy Action sequence

Table 2: Taxonomy of knowledge types for VE presentations (per Munro et al, 2002).

Ultimately, the visual analytic process of perception, interpretation and making sense drives some actionable outcome or decision. However, there are clear patterns of human irrationality when it comes to reasoning about probabilities, seeking disproving evidence, and evaluating syllogisms, among others (Kahneman and Tversky 1979; Kahneman 2003). Taking the experimental psychology and cognitive science evidence in sum, there are two main sources of these cognitive biases: 1) *wrong heuristics* and 2) *lazy evaluation*. **Wrong Heuristics** deals with the strategies users subconsciously adopt to reason under uncertainty. Typically, these constructs of the algorithmic mind are incomplete or simply erroneous. While Evans pioneered the dualist model eg (Evans 2003), Stanovich (Stanovich 2011) has proposed a tri-partite theory that distinguishes these errors as a results of 'mindware gaps' or 'contaminated mindware'. Several early cognitive science researchers have noted the potential for interactive computer visualization tools to mitigate these biases by replacing wrong heuristics with correct ones (e.g. (Evans 1989)).

Secondly, **Lazy Evaluation** refers to the mind's default to "miserly" information processing. For example, in several predictable situations, there are clear tendencies to ignore relevant information or to favor the most convenient explanation. One strategy to combat this is the integration of checklist tools that encourage users to seek disproving evidence for their hypotheses (i.e. (Heuer 1999)). In our alien pilot scenario, we might imagine it as a supremely rational being (unlike us) or that the ship dashboard and controls are built with an advanced intelligence that can reason through complicated probabilities, chains of events, contingencies and constraints and only give the pilot the top *reasonable* options.

Information Design

Through Virtual Environment technology (the scene graph and interactive 3D rendering), there is a vast design space for information visualization and visual analytics. Visual markers, multiple views, immersive displays and interaction modalities all provide a rich palette for the transformation of data to information. Facing this enormous challenge, designers *should* be intimidated. For developers and users there are many risks, but also many rewards. In this section, we will look at the latest research into the tradeoffs of applying information visualization techniques for insight in VE applications.

There are two crucial properties of mappings from data to visual information: the first is that they must be Computable, that is able to be calculated by the renderer in a reasonable time; and second they must be Comprehensible, meaning that the user must be able to invert the mapping function to determine the properties of the data that produced the visual representation. This last step is greatly aided by color legends for example. There is also a third property that should not be underestimated: Creativity. Creativity in the mapping process can lead to novel views that can further drive new insights.

3D Rendering

Tradeoff 1: (+) Perspective rendering can provide pre-attentive cues for depth and distance judgements
(-) Perspective rendering can introduce distortions of space that make traditional methods of measurement difficult

Guideline 1.1: If measuring X Y or Z position, include axis-aligned Orthographic camera positions and background grids

Rationale: Computer-Aided Design (CAD) and Digital Content Creation (DCC) modeling tools do this all the time – effectively making multiple 2D views from one 3D scene. Orthogonal cameras provide a view frustum with parallel sides, therefore objects are not drawn with perspective rendering.

Guideline 1.2: If additional accuracy is required with perspective renderings, introduce additional rendering tools such as stereoscopy or pop-out textual/numeric labels (details-on demand by selection)

Rationale: Stereoscopy (binocular disparity) is a strong depth cue in 'personal space' (within a few meters) and loses its effectiveness linearly with distance through the 'actions space' to the 'vista space' (Cutting and Vishton 1995). Numeric labels explicitly represent the data value but require that these data values are available, can be converted to strings for display and that there is display space for the labels.

Guideline 1.3: If additional user flexibility is required with perspective renderings, introduce additional interactive tools such as head tracking, axis-aligned measuring planes or 3D tape measure widgets

Rationale: head tracking (below) can provide strong, somatically-congruent cues for the sense of motion parallax. Provide interactive widgets, such as 3D measuring tape, to give the user the ability to designate arbitrary objects to measure; for example (Hagedorn, Dunkers et al. 2007).

Guideline 1.4: For Search tasks, use a higher Software Field of View (SFOV); for Comparison tasks, use a lower SFOV

Rationale: In general, matching the SFOV to the FOR is a good idea. Higher SFOVs act like a fish-eye lense, rendering more of the scene, but distorting the space at the periphery. Low SFOVs provide more of telescoping effect toward the focal ray. (Polys 2005c) showed that overall, users can be more accurate and faster on IRVE tasks with a higher SFOV; this is true especially on search tasks. Heads-Up-Displays (HUDs) or visualizations in Viewport space (HUDs) can compensate for low SFOVs on crowed environments.

Color & Lighting

Tradeoff 2: (+) Scene graphs provide expressive parameters to define the appearance of 3D objects in an illuminated space
(-) Real-time rendering includes shading surfaces, which can introduce perceptual artifacts distorting understanding of the underlying data

Guideline 2.1: Avoid the rainbow color scale. For nominal and categorical data, select opponent color channels first (red, green, yellow, blue, black, white) and then perceptually-distinct colors (pink, cyan, gray, orange, brown and purple).

Rationale: The perceptually distinct color choices listed here come from Colin Ware's excellent book Information Visualization: Perception for Design (Ware 2004). Borland and Taylor summarized the pre-attentive properties of color and luminance scales especially regarding linear perceptual ordering and sensitivity to spatial frequencies (Borland 2007).

Guideline 2.2: Use perceptually linear color scales for mapping. For high frequency ordinal data, use black-body radiation color scale (black to red to yellow to white). For interval and ratio data, consider a scale with equally-sized bands of ordered colors.

Note Bene: Data values should be interpolated through these spaces before becoming RGB animation values in the scene graph!

Rationale: Ordering and judging distance in color spaces is something our visual systems are naturally tuned to, thus the perceptual linearity requirement. While the luminance channel is especially attuned to details, it is also sensitive to context and field effects of brightness. This is why X-Rays are still grey-scale and why radiology reading rooms have such controlled lighting. The black-body radiation scale was originally described in the area of ultrasound imaging (Pizer and Zimmerman 1983) to keep this sensitivity to high spatial frequencies despite changes in the brightness of the context/surround**.** The X3D scene graph, for example, provides interpolation through HSV space between the RGB keyframes of the ColorInterpolator node.

Guideline 2.3: If the accurate presentation of a 3D object's shape or surface is important, use an iso-luminant color scale that varies saturation; for example, from red to gray to green. Use diverging color maps to generate double-ended color maps; for example from blue to white to red.

Rationale: Luminance information is heavily used by the visual system to judge the 3D properties of objects such as shape and curvature. Thus, (Ware 2004) recommends that color scales with a constant luminance value be employed for 3D objects. The diverging color scale method as formalized by (Moreland 2009) provides a good balance among the requirements for perceptual linearity, color-blind readers, and low impact on 3D object shading. These color scales are built into the Paraview toolkit.

Multiple Views

Tradeoff 3: (+) Scene graphs provide additional dimensions to represent high dimensional spaces and complex relationships among multiple variables
(-) Working memory is limited, so relationships between views must be explicit

Guideline 3.1: Provide clear visual feedback on how the views are related, for example, by coloring highlighted (or active) items across views consistently. In the case of multiple-view scientific visualizations, coordinate the camera positions and orientations relative to the 3D scene.

Rationale: Visual correspondences between related items across multiple views such as shared color, blinking or motion leverage the pre-attentive powers of perception and load on the Gestalt association cues of similarity (color) and common fate (items across the views change in synchrony from one user action-selection). These techniques are generally known as 'brushing and linking' interaction. Automatic synchronization of the virtual camera viewpoints for users avoids requiring the users to duplicate interaction or perform and maintain these 3D transformations (mental rotations) in their head.

Guideline 3.2: Evaluate multiple view layouts by the following criteria: diversity, complementarity, parsimony, and decomposition. In addition, consider the Task-Knowledge Structure and Gestalt principles in choosing a layout.

Rationale: Baldonado, Woodruff, and Kuchinsky (Baldonado 2000) originally proposed these four criteria. They also put forward four additional criteria for the presentation and interaction design of multiple view visualization applications: space/time resource optimization, self-evidence, consistency, and attention management. Recent empirical research supports these guidelines (Convertino 2003) and methodologies for designing multiple views should evaluate their design according to these criteria. Here, the Task-Knowledge Structure ((Sutcliffe 1994), (Sutcliffe 2003)), the Gestalt principles and the 'squint test' (van der Geest and Loorbach 2005) can be useful methods to apply.

Information-Rich Virtual Environments

Tradeoff 4: (+) Information visualizations can be spatially-referenced to 3D objects
(-) Tighter graphic associations cause more occlusion between objects and views of their properties

Guideline 4.1: **In general:**

A) choose Visibility over Occlusion & Association
B) increase the Proximity between annotations and their referent
C) minimize the relocation of annotations
D) display global and group attributes in a visible, screen-aligned display space
E) for speed, choose Legibility of annotations; for accuracy, choose Relative Size annotations
F) for Search tasks, choose strong connectedness; for Comparison tasks, choose minimal connectedness

Rationale: A set of experiments was conducted to understand the dynamics of the principal main tradeoffs of IRVEs: the Occlusion-Association Tradeoff and the Legibility-Relative Size tradeoff (Polys 2006; Polys, Bowman et al. 2011). The first tradeoff addresses the interaction of depth cues and Gestalt cues in IRVEs where the objects in a 3D space are augmented by additional visualizations, which we generally refer to as 'annotations'. For example, a 3D part in a machine may be annotated by a text label of its name, a visualization of its temperature status, its pressure tolerances, or a time series prediction of its failure profile under current conditions. Annotations in our view may be textual or graphic, and may be co-rendered with their referent in any of several coordinate systems (world, object, user, viewport, and display).

In general, the evidence shows that insuring visibility of both spatial and abstract information types is one of the most important design concerns. By the empirical data, we have shown that advantageous user performance can be achieved with very few cues (the less Association) in an IRVE. There are, however, particular circumstances where visual configurations of high Association and high Occlusion can be advantageous. Specifically, cases where the Depth cue of Occlusion and the Gestalt cue of Proximity can be beneficial. For example, on large displays, high Software Field-Of-Views, and tasks that require accuracy in Comparisons.

The second IRVE tradeoff of Legibility-Relative Size speaks specifically to the problem of rendering the annotation and its referent with consistent depth cues versus rendering the annotation with a guaranteed scale to be legible. This work shows that overall, the legibility of annotations is more important than the depth cue of Relative Size. It also presents a classic user interface tradeoff of speed and accuracy. The results show that when annotations are scaled for Legibility, users are faster to complete the tasks but also less accurate than when they are rendered with the consistent depth cue of Relative Size. This also suggests that users can gain valuable spatial information simply by the act of navigation (to achieve Legibility).

Platforms

Tradeoff 5: **(+) Increased immersion can improve spatial awareness and task performance**
(-) Increased immersion can be dis-orienting or otherwise taxing to some users

Guideline 5.1: Choose immersive rendering platforms with special attention to task requirements and tailor the information design to the platform

Rationale: User task performance can be improved through effective use of various components of immersive technology; for example by increasing the Field-of-Regard (FOR = screen-surround), or adding stereo rendering and 6 DOF tracking. (Prabhat, Forsberg et al. 2008) tested a range of immersive platforms including, desktop with head tracking, desktop with stereo with head tracking, and stereo with head tracking in a 4 wall CAVE; subjects were asked questions about the spatial relationships among items in volume renderings of microscopy data sets. While not tested as independent components, they found a similar pattern across data sets that increased immersion was a significant contributor to improved performance.

(Schuchardt and Bowman 2007) showed that performance on spatial search and comparison tasks regarding natural underground structures was significantly better by time and accuracy with a higher level of immersion: 4 walls with stereo and head tracking outperformed 1 wall with mono-scopic rendering and no head tracking. A follow-up study was conducted, which independently varied these three components of immersion for small-scale spatial judgment tasks (Ragan, Kopper et al. 2012). This study showed that accuracy is improved by increasing the FOR or including head tracking; stereo and head tracking together are advantageous for time.

Finally the highest immersion condition (with all three components of immersion) had the fewest errors while the lowest immersion condition took the longest time.

Tradeoff 6: (+) Greater screen size and resolution can present more information
(-) Legibility and sense-making requires proper management of overview-and-detail and focus-plus-context

Guideline 6.1: On large displays, increase the Proximity of visualizations/annotations to their referents

Rationale: Yost & North (Yost and North 2006) evaluated the perceptual scalability of attribute-centric or space-centric visualizations on large, high-resolution displays. They found that large displays can support faster access to more attributes across several glyph types, and that embedded space-centric views yielded faster performance on large displays. In (Ball and North 2007), the authors note that larger displays with head and input device tracking were advantageous by speed for reading 2D maps with overlaid information visualizations and that this was due to user's preference for physical navigation over virtual navigation.

(Andrews, Endert et al. 2011) provided a good overview of the challenges and opportunities with large, high-resolution displays. Summarizing their research, the authors describe some guidelines to applying information visualization design techniques to large displays. For example, balancing physical and virtual navigation, exploiting multi-scale aggregations, and using embedded visualizations and legends. Evidence from the information design of Information-Rich Virtual Environments (IRVEs) also lends support to this guideline for the tighter spatial coupling of annotations and referents on larger screens (Polys 2005c; Polys 2007). In addition, increased display size and resolution have been shown to significantly improve user performance in navigation, search and comparison tasks in IRVEs (Ni, Bowman et al. 2006).

Interaction Design

In recent years, the spectrum of immersion has expanded as high-end trackers become more multi-modal, more sensitive and more accurate; on the low end, the interaction capabilities of commodity gaming and handheld devices are also growing. In the vast area between these extremes, there is a huge design space for user interaction. In this section, we will consider how virtual environment technology can be leveraged to enable interactive information visualization applications.

Navigation

Tradeoff 7: (+) Virtual environments provide a natural 3D spatial basis for visual representation
(-) Users can still get dis-oriented and confused in the virtual space

Guideline 7.1:

- **A) Include clearly-named Viewpoints in the scene; include an easy way for users to reset their Viewpoint**
- **B) Consider using invisible walls to guide users toward targets**
- **C) Provide navigation aids such as a compass, maps and worlds-in-miniature**
- **D) Consider magic metaphors and combinations of ego and exocentric navigations**
- **E) Provide an easy means for expert users to switch between navigation modes as needed**

Rationale: In an experimental evaluation of travel techniques in a maze environment, all subjects commonly travelled to higher elevations to get a bird's-eye (survey) view of their location in the environment (Bowman, Davis et al. 1999). Several metaphors and techniques have been developed over the years; a comprehensive survey of 3D User Interface (3DUI) technologies and techniques can be found in the book, 3D User Interfaces-Theory and Practice (Bowman 2004).

Guideline 7.2: Strive to balance navigation techniques with the structure of the environment and the task

Rationale: there is a demonstrable interaction effect of navigation metaphors on user performance depending on the IRVE layout technique used. For example in a crowded environment, Chen et al. compared Homer versus Go-Go navigation techniques and Object versus Viewport (HUD) space for annotation rendering. The HUD labels provided significantly better performance overall, and there was a significant advantage to the combination of Go-Go and HUD (Chen, Pyla et al. 2004). In an experiment to assess **s**patial understanding of network graphs as measured by Landmark, Route and Survey knowledge, researchers independently varied FOR (one vs. four screens) and navigation paradigm (ego vs. exo centric) (Henry and Polys 2010). They found that for survey tasks, such as how many nodes of type T are in the graph, egocentric flying was significantly more accurate than exocentric orbiting across FOR. However for route tasks, such as counting the number of nodes between nodes X and Y, the exocentric orbiting technique provided comparable accuracy on the low FOR condition.

Guideline 7.3: Use Head tracking and stereoscopy to promote naturalism in perspective rendering on large-screen immersive setups

In an early VE experiment, Travel in an immersive VE was evaluated with tracked Head-Mounted Display (HMD) and showed that view direction should be separable from travel direction (Bowman, Koller et al. 1997b). (Raja, Lucas et al. 2004) and (Raja 2006) evaluated immersive platforms for information visualization tasks using scatter plots and surface plots (Figure 9). They found speed, accuracy and subjective trends favoring head-tracking for answering questions about scatter plots and surface plots. Stereo rendering showed a similar speed improvement with scatter plots.

There have been a number of studies over the years that have evaluated the benefits of stereo, and/or head tracking on human performance. Tracking technologies continue to improve in accuracy and reduce in latency and cost; new stereo rendering technologies are rapidly improving with stereo being used to deliver compelling content from live sports events to home gaming systems to and feature Hollywood films! A recent study with volume analysis tasks (LAHA 2012) found that each of these immersive technologies (FOR, stereo, and head tracking) contributed a statistically-significant positive effect on performance. It is worth noting the interaction effects that were observed: it seems that for complex visual and spatial searches, FOR and Head tracking together cause high significantly more accuracy and user confidence, less time to completion and lower difficulty ratings.

(Bowman and McMahan 2007) pose the potent question 'how much immersion is enough?' (McMahan, Bowman et al. 2012) worked to separate the effects of display fidelity and interaction fidelity in a VR target-based shooter game. They found that certain tasks benefit more or less from immersive technologies and that mixed levels of display and interaction fidelity can be detrimental to performance. Therefore visualization designers must consider the nuances of their application and platform when developing 3D user interfaces.

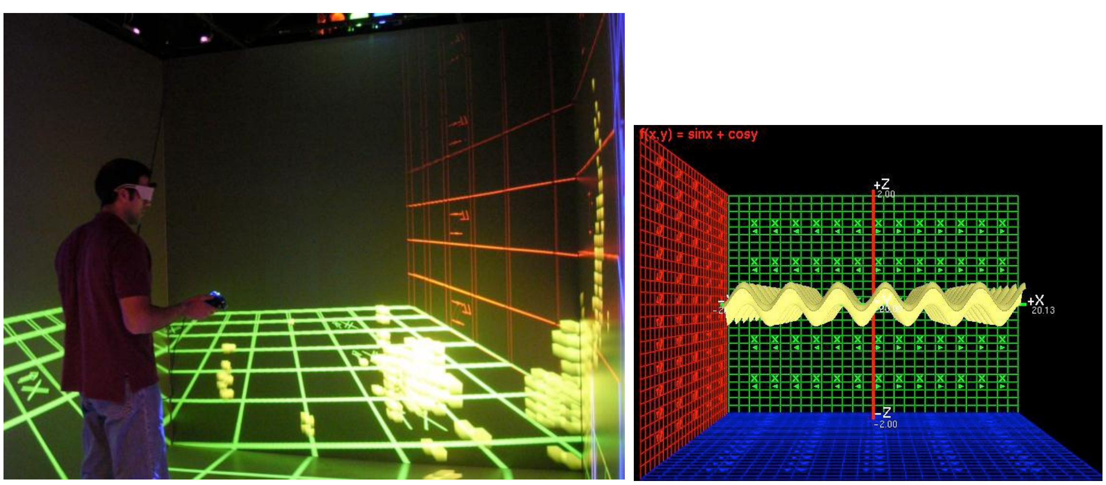

Figure 9: Images from Raja's studies – immersive scatterplot (left) and equation viewer screen shot (right)

Selection

Tradeoff 8: (+) Virtual environments provide flexible algorithms and techniques for real-time picking
(-) Odd-shaped, distant and sparse objects are difficult to select or group in 3D

Guideline 8.1: Consider magic techniques in developing 3DUIs

Rationale: The virtual world offers the opportunity to execute our tasks more easily and efficiently than we can in the real world, where we are constrained by physics. A number of techniques are worthy of note: selection by image plane (Pierce 1997), spotlights (Liang and Green 1994), dynamic aperture spotlights (Forsberg, Herndon et al. 1996) and other '3D cursors' (Zhai, Buxton et al. 1994). (Peck, North et al. 2009) developed and tested multi-scale interaction techniques on a large, high-resolution display for a hierarchical puzzle completion task. Similar to the Forsberg aperture technique, this technique scaled the size of the cursor based on the user's physical distance to the display.

(Dykstra 1994) showed that VEs could be coordinated with embedded 2D windowing (X11) spaces. Snap2Diverse (Polys, North et al. 2004a) used the Snap-Together Visualization toolkit to coordinate multiple views of a molecule database where interactive 2D views were displayed on one wall and other walls displayed the coordinated 3D view. These 2D 'application textures' embedded in 3D space provide quick federation and prototyping of VEs with other visualization tools and GUIs.

Guideline 8.2: Consider alternative metaphors for distant selection and for selection in crowded environs

Rationale: In some early research on how to improve selection techniques, Wingrave et al examined the role of individual differences among users (Wingrave, Tintner et al. 2005) and found that magic techniques can be detrimental if users are highly automatized in 'over-learned' tasks such as reaching. General mathematical models of 3D distal pointing have been developed and described based on experimental evidence (Kopper, Bowman et al. 2010). Pointers that can curve around obstacles have been proposed (Olwal and Feiner 2003). 'Flavors' have been proposed that extend or nuance existing techniques for some advantage; for example, raycasting selection and SQUAD selection to handle dense environments (Cashion, Wingrave et al. 2012).

Manipulation

Tradeoff 9: (+) 3D input devices offer additional degrees-of-freedom to define natural user interactions
(-) the metaphors and usability for 3D User Interfaces (3DUIs) are still an evolving research area

Guideline 9.1: Explicitly map your device degrees of freedom; balance learnability and efficiency per application

Rationale: (Wilkes and Bowman 2008) looked at extending the HOMER technique; with the same device and degrees of freedom, they mapped a more natural interface for selection and manipulation at a distance. The 2010 3D User Interface Contest held in association with the IEEE VR and the Symposium on 3D User Interfaces (Figueroa, Kitamura et al. 2010) has demonstrated several innovative approaches to the task of collecting items in a structured and crowded virtual environment. Deep consideration of user's task seems to be the most important criteria for a successful 3DUI: 'Naturalism' and magic in 3D User Interface techniques is clearly an area where this applies (i.e. (Bowman, McMahan et al. 2012)).

Reflections on 'The Next Reality'

Scene graphs and 3D graphics libraries bring real expressive power to visualization design. The additional dimension of 3D in real time spatial views provides a rich palette of visual representations for data. As virtual environment content becomes more prevalent and scene-graphs are supported natively across the web, we will continue to see development of innovative and dynamic info-graphics and dashboards. Building these new interfaces and applications, we must remember to *test early and often*. Pilot studies and 'discount' usability methods can support quick design iterations with large gains.

Computing technology is becoming ubiquitous and is infiltrating everyday aspects of our lives from our education, research, and work to our entertainment. Mobile devices are rendering hardware-accelerated interactive 3D worlds today. Relatedly, 2D multi-touch and 3D gesture interfaces are becoming more refined and widespread. It is an exciting prospect as these display and interaction devices begin to communicate in a user-centered information ecology. The Wild room (Beaudouin-Lafon, Huot et al. 2012) is an exciting example where this transparent sharing and coordination of views across display devices can bring new insights. Like sonification + visualization, we will continue to build and evaluate coordinated multi-modal interfaces including haptic rendering and feedback. In addition, new perspectives such as affective computing and Brain-Computer Interfaces (BCIs) will continue to evolve and offer value for information visualization and virtual environment designers.

Considering the state-of-the-art of networked devices, sensors and virtual environments, the imminent horizon is the fusion of real and virtual information spaces. There several examples of 'Mirror Worlds' out there today: persistent virtual worlds that, through various sensors and services, reflect the objects and events in the real world. As the technology and techniques underlying Augmented Reality improve, it will be increasingly possible to register and composite virtual environment graphics with objects in the real world. Indeed, we can expect to see end-user applications becoming smarter as they integrate sensor information from local and online sources to augment our cognition and situational awareness.

Technology churns with market forces and despite the clear potential, several rounds of software and companies have been born with great fanfare and then died. Across all these re-invented flavors of the wheel, the scene graph is the true enabler. Readers are encouraged to examine the flexible and expressive scene graphs such as Virtual Reality Markup Language (VRML), Humanoid-Animation (H-Anim) and Extensible 3D (X3D) (Web3D 1997; Web3D 2012). As ISO Standards, this content has shown an amazing durability; virtual worlds built 1997 are still being run across the latest hardware and operating systems with the most modern input sensors and displays.

Like our alien pilot, human users browse, search, compare, look for patterns, and evaluate alternatives through visual analytic environments. Through further research into the perceptual and cognitive capacities of humans, perhaps one day the interfaces to these environments will be transparent. As we better learn how to take advantage of the natural pre-attentive and pattern-recognition skills of the human, we can increase the transfer of information between the computer and the mind. Thus in my view, the grand challenge is ultimately an optimization problem: across all these channels of communication (aka the bandwidth of the senses), we are looking to increase the throughput of information across the real 'last mile': the distance between the data and the information.

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