Virtual Reality and Abstract Data:

Virtualizing Information

by

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Abstract

Virtual reality interfaces may be used to display and analyze abstract data. This paper addresses some of the principles that may be employed in creating a mapping between abstract data and dimensions of a virtual reality.

I. Introduction

The term virtual reality subsumes many different kinds of activities. Spring(1990) provides a taxonomy that classifies various efforts along three dimensions: interaction mode, reality base, and locus of control. The interaction mode continuum ranges from symbolic or artificial interactions to natural interactions. The reality base spans a gamut from real to constructed realities. The locus of control dimension goes from total user control to shared control with any particular user exerting a small amount of control over the behavior of the system.

This paper discusses the design of virtual realities based upon a constructed reality base derived from some abstract data set. The interaction mode used is of little relevance, and the user is envisioned as the primary locus of control. The ideas presented are rooted in work on scientific visualization, algorithm visualization, hypertext and hypermedia browsers, etc.

Spring(1992) suggests research on virtual reality tends to focus either on the construction of the virtual reality environments or the interface to them. The goal of virtual reality interface research is to allow users to more fully experience the environment being simulated through some combination of immersion technologies such as stereo visual and auditory stimulation; head, hand and body tracking; voice recognition and speech understanding; and force feedback, olfactory and gustatory stimulation. The goal of research on virtual reality environments is to construct spaces and agents can be meaningfully experienced via virtual reality interface technology. This paper addresses the construction of a virtual reality space based upon abstract data sets. More specifically, the paper is concerned with creating environments, and ultimately agents to inhabit the environment that will help a user to solve some problem in the abstract data space. The mapping of abstract data to a virtual space, which we call virtualization, is discussed in the a context of scientific visualization, modeling, and simulation.[1]

The paper begins with some background and examples of virtualization. The overall process of virtualization is then discussed. Finally, the considerations upon which the dimensions of a given data set might be mapped to the dimensions of a virtual space are discussed.

II. Background and Examples of Virtualization

The foundation for virtualization includes work on scientific visualization, cyberspace design, visual languages, and hypertext browsers. Scientific visualization(McCormick,1987; Defanti, Brown, and McCormick,1989) establishes a baseline for the effort. While the principles of scientific visualization are important to virtualization, scientific visualization has tended to focus on the visualization of data sets that have some spatial origin; that is, aspects of the data set are anchored to spatial dimensions. Wind velocities are plotted on a spatial coordinate system, the intensity of stellar radiation is plotted on a stellar map, etc. When the data is inherently spatial, the problem of depicting data in a virtual space is in some ways easier -- there are more constraints and affordances applied to the problem. However, there is no reason why non spatial data sets can't be mapped into a virtual space. The process of mapping these kinds of data sets is the primary focus of this article.

A number of authors have begun to address the design of cyberspace, in some cases specifically to enhance problem solving in that space. Benedikt(1991) provides an overview set of principles for cyberspace. More broad ranging than the current study, Benedikt sets out a series of principles and corollaries for cyberspace. The current work might be placed within his discussion of the dimensionality of cyberspace. Wexelblat(1991) provides a specific set of rules for mapping abstract data sets in cyberspace. His work, discussed further below, relates primarily to the nature of the dimensions being mapped. Lewis extends visualization techniques to the problem solving arena, suggesting that "order of magnitude improvements in reasoning can be obtained by transforming unfamiliar situations into familiar ones"(Lewis, 1989, p.1). More recently, he has proposed a series of techniques for developing situated visualizations(Lewis, 1992).

Support for this effort may also be found in the visual languages field and in the research on hypertext/hypermedia browsers. Rohr(1984), Selker and Koved(1988) and others have developed metrics and rules for the application of visual techniques to information. Henderson(1989) describes the use of three-dimensional scatter plots to guide the work on a trauma data base. Conklin and Begemen(1987), Crouch(1987), and Lesk(1989), among others, have experimented with depicting large idea spaces, particularly with reference to hypertext. Chaney, Shipman, and Gorry(1989) describe the use of hypertext systems to increase information sharing. Petersson and Kindborg(1991) develop a classification of navigational principles for hypertext.

Just as visualization provides an opportunity to see trends and instances in the data that might be lost using statistical techniques, virtualization provides an opportunity to see, hear, feel, smell, and taste trends and instances in data. As we see it, virtualization might also allow a situation where aggregate data might be used to animate agents in an environment. Consider two examples.

1 The term virtualization is used here because of the strong relationship to visualization. Indeed, from a purist perspective, what is being done here is little more than visualization. However, because it is not common to use non-visual data, e.g. auditory and tactile, in visualization, and because we imagine the process taking place using the kinds of immersion interfaces associated with virtual reality, the term virtualization is suggested to help capture the flavor of the process.

One might imagine virtualizing a document collection. Rather than creating a virtual library where the user would see shelves and book spines, the goal is to allow a user to navigate an idea space:

> *Consider a system that allows the user to visualize the potential importance of the volumes to a particular research problem. Imagine walking into a virtual library with a query and having all irrelevant data sources appear black, all contrary evidence appear in shades from maroon to bright red, and all supporting ideas represented in shades from midnight blue to blue-white. Related concepts might be depicted in shades of green and yellow. As the researcher proceeds and the research problem is modified, the shades and colors of the entire collection of ideas are modified to reflect the support and contradiction of the new theories....The example could be taken further to associate names in different sizes floating near the bright splotches of color as a mechanism for depicting the authors who have written major pieces or are frequently referenced in works related to the query.(Spring, 1990)*

Further consider that documents might be active, like a knowbot(Cerf, 1991, p. 74), but for out purposes more like the converse of a knowbot -- an infobot.[2] An infobot is an active document that looks for humans to inform. Attached procedures include processes for duplication, charging, and navigating the cyberspace looking for readers. An executive information system might be developed where the various divisions of the corporation would be represented as spheres in space. The size of the sphere is representative of its gross revenues. The sphere pulsates showing fluctuations in sales with time compressed by 1000 to one. The color of the sphere is a factor of the return on investment. The luminance of the sphere represents some measure of new products or markets, the texture of the sphere represents the health of labor relations, etc. Upon request, the spheres could be sliced open, or the participant could move inside them. The internal view might depict the levels of management in each organization. Finally, imagine that data about negotiations with the union is so structured that it causes an increasingly loud rumble to come from the related sphere as tension grows or negotiations falter. The use of the auditory dimension to depict this data would make it available to the participant regardless of where their visual attention was focused.

These examples are very incomplete, and in one or more ways beyond the capabilities of today's technology. For example, both examples assume immense data sets that must be continually searched, organized, and filtered to support virtualization. The results must then be presented to the user. The computational demands[3] can be significant. Further, the ability to take this kind of approach to its ultimate end is dependent on a high degree of standardization and interconnection. It also seems to be more consistent with an object oriented approach to analysis, design, and implementation. The adoption of standards and the evolution of object oriented approaches are not things that are going to happen overnight. In the scenarios depicted, there was no description of what dimensions of the data defined the virtual reality dimensions. (In the library example, no rules are given explaining the dispersal of ideas in an X-Y-Z space.) In reality, no principles have been set down for the mapping of data dimensions to spatial dimensions. Also, the examples generally avoid the use of the auditory and tactile dimensions. We as yet have very limited experiences with the use of the dimensions available through these senses for data mapping. Finally, allusion is

2 The scenario assumes a cyberspace infrastructure that is based at the very least on the existence of interconnected and interoperable machines. This particular scenario is based further on the assumption that directory information of the type imagined by the X.400 standard is available--under X.400, information about the user is stored as an adjunct to the user's identifier, and there is a high level of standardization in data interchange formats.

3 See Spring(1990, pp 10-11) for an estimate of the computational demands of a system like that suggested for querying a document collection.

made to complex active objects, i.e. divisions of a corporation and documents. No account is provided of how these objects are constructed, the rules that determine the "functioning" of these objects.

III. The Process of Virtualization

Virtualization is the mapping of an abstract data set to a virtual space. Mapping abstract data to a virtual space is a process with which most people are familiar in a limited context, i.e., many people have mapped abstract data dimensions to a plane defined by two orthogonal lines -- a graph, or an X-Y plot. However, beyond this mapping of data to X-Y spatial coordinates, the process is less familiar and more difficult. Scientific visualization often incorporates a third spatial dimension, a fourth time dimension, and some other visual dimension such as hue or brightness to represent data. A good example is weather data on cloud cover.

Virtualization involves four intertwined steps. They include:

1. Selecting the data to represent the problem space
2. Selecting the dimensions of virtual space to emphasize, and defining the assumptions that will guide the operation of the space
3. Developing a metaphor
4. Mapping of data dimensions to space dimensions

While the primary focus of this article is on the last step, discussed in part IV, the overall process is briefly discussed first.

A. Selecting data to represent the problem space

As will be shown soon, the number of dimensions available to the designer is large. At the same time, varying data over too many dimensions can cloud rather than clarify the problem. While the number of available dimensions exceeds twenty, the designer may be well advised to keep the number of active dimensions under ten for experts, and under five for casual users.[4] Prior to virtualization, irrelevant data dimensions need to be pared away. If the relevance of data can't be determined, it should be kept in the data set. Generally, it is the designer's responsibility to make sure that the importance of, and the need for, data is considered.

Beyond the exclusion of irrelevant data, some preliminary data analysis should be done prior to virtualization. For example, not all data dimensions are orthogonal. Every effort should be made to organize and relate the data and virtual space dimensions. For example, if heart rate and body temperature are not completely independent, an effort should be made to associate them in the virtual space as well, e.g. by representing them as closely related dimensions such as color saturation and brightness.

B. Selecting dimensions of the virtual space

While data dimensions vary with each project, the possible dimensions of a virtual space are constant. The taxonomy presented here represents a first effort to provide a common perspective on the

4 Some of our colleagues have suggested that the limits of human information processing are indeed very low. We believe that with training, it is possible to manage large data sets semiautomatically, only turning direct attention to stimuli when they are not in the proper range.

dimensionality of a virtual space. The listing is by no means final. Some of the dimensions may not be fully orthogonal from a user perspective, e.g. brightness and saturation in the visual domain or texture in the tactile and visual domains, while others may be internally orthogonal, e.g. the object dimension of location is capable of representing three dimensions of data--in a three dimensional space. The focus of this effort is on the visual, auditory, and tactile senses. While dimensions also exist for the gustatory and olfactory senses, they are not defined here.[5] For each sense, the dimensions of a virtual space are defined along with the dimensions for objects that might exist in that space. The dimensions of objects in a virtual space are delimited by the dimensions of the space. Thus, three dimensional objects may not exist in a two dimensional space. The list of object dimensions might be expanded by including secondary dimensions--dimensions that may exist for an object, or as dimensions that are dependent upon some other dimension.[6] The reality and object dimensions defined at this point include:

1. Visual Sense
   a. Reality Dimensions
      i. Dimensionality
      ii. Density
      iii. Continuity
      iv. Background illumination
      v. Mobility[7]
   b. Object Dimensions
      i. Hue
      ii. Saturation
      iii. Brightness
      iv. Location
      v. Shape
      vi. Size
      vii. Opacity
      viii. Texture
2. Auditory Sense
   a. Reality Dimensions
      i. Conductivity
      ii. Background Noise
   b. Object Dimensions
      i. Loudness
      ii. Pitch
      iii. Purity
      iv. Location
      v. Duration
      vi. Melody
      vii. Harmony
3. Tactile Sense
   a. Reality Dimensions
      i. Ambient Temperature
   b. Object Dimensions
      i. Temperature
      ii. Hardness/solidity
      iii. Texture
      iv. Location
      v. Shape
      vi. Weight
      vii. Size
4. Olfactory Sense (not defined)
5. Gustatory Sense (not defined)

The reality dimensions selected may be viewed as limiting the object dimensions that may be used. For example, if a two dimensional space is selected as the basis of the reality, three dimensional shapes

5 The reasoning for excluding these sensory dimensions has to do with the relative lack of devices for employing feedback to these senses as well as the paucity of research on the discriminability of the stimuli.

6 One dimension that has some relevance to the current efforts but which is excluded as a dimension is closure. It may well be that closure should be defined as a secondary dimension dependent upon the shape of an object.

7 This dimension of the visual reality was difficult to specify. From the users perspective it has to do with mobility, from the perspective of the space it has to do with the ability to transform the view of the space by changing perspective

may not be depicted, and tactile texture would be eliminated.

Visually, five reality dimensions are suggested:

1. dimensionality
2. density
3. background illumination
4. continuity
5. mobility

The first may seem redundant, but it specifies the number of spatial dimensions in the reality. There may be one, two, three, or possibly four for those viewing time as a fourth dimension. Obviously choosing a one or two dimensional reality would limit the kinds of shapes that might occur in the reality. Similarly, a reality with no background illumination would make it difficult to see shapes. Similarly, a discontinuous space would limit the placement of objects in space. The mobility dimension, as mentioned above is a measure of the transformability of space.

In the auditory realm, the reality will have some degree of conductivity and background noise. The amount of background noise will affect the sounds we are able to distinguish and those that are masked. The conductivity of the reality will affect what sounds we hear at that distance. Similarly, in the tactile dimension, ambient temperatures will affect whether objects feel hot or cold, and to what extent they exhibit these characteristics. All of these characteristics should be considered in the development of the base metaphor for reality.

C. Developing a metaphor

The development of metaphors owes its heritage to the development of metaphors for graphical user interfaces. Whether an underlying metaphor selected is appropriate is beyond the scope of the current work. There are general suggestions for the metaphor--namely that the data space is mapped to some metaphorical physical space. While we avoid the suggestion of particular metaphors, we do commend Kay's concern with metaphors:

> *My main complaint is that metaphor is a poor metaphor for what needs to be done. At PARC we coined the phrase user illusion to describe what we were about when designing the user interface. There are clear connotations to the stage, theatrics, and magic--all of which give strong hints as to the direction to be followed. For example, the screen as "Paper to be marked on" is a metaphor that suggests pencils, brushes, and typewriting. Fine as far as it goes. But it is the magic--understandable magic--that really counts. Should we transfer the paper metaphor so perfectly that the screen is as hard as paper to erase and change? Clearly not.(1990, p. 199)*

Thus, whatever metaphor is developed, it is important that the developers are not overly bound by the metaphor. The development of an appropriate metaphor, with attendant illusions, is critical. If the metaphor chosen is totally inappropriate or misleading, the effort may be bound to failure.

IV. Considerations in Mapping Data Dimensions to Spatial Dimensions

Three considerations for mapping data space dimensions to the virtual space dimensions are discussed in the next section. The rules, with no particular priority implied, are:

1. match data dimension **type** and virtual space dimension **types** as closely as possible
2. match the discrimination needs of the data dimension to the discrimination capabilities of the virtual space dimension
3. select preattentive virtual space dimensions for critical data dimensions.

Each of these is briefly discussed below.

A. Matching Data Dimension to Virtual Space Dimensions

Wexelblat has suggested that cyberspace has absolute and relative dimensions, and that each kind is one of six types--linear, ray, quantum, nominal, ordinal, and functional(1991, p.257). Absolute dimensions are those which may be defined for an object in isolation; relative dimensions are those that express a relationship between objects. Wexelblat(1991, pp 259-261) distinguishes between various forms of interval and ratio data. For example, ray and quanta appear to be interval/ratio data types. Quanta data are integer in nature while ray data have an upper or lower limit. While these distinctions are all well founded, we opt for a simpler set of classes based on the traditional classification of data as:

1. nominal
2. ordinal
3. interval
4. ratio

Nominal data is data that can only be named--there is no implication of ordering. Ordinal data can be ordered, but there is no implication that the difference between any two positions is equal. Interval data is ordered and the units of the scale are constant. However interval data does not imply a zero point such that any point may be defined as a ratio to another point. Ratio data implies a zero point allowing the specification of ratios. The following examples provide simple illustrations:

1. nominal data: 1 apple and 1 banana -- classified; no order implied
2. ordinal data: 1 adolescent and 1 adult -- ordered; no interval implied
3. interval data: 1 temp 98.7^{o} and 1 temp 99.7^{o} -- ordered, interval, no ratio implied
4. ratio data: 1 180lbs and 1 190lbs -- ordered, interval, and ratio

If a data dimension is ordinal, it should be mapped to an ordinal spatial dimension. Mapping ordinal data to a nominal dimension would not eliminate the ordering from the data causing potentially important trends to be overlooked. Mapping ordinal data to an interval or ratio data dimension would imply more than the dimension offered, potentially showing apparent trends where none existed.

Below, the various sensory dimensions that might be used in a virtualization are classified by type. Caution needs to be exercised in interpreting the classifications provided for at least two reasons:

1. The type of a given dimension is not always clear. For example, while the wavelength of light is interval, if not ratio, in type, the colors that result, that we perceive are more like a nominal data type. For certain classes of user, the ordering of colors might be meaningful, while for others, no ordering would be implicit.
2. The type of a dimension varies for classes of user. Again, consider color--for most users, color is nominal, but for physicists, it may well be an ordinal or even an interval type. Generally speaking, the more expert a user is in dealing with a given dimension, the more likely they have provided additional structure along that dimension.

Thus, we might imagine using the three dimensions of color in something along the following lines. Hue is best used as a nominal data type. Brightness on the other hand is at least an interval, and more than likely, a ratio dimension. Saturation, a third dimension, is less well understood. Surely we can sense more of less of a given hue at a given brightness, whether we can articulate interval differences or only ordering is less clear. The best choice for an interval dimension would probably be brightness. The best match to an ordinal dimension would be saturation, with caveats. The best match to a nominal dimension for the general population would be hue.

Other dimensions may also be used. Location clearly has interval characteristics, and with the specification of an origin, takes on ratio characteristics. The shape dimension may be used to specify a variety of nominal categories. Size may be used for ratio dimensions. Below, the various dimensions of virtual space are roughly classed by dimension type. As has been noted above in the discussion of hue, these classifications can be modified slightly depending upon the user population and conventions used in establishing a broader framework.

Sense/Type	Dimension	Data Type
VO	**Hue**	**N/O**
VO	**Saturation**	**O/I**

VO	**Brightness**	**I/R**
VO	**Location**	**I/R**
VO	**Shape**	**N**
VO	**Size**	**I/R**
VO	**Opacity**	**I**
VO	**Texture**	**N/O**
AO	**Loudness**	**I/R**
AO	**Pitch**	**O/I**
AO	**Purity**	**N/O**
AO	**Location**	**I/R**
AO	**Duration**	**I**
AO	**Melody**	**N**
AO	**Harmony**	**N/O**
TO	**Temperature**	**O/I**
TO	**Hardness/solidity**	**O/I**
TO	**Texture**	**N/O**
TO	**Shape**	**N**
TO	**Weight**	**I/R**
TO	**Size**	**I/R**

B. Match Dimension Discrimination

This criteria attempts to map data to the sensory dimensions in accord with the discriminability needed in that dimension. For example, while we can distinguish a wide range of colors, we are less capable of distinguishing the range of saturation of a given color. There are significant complications that arise in trying to develop simple numbers about the discriminability of a given dimension. For example, it is relatively easy to discriminate along a dimension when both objects are present contemporaneously. It is much more difficult to make the discriminations absolutely. We may know that X is more red than Y, but we are not able to specify that X is 52% red. We know that Bob is taller than Fred if we see them both together, but it is more difficult to say that without a common reference. Similarly, it is difficult to say that Fred is 6 feet tall without some measure. With these limitations in mind, we have tried to provide the maximum relative discriminability along the object dimensions selected. The reader can reference the cited research which directly or indirectly provides not only the corresponding data on absolute discriminability, if it exists, but a wealth of qualifying data about the relative discriminability.

Knowing the discriminability of the sensory dimension, we can map to it an appropriate data dimension. Data dimensions may be classified in terms of the data range and critical delta of the data--the change in data value which reflects a significant change along that data dimension. Take as an example heart rate data. Given a data set where heart rate varies over an operational range of 100 units and a need to discriminate differences of 2 units,[8] we need to be able to pick out 50 different values. A sensory dimension is needed that allows 50 different values to be noted. As is discussed below, hue would make a better dimension match than saturation.

The general formula is:

discriminable categories =
operational range / discrimination difference

If the range were 10, and the discrimination difference was .1, the formula provides for 100 discriminable entities. Below, we summarize some of the relevant research. In an effort to be concise, we have made rather simple calculations to provide the reader with a general sense of the discriminability that might be expected for a given dimension.

Hue 156 discriminable hues (Geldard, 1972)

Calculation of inverse Weber fraction = ($I/\Delta I=300/1.923=156$) Jones (1917) found a total of 128 just-noticeable-differences (j.n.d.'s) within a spectral range of 400 nm to 700 nm. Some differences were 1 nm apart, while most of them were 3 nms in length. Smith (1925) found 28 additional j.n.d.'s for groups of colors made up of non-spectral purples and the purplish reds bringing the total number of discriminable hue steps to 156. One hundred

8 That is, we don't need to be able to distinguish between heart rates of 71 and 72 but we should be able to distinguish a heart rate of 50 from a heart rate of 54

(100) Munsell Hues have been documented to be discriminable (Boff et al., 1986).

Saturation 15-25 distinguishable levels of saturation.

Distinguishable levels of saturation varies with hue. The numbers provided are obtained by using the inverse Weber fraction for each color. There are 23 discriminable reds (ΔI=3.391 nm; inverse Weber fraction for reds (I/ΔI=78/3.391=23)), 23 discriminable violets (ΔI=2.391 nm; inverse Weber fraction for violets (I/ΔI=55/2.391=23)), and 16 discriminable yellows (ΔI=1.25 nm; inverse Weber fraction for yellows (I/ΔI=20/1.25=16)). All other colors are intermediate with ΔI's of 1-3 nm (Jones and Lowry, 1926; Geldard, 1972).

Saturation is defined as "that attribute of all colors possessing hue which determines their degree of difference from a gray of the same brightness.

Brightness Approximately 60 discriminable levels of brightness (Schiffman, 1976). (ΔI/I=.016) or 1/60 of white light; (I/ΔI=60/1=60).

An average of 600 quanta of 555 nm light (Baumgardt, 1972). Five levels of brightness have been proposed by AFSC DH 1-3, 1980. The amount of light required to produce a noticeable sensation of light, but no color, is estimated to be 1/1,000,000,000 of a lambert (AFSC DH 1-3, 1980). The visual system is not equally sensitive to lights of all wavelengths. For lights that differ in wavelength, equal numbers of quanta (packets of energy) do not imply equal detectablity or equal brightness. Specifying the amount of electromagnetic energy in a stimulus gives no information about the ability of that stimulus to elicit a response. For the cone system, the minimum energy threshold is about six to ten times higher. Marriott (1963) used a small (1 min arc), brief (1.2 msec), foveal light of 550 nm., a wavelength near the peak of the photopic luminosity function. For nine observers, the number of quanta required for 50% detection ranged from 494 to 879 with a mean of 606. An average of 600 quanta of 555 nm light represents a reasonable estimate for the minimum energy threshold for the fovea and consequently for the cone systems (Baumgardt, 1972).

Location 15,600 discriminable locations

The diameter of the fovea (central portion of the retina where acuity is greatest) may be expressed as 30 min of arc (Boff & Lincoln, 1988). Normal resolution of visual acuity is expressed as 1 min arc. The maximum field of view of the normal observer for both eyes together extends 60 degrees above and below the center of the visual field (120^o) and about 65^o to the sides (130^o)(Harrington, 1988). Using a much larger arc to accommodate less sensitive peripheral vision, we suggest that 10 min of arc averaged across the visual field as a reasonable number. For targets 1^o in size, this yields 15,600 discriminable locations in a 120^o by 130^o visual field.

This however is not the full story. For a brief period of time during saccadic eye movements, the visual system is relatively insensitive to movements of visual targets (Boff, Kaufman and Thomas, 1986). This sensitivity is proportional to the size of the saccades: displacements less than 20% of saccadic extent are generally not detected (Mack, 1970). Under natural, unrestricted viewing conditions, the perception of distance is reliably accurate or, at least, consistent. The relation between perceived distance and physical location, on the average, can be described by a power function with a constant exponent approximately equal to 1.0 (Boff and Lincoln, 1988). Observer's require 0.6 seconds to change visual fixation from near to far (AFSC DH 1-3, 1980).

Shape Approximately 70 discriminable shapes (Veniar, 1948).

Horizontal or vertical distortion of a square shape will not be perceived if the distortion is less than 1.4% of the original length. Unlike other visual functions, shape discrimination does not vary systematically with target size and illumination. Veniar (1948) found that the difference threshold for shape distortion of a square (smallest perceivable length change in the horizontal or vertical sides of a square) is 1.4% of the original length of the sides. The difference threshold for shape distortion of a square is roughly the same regardless of the original size of the square or whether distortion is in the horizontal or vertical dimension, with no consistent differences due to illumination levels (Boff and Lincoln, 1988) Using estimates from Veniar (1948) for a 100 x 100 cm square, the next largest distinguishable square was calculated as (1.4% - 100). Continuing until the last 1.4% of the smallest square yields approximately 70 discriminable square shapes. (Kaess, 1978), suggests .1 to .5% of original or standard object shape, or 3 to 10 discriminable shapes. The perception of form, shape and spatial relations are dependent on the duration of the stimulus. For the perception of form, however, the relationship between time (duration) and stimulus intensity appears to be complex (Kahneman, 1966).

Size approximately 100 distinguishable sizes.

Research suggests that any two objects may be distinguished when one is plus or minus 4% of original or standard object size (Gibson, 1947). For the estimate given above, the largest object considered is one that subtends 60^o of the visual field--the total vertical field. Beginning with that object, the next largest distinguishable object was calculated--.96x60. Continuing in this fashion to objects 1^o in size yields 100 distinguishable sizes.

Size constancy has been demonstrated for standards of 63-75 in. up to 784 yds; averaged over standard heights matched size rose only slightly and irregularly, by about 4%. Percentages may vary up to 30% for polygons with average heights of 3-25 inches (Teghtsoonian and Teghtsoonian, 1970). Linear perspective relations provide scales for judging the size of objects in an observer's visual field. Size perception is directly influenced by changes in the height of a visible horizon. In visual simulation, the apparent size and/or distance of objects can be purposely or inadvertently modified through manipulation of linear perspective cues and visible horizons (Boff and Lincoln, 1988).

Opacity No documented statistical method of determination

Texture No documented statistical method of determination.

Optical texture becomes denser and more compressed as the ground recedes from the observer, but the rule of equal amounts of texture for equal amounts of terrain remains invariant (Gibson, 1986). With a constant spacing of elements, perceived slant increases as element size increases up to the point at which elements are nearly touching; at this point perceived slant decreases. Human observers perceive texture gradients as being slanted in depth, although perceived slant underestimates objective slant (Boff and Lincoln, 1988). However, no physiological bases have been proposed (Hochberg, 1964).

Loudness Weber fractions varied roughly between the limits of 1/20 (2500 Hz at 100 dB) or $I/\Delta I$=20/1=20 discriminable levels of loudness (Riesz, 1965).

Several variables influence the magnitude of ΔI for audition. Intensity is the major variable for loudness. The size of ΔI (and of $\Delta I/I$) is seen to be minimal, i.e., differential sensitivity is greatest, in the region of 2500 Hz. (Shower and Biddulph, 1931). The effect of intensity measured for a dB range of 5 to 80 dB and a frequency range of 16 to 16,384 Hz showed that Weber fractions varied roughly between the limits of 1/20 (2500 Hz at 100 dB) or $I/\Delta I$=20/1=20 discriminable levels of loudness (Riesz, 1965).

Pitch Approximately 12 discriminable pitches over a 125 Hz to 12000 Hz range (125, 250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000, 8000, and 12000 Hz).

Information theory makes attractive the concept of an equal number of just noticeable differences (JNDs) for pitch representing equal lengths on the frequency axis. Since the number of JNDs does not vary substantially with intensity above a sensation level of about 40 to 50 dB, and since it is the ratio between adjacent frequency intervals that is important, the 12 frequencies (JNDs) listed are the most reasonable compromise. The JNDs are based on data on the localization of frequencies along the basilar membrane and on the topography of the blood supply from Foss and Flottorp (1974). Early determinations of differential thresholds for pitch were inexact. For example Luft (1888) found .25 Hz and Vance (1914) found 1.80 Hz, and Shower and Biddulph (1931) found 2.60 Hz (Carterette, 1978). Empirical support is weak for current theories of frequency discrimination whether temporal or place theory is used. It is suggested that temporal coding operates at low frequencies and place coding at high frequencies. The boundary between low and high may be near 5,000 Hz, where many phenomena associated with frequency coding show a more or less abrupt change (Moore, 1982). The Weber fraction ΔF/F, the smallest change in frequency that is just detectable is specific to many frequency intervals within the 20 Hz to 20000 Hz range, and radically different results are obtained at low and high frequencies depending on the methodology used for measurement (i.e., frequency modulation, or separate bursts differing only in frequency, temporal or place coding (Boff, Kaufman and Thomas, 1986).

Purity No documented statistical method of determination

If a trumpet, a violin and a piano were each to play the same note (say the middle C of 256 Hz), a listener could tell the instruments apart because of experience with timbre. It does not require an expertise and familiarity with the sounds of the instruments (Gerow, 1986).

Location No documented statistcial method of determination.

It would appear to be a single order of magnitude discrimination. We can clearly locate sounds to the front, rear, left, and right. Indeed some simple experiments suggest that 45 degree separations appear to be distinguishable.

Duration Approximately 3 to 20 discriminable durations over a 200 Hz to 3500 Hz range at 85 dB (Abel, 1972).

Changes in duration thresholds with stimulus duration can be well described by a line with a slope of 0.5 msec for durations less than 50 msec and by a line with a slope of 1.0 msec for durations greater than 50 msec. The discrimination of the duration of noise bursts is independent of signal bandwidth, amplitude and waveform. For a 200 Hz tone, and a 1000 Hz tone at 85 dB SPL, there are 6 discriminable durations over a .1 to 2000 msec standard range of stimulus duration. For a 3500 Hz at 85 dB SPL, there are 14 discriminable durations. However, for a 3500 Hz tone at 65 dB, there are 3 discriminable durations over a .1 to 2000 msec standard range of stimulus duration (Boff and Lincoln, 1988). Abel (1972) suggests .75 msec of noise bursts.

Melody Approximately 1 to 40 discriminable tones over a 10 to 50 dB SPL (Scharf, 1970)

The total stimulus energy required to detect a multitone complex (sequence of tones) presented in noise or in quiet remains constant regardless of the number of tones in the complex, provided all tones fall within a narrow frequency range (critical band); that is, as tones are added to the complex, the level of each tone can be decreased so that overall stimulus level is constant and the complex will remain equally detectable provided all tones are within the critical band. When the frequency separation of the components is greater than the critical band, the total energy of the complex must be increased as the number of tones increases for the complex to remain audible. Threshold for a multitone complex increases linearly with the number and frequency separation of the components when components are added outside of the critical band. For example from 10 dB to 50 dB within a frequency range of 1 to 200 Hz (critical band), up to 10 tones are discriminable. Outside the critical band from 10 dB to 50 dB for a frequency range of 200 to 1000 Hz, the number of discriminable tones ranges from 10 to 40 (Scharf, 1970; Boff and Lincoln, 1988). Among right-handed subjects who hear lateralized patterns, there is a tendency to hear higher tones in the right ear. Left-handers do not display this tendency. A sequence of two tones are heard as a single string when the frequency difference is 15%; otherwise two repeating tones are heard. Thus, 15% of the frequency of the tone sequence is suggested by Deutsch (1980).

Harmony 1 to 6 coincidences of harmonic proportions or ratios for a 250 Hz low tone, and high tones of 500 Hz and 750 Hz over a -20 dB to -25 dB range (Rasch, 1978)

When a low musical note (complex tone with low fundamental frequency) is presented simultaneously with a high musical note (complex tone with high fundamental frequency), the low tone may mask the high tone (i.e., reduce its discriminability). The degree to which the presence of the low tone will raise the threshold for discriminating the pitch of the high tone depends upon the amplitude of the masking tone, the degree of coincidence of harmonics between low-tone mask and high tone, the amount of mistuning of the high tone relative to the low tone, and the frequency modulation of the high tone. Proportions of high tone harmonics coincidental with low tone harmonics are 1/1, 1/2, 1/3, 1/4, 1/5, and 1/6. When all harmonics coincide (1/1), threshold is within a -20 to -25 dB range relative to the intensity of a masking (low) tone (250 Hz), when phase differences are 0 degrees or 90 degrees, with threshold lowest when harmonics are in phase; but threshold is raised to 0 dB relative to masking tone level when phase difference is random. For a 250 Hz low tone, and high tones of 500 Hz and 750 Hz over a -20 dB to -25 dB range, coincidences of harmonics range from 1 to 6 discriminable harmonic proportions or ratios (Rasch, 1978). Boff, Kaufman and Thomas (1986) suggests 10^o to 40^o of phase angle displacement. When the phase of one component of a complex tone is different from the phase of the other components, the out-of-phase component can be perceptually segregated from the rest. For example, when a complex tone comprised of 12 sequential harmonics of a 200 Hz tone is played so that all the components but one are in phase and the out-of-phase harmonic is periodically changed in ascending or descending order, the out-of-phase harmonics can be heard as a scale. Perception is almost perfect for phase angle displacement of 40 degrees or more, but is at the chance level for phase angles of 10 degrees or smaller (Boff and Lincoln, 1988).

Temperature approximately 1000 different temperatures

People are able to distinguish temperature differences of $.08^o$ for cold; $.13^o$ for warmth (Boff, Kaufman and Thomas, 1986). Assuming reasonable accuracy within 100 degrees--i.e. 30^o to 130^o, approximately 1000 different temperatures are distinguishable. The human observer can readily differentiate "touch" from "touch plus warm" or "touch plus cold" for the most part. All nerves, however show variable temperature coefficients under appropriate conditions. A steady state discharge for a temperature receptor depends on the temperature. Each body part has both cold and warm spots. On average the area size is 1 to 1.5^o variable across all body areas for a zone of thermal indifference no larger than 8^o wide (29^o to 37^o C)(Bazett and McGlone, 1932; Geldard, 1972).

Hardness/Solidity No statistical method of determination proposed.

The rigidity principle states that we perceive the layout and structure of an object through motion (Gibson, 1979; 1966).

Texture No statistical method of determination proposed.

Judged roughness of a grooved surface felt with the fingers increases as groove width (space between grooves; constant at 0.25 m) and contact force of the finger tip increases (low = 25 g, medium = 112 g, high = 448 g). Perceived roughness decreases as the flat surface between narrow grooves (land width or ridge width) increases, but only for wide land widths. For wide grooves, perception of roughness does not change as land width decreases. Perceived roughness is also influenced by shear force, skin temperature and vibration (Boff and Lincoln, 1988).

Shape No statistical method of determination proposed.

Cues by the proprioceptive triggering of movement generated in the muscles, their attachments, and bone articulations are responsible for mediating the perception of shape by spanning an object with the fingers (Helson, 1964).

Weight No statistical method of determination proposed.

Difference Limens (DLs) = 9.02 gm with a 500 gm cuff; and 12.65 gm with cuff.

Discrimination is best at the level to which the sensorimotor system is adapted. Cues by the proprioceptive triggering of movement generated in muscles, their attachments, and bone articulations are responsible for guiding action in such diverse performances as hand grip, knob and lever manipulations, estimating hardness or viscosity of compliant materials, spanning objects with the fingers, exerting pressure on pedals, and gross motor functions of walking, running, swimming and guiding food to the mouth (Helson, 1964).

Size No statistical method of determination proposed.

Cues by the proprioceptive triggering of movement generated in the muscles, their attachments, and bone articulations are responsible for mediating the perception of shape by spanning an object with the fingers (Helson, 1964).

C. Preattentive Dimensions for Critical Data

Triesman(1984;1985;1986), Julesz(1983;1984), Conners and Ng(1989), Callaghan(1989), Hansen and Hansen(1988), Matthews and MacLeod(1986), and others have worked on various aspects of preattentive stimuli. The research suggests that some stimuli are recognized preattentively -- the stimuli are detected by sensory activity that is massively parallel in nature. Other stimuli are detected only after sequential search of the data. As a consequence, preattentive stimuli are generally immune to the size of the set in which they appear[9] while the time to locate non-preattentive stimuli increase with the size of the search set. Thus, for example, finding a red letter on a greeting card and a newspaper page take approximately the same amount of time. Finding a capital P on a greeting card and a newspaper page take vastly different amounts of time. Hue is a preattentive stimulus while compound shape -- the composition of lines and curves that make up a P is not. Color is recognized; Complex shapes are searched for.

Unfortunately, the research on preattentive stimuli is not quite so simple as the above would lead one to believe. While visual stimuli tend to be preattentive only when they are not compound, certain combinations do tend to reinforce each other. At the far end of the continuum, there seems to be some evidence that one category of complex visual stimuli is recognized preattentively--threatening faces. Similarly, there is some evidence that auditory stimuli that constitute a threat are recognized preattentively.

The table below summarizes the various dimensions of a virtual space indicating whether they are normally preattentive, conditionally preattentive, or normally not preattentive. In all cases, the relevant literature should be consulted, and careful consideration given to the precise conditions under which there will be a preattentive stimulus search. In general, the virtual space should use strongly preattentive dimensions for critical data.

Visual Sense	
Hue	**Normally Preattentive**
Saturation	**Seldom Preattentive**
Brightness	**Conditionally Preattentive**
Location	**Seldom Preattentive**
Shape	**Conditionally Preattentive**
Size	**Conditionally Preattentive**
Opacity	**Seldom Preattentive**
Texture	**Often Preattentive**
Auditory Sense	
Loudness	**Normally Preattentive**
Pitch	**Normally Preattentive**
Purity	**Seldom Preattentive**
Duration	**Seldom Preattentive**
Melody	**Conditionally Preattentive**
Harmony	**Seldom Preattentive**
Tactile Sense	
Temperature	**Conditionally Preattentive**

9 Almost all of the work in this field is on visual stimuli.

Hardness	**Seldom Preattentive**
Texture	**Seldom Preattentive**
Shape	**Seldom Preattentive**
Weight	**Seldom Preattentive**
Size	**Seldom Preattentive**

V. Conclusion

The goal of virtualization is to help people solve data intensive problems that are resistent to reductionist techniques and amenable to data visualization, or in this case virtualization efforts. Effective use of the virtual reality interfaces can be defined operationally in terms of how well the data set exercises the full capabilities of the technology both in terms of the number of mechanisms used and in terms of the complete use of the channel. For example, a data set that only used the visual channel would not be as good as one that used the visual and auditory channel. A data set that exercised the visual channel in a two dimensional form would not be as good as one that used the three dimensional form. In this fashion, it is possible to develop an operational definition of "effective". It is also possible, and ultimately the goal, to define effective in terms of the results achieved using the interface to reach some goal. This current work provides a framework within which efforts might be compared and contrasted.

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