Abstract
Research at NCGIA, funded under the National Imagery and Mapping Agency's University Research Initiative, has concentrated on the elements, measurement, modeling, propagation, and cartographic portrayal of uncertainty in the national geospatial information infrastructure. As part of this work, cartographic methods for dealing with both positional and attribute components of uncertainty have been reviewed, and the most promising methods designated for implementation and testing. Our work has focused on using a combination of methods, including color manipulation, animation, and visual depth to represent at least positional uncertainty in an active way; that is, the user has control within the display as to what or how much uncertainty becomes part of the visualization. The environment in which we are working is the virtual world, and interaction is established using the Virtual Reality Modeling Language as well as an immersive Head Mounted Display. Uncertainty within the three dimensional environment is reflected as a floating point value assigned to features, and features change their color properties, move, and are present or absent based on the user's chosen level of uncertainty portrayal. User responses are then to be measured based on interactions established to indicate virtual position of the user's eye focus within the virtual field. This paper presents some initial findings of building and testing a prototype system, and examines methods to be used for more rigorous human subjects testing.

1. Introduction
Of growing interest in the cartographic community, the portrayal of uncertainty has lately been the subject of much research in the cartographic community. In 1997, a three year project began at the National Center for Geographic Information and Analysis examining five aspects (elements, measurement, modeling, portrayal and propagation) of uncertainty in the national geospatial information infrastructure. The fourth portion of the project was tasked with comprehensively determining suitable methods for uncertainty portrayal. Existing methods of uncertainty representation were revisited and the development of innovative techniques undertaken with the goal of eventual identification of the most effective methods through human subjects testing.

Past research on the display of uncertainty or its components has centered on the use of traditional cartographic visual variables, animation, and three-dimensional representation techniques. Cartographic methods using traditional variables for uncertainty portrayal are based primarily on an extended set of Bertin's visual variables: position, size, value, texture, color, orientation, and shape (Bertin, 1983). Beard, Clapham, and Buttenfield (1991) suggested size, shape, and color as useful variables for uncertainty in point and line data, while suggesting color value, saturation, and possibly size and shape for continuous data. MacEachren (1992, 1994) favored the use of color saturation for uncertainty portrayal and added focus as a variable that could be changed by manipulating edge crispness, fill clarity, resolution or by adding fog. McGranaghan (1993) favored creating visual ambiguity using Benin's variables as well as focus, realism, time, and interaction. The use of time as a variable to represent uncertainty cartographically requires the use of animation.

Animation has been used by several cartographers to communicate uncertainty information to map users by focusing on the different ways time can be used as a variable and by portraying multiple realizations of data at the same point in time. Peter Fisher (1993, 1994, 1996) used animation to display the set of possible maps created by multiple equiprobable outcomes or realizations using, both
soil and remotely sensed data. Ehlschlaeger, Goodchild, and Shortridge (1997) used single frame sequential animation of equiprobable stochastic images for line (shortest path) and Digital Elevation Model data. Even though it is relatively new to cartography, animation has proven itself, by incorporating time as a variable to be a valuable technique for uncertainty portrayal.

Much less research has been conducted investigating the three-dimensional display of uncertainty. 2.5-dimensional static displays have been used with some success but as yet, the potential of 3-d display has yet to be realized. Most recent innovative research has been carried out at the Santa Cruz Laboratory for Visualization and Graphics where vectors, glyphs, and multivariate point symbols have been used effectively in 3-d space (Pang, et al., 1996). The use of 3-d space animation, and the modified set of Bettin's variables are all seen as valuable portrayal methods that could be valuable for the representation of uncertainty.

The advent of virtual environment technology offers a means with which to incorporate various uncertainty portrayal techniques based on traditional cartographic variables, animation, and three-dimensional representation into a single research environment. The Virtual Reality Modeling Language (VRML) was selected for creation and display of virtual environments because of its ease of production, its widespread use, its capabilities for symbolization of features, and its capabilities for user interaction definition. After preliminary examination of the potential of virtual environments for cartographic portrayal, it became evident that depiction of uncertainty based on the use of depth as a cartographic variable offers some distinct advantages over other methods.

Use of a virtual environment for research into depth-based uncertainty portrayal necessarily entails the employment of stereoscopic visual effects as a means for portrayal of depth in threedimensional cartographic products. A Head-Mounted Display (HMD) is required to provide the cues to the human vision system necessary for effective depth perception in the VRML scene. This work reviews the means by which depth information is attained in the natural environment, discusses the effect the use of the HMD has on depth cues, and proposes a suite of methods to employ depth in the representation of uncertainty.

2. Depth cues and the human vision system
Before depth can be used in the depiction of some facet of cartographic data, it is necessary to briefly examine exactly what contributes to humans' visual perception of depth. For this research, the cue theory of visual depth perception is useful, forming the basis for a large portion of this work. The cue theory states that the human visual system determines the depth, or distance, of features in the environment from the posture of the eyes and from the patterns of light projected onto the retinas by this environment (Hanger, et al., 1992). Depth information is gained from both of these sources through certain cueing elements in the natural environment as well as in the virtual world.

2.1. Depth cues
The depth cues are of two types, physiological (those related to the visual system itself) or pictorial (those related to an objects structure or resulting image) (Kraak, 1988). Through the use of depth cues, humans are able to perceive depth information from two-dimensional retinal images. The following are usually grouped into the category of physiological depth cues:

- convergence- the ability of the eyes to rotate inward when focusing on an object
- accommodation- the ability of the eye lens to change convexity to bring objects at different distances into focus
- binocular disparity- the distance between the eyes that causes the generation of two disparate retinal images
Figure 1. Use of a Head-Mounted Display provides the user with pictorial as well as physiological depth cues.

- motion parallax - depth perceived from the relationship between the motion characteristics of the point of observation and the motion characteristics of objects in the field of view.

The pictorial cues, which have been used in maps and artwork for some time with varying degrees of success are as follows:
- occlusion - features that overlap others appear nearer than those overlapped
- linear perspective - depth perception generated by convergence of lines on the horizon
- shading and shadow - light provides external relief to features as well as locates them in 3-d space by the characteristics of the feature's cast shadow
- color - objects of color appear at different depths according to their wavelength (chromostereopsis)
- texture gradient - low density textures seem nearer than high density textures; “sharp” textures appear nearer than “fuzzy” textures
- size - larger objects appear closer; if the size of a feature is known, depth perception is influenced
- reference frame (or moon illusion) - distance cues, such as the horizon, that provide an environmental indication of object distance or size
- aerial perspective - distant objects appear hazy

The decision on which and how depth cues should be used, either independently or in conjunction, is the topic of ongoing research. It appears that some of the depth cues complement each other in their ability to indicate depth (Chan and Yeh, 1995) while others counteract each other (Rock, 1984). To use cartographic depth effectively in the portrayal of uncertainty, interference between the different depth cues must be attended to carefully.

2.2. Immersion and depth cues in the virtual environment

The use of a Head-Mounted Display for cartographic depth research introduces an artificial representation of the environment that affects a user's perception of surroundings through the results of immersion and, of greater interest here, the presentation of pictorial and physiological depth cues. Spatial immersion via the HMD allows the user to gain visual information from within the three-dimensional virtual scene as opposed to subjective immersion where information about the 3-d
Figure 2. Stereoscopic depth effects are generated in the HIM by a pair of liquid crystal displays. Environment is gained by the use of a 2-d display (Hamill, 1994). The sense of spatial immersion is seen as a means to maximize the user's understanding of a three-dimensional environment by enlisting the natural characteristics of the human vision system. By taking advantage of the full range of the available depth cues, the user is able to detect patterns in a data set that might not be apparent with a less holistic approach.

Using HMDs to display virtual scenes for cartographic purposes requires the investigation and understanding of the medium itself for the medium to be useful. Hamill (1994) sets forth three requirements for the effective use of virtual environments for problem solving:

- the ability to navigate appropriately within the virtual environment
- the ability to reason appropriately about virtual objects in the virtual scene
- the ability to learn in the virtual environment and apply this knowledge outside the virtual environment.

For this particular research, the perception of depth cues in the virtual environment directly affects the first two of these requirements.

Unfortunately, the presentation of depth cues in the virtual environment through the use of a HMD differs in some respects from the presentation of depth cues in the real environment. A HMD uses a pair of liquid crystal displays located before each eye to render the virtual environment and produce the effect of stereopsis. To make the most efficient use of depth information, the full suite of depth cues should be presented to the user. Existing virtual reality systems can implement all of the depth cues with the exception of accommodation and its resulting depth of field effects (Rokita, 1996). This shortcoming causes all objects represented in the scene to remain in focus, no matter the distance at which they are viewed. This failure can be remedied through the use of an eye tracking device to determine the point at which a user looks in conjunction with a HMD locational tracking device to determine virtual distance to objects in the scene. Real-time information from this hardware can he
used to create the appropriate depth of field effects of accommodation by employing Rokita's (1996) adaptive convolution filter (executable on existing hardware). This will introduce defocus effects into the virtual scene allowing cartographers to utilize, at least theoretically, every depth cue.

3. Construction of the virtual research environment

This work seeks to apply depth cues in the representation of cartographic uncertainty through the use of a HMD. The goal is to create a virtual map and environment in which a user is able to specify a level of uncertainty and features with less than that level are defocused. As the user decreases the threshold, features will become blurred and more distant according to the features uncertainty value.

The hardware and software used for this research include a CyberEye HMD with tracking device, Silicon Graphics INDY workstations, ARC, INFO GIS, and the CosmoWorlds VRML authoring package. Source data for the project consist of a subset of the U.S. Census Bureau's TIGER road data for Santa Barbara County, California. The TIGER tile, originally in ARC/INFO was converted to the VRML97 specification using an ARC Macro Language script producing a .wrl file directly as output. Each road segment, defined by endpoints in the ARC format, exists as a cylinder in VRML defined by the segment midpoint's translation from the origin, its rotation about the z axis, and its length. A local coordinate system was created for the VRML data by subtracting the data set's minimum Easting and northing UTM values from each midpoint.

Each cylinder is located along the z-axis at a depth reflecting its attached uncertainty value. For the purposes of this work, it is assumed that uncertainty is continuous and can be measured by floating point value on a scale from 0 to 1. The z value of each road segment is, with the exception of x-y location, the only factor that varies in the road network. Each cylinder has the same radius, color characteristics, and texture. The result can be considered a data 'cube' with features of high certainty nearer the top of the cube. Ten .wrl files need to be constructed, one for each available uncertainty setting.

Initially, the user is presented with a virtual scene in which the entire road network appears at the same depth. The user is able to select from ten uncertainty settings ranging from 0 to .9 at .1 unit increments by specifying the desired increment on a slider bar visible at the bottom of the display. The slider bar triggers a VRML Anchor node, causing the initial scene to be replaced by the scene corresponding to the selected uncertainty level. If the .5 unit is chosen, features with less than a .5 uncertainty value are shown at surface depth with other features appearing deeper in the map according to their level of uncertainty.

User navigation ability in each virtual scene is limited to movement in the x-y plane to the areal extent of the presented features. Depiction of the virtual scene in this manner allows information about the depth of each feature to be gained from physiological as well as pictorial depth cues, creating a more realistic perception of feature depths. Success of this form of uncertainty portrayal is viewed as being closely related to the realism in depth perception generated by use of the full set of depth cues.

4. Future Directions

Human subjects tests will be conducted to examine the effectiveness of the use of depth as a cartographic variable. It is clear that a certain amount of user preparation will be required, with training sessions prior to actual testing carried out. Detailed explanation of the depth representation will be necessary will also be necessary to ensure the user has a solid understanding of what is being viewed. The psychological and physiological effects of viewing the virtual environment through the HMD will also be examined.

Close attention must be given to the determination of an optimum range of z values for each scene, noting the possibility of an attention gradient related to depth or vary ins effectiveness with changes in x-y location. Until more can be learned, the data set will be relatively small and simple to avoid any confusion more complex data sets could introduce. To ensure maximum efficiency during
testing, special care must be taken to avoid visual stress caused by the HMD. Mon-Williams and colleagues (1993) have shown that deficits in the binocular vision system can occur after as little as ten minutes of HMD use. There does not appear to be a simple remedy for this problem of visual stress when a large range of stereoscopic depth is required for conventional binocular designs (Wane et al., 1995). The range of stereoscopic depth implemented in the uncertainty displays will therefore need to be scaled to reduce the effects of visual stress.

Other depth cues will be incorporated into the display by their application to the road cylinders. For example, color or texture will be added to enhance the user’s perception of depth by employment the effect of chromostereopsis or the effect of texture gradient. Conversely, the same depth cues may be applied in a contradictory manner to heighten the perception of uncertainty attributed to a particular feature. Of great importance are the possible confusion generated by the use of these additional depth cues. For example, red may intuitively represent uncertainty to a greater extent than blue, but because colors of shorter wavelength appear closer, red objects will appear closer than blue objects. Since uncertain objects are located deeper in the scene, these cues could generate confusion for the viewer.

5. Conclusions

This paper has examined and reported upon some early investigations on the use of depth-based immersive virtual worlds as a potentially productive environment for the cartographic portrayal of spatial uncertainty. In this work, we have constrained the uncertainty model to one of positional error only, but anticipate that in addition attribute and level of confidence information uncertainty can be handled by the same methods. Our examination of the cartographic literature pointed us to the combination of depth with color display and animation as having the highest potential for use in virtual uncertainty display. Innate human perceptual abilities that cue depth discovery are likely to be powerful information channels along which to send information about positional and attribute uncertainty. The physiological and pictorial cues, over which we have complete control in the immersive virtual world, each hold elements that can be manipulated by animation and coloring to communicate uncertainty. The selective ability, that gives the user complete control over the level of acceptable uncertainty, is we believe the best approach to generating a useable prototype system. We anticipate creation of a prototype and human subject tests during the current project year, and will then be able to isolate the most and least effective depth tools, as well as the relative shortcomings and strengths of the overall approach to the cartographic portrayal of map uncertainty.

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References


University Press, Delft.