Interaction and visualization techniques for immersive exploration and perception of 3D datasets

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ABSTRACT

The objective in this case is not only to be realistic, but also to provide new and intelligible ways of model representation. This raises new issues in data perception. The question of perception of complex data, especially regarding visual feedback, is an open question, and it is the subject of this work. This PhD thesis studied the human perception in Immersive Virtual Environments of complex datasets, one of the applications is the scientific visualization of scalar values stemming from physics models, such as temperature distribution inside a vehicle prototype.

The objective of the first part is to study the perceptive limits of volumetric rendering for the display of scientific volumetric data, such as a volumetric temperature distribution rendering using point cloud. We investigate the effect on the user perception of three properties of a point cloud volumetric rendering: point size, cloud density and near clipping plane position. We present an experiment where a series of pointing tasks are proposed to a set of users. User behavior and task completion time are evaluated during the test. The study allowed to choose the most suitable combination of these properties, and provided guidelines for volumetric data representation in VR immersive systems.

In the second part of our work, we evaluate one interaction method and four display techniques for exploring volumetric datasets in virtual reality immersive environments. We propose an approach based on the display of a subset of the volumetric data, as isosurfaces, and an interactive manipulation of the isosurfaces to allow the user to look for local properties in the datasets. We also studied the influence of four different rendering techniques for isosurface rendering in a virtual reality system. The study is based on a search and point task in a 3D temperature field. User precision, task completion time and user movement were evaluated during the test. The study allowed to choose the most suitable rendering mode for isosurface representation, and provided guidelines for data exploration tasks in immersive environments.

Keywords: virtual reality, scientific visualization, volumetric data, interaction, rendering methods, human visual perception.

RESUME

L’objet de cette thèse est la perception dans les environnements immersifs de jeux de données complexes, une des applications est la visualisation scientifique de données volumiques scalaires issues de simulations de modèles physiques. Un exemple classique de ceci est la distribution de températures à l’intérieur d’un habitacle de véhicule.

Dans la première partie de ce travail, notre objectif est d’étudier les limites perceptives dans le cadre d’un rendu volumétrique de données scientifiques dans un système de réalité virtuelle offrant la vision en stéréoscopie, et le suivi du point de vue de l’utilisateur. Nous étudions l’effet sur la perception de l’utilisateur de trois facteurs principaux : la taille des points utilisés pour le rendu, la densité du nuage de points, et enfin la position par rapport à l’utilisateur du premier plan de coupe. Nous présentons une étude dans laquelle une tâche de pointage est proposée à un ensemble d’utilisateurs. Les déplacements de celui-ci ainsi que les performances de pointage sont mesurées. L’étude a permis d’évaluer l’impact des paramètres de rendu du nuage de points et proposer un rendu améliorant la perception.

La seconde partie du travail propose d’ajouter une dimension interactive à la première approche en permettant à l’utilisateur d’explorer plus activement la scène. L’hypothèse d’une meilleure compréhension des données par l’action est ici mise en avant. Nous évaluons une méthode d’interaction et quatre méthodes de rendu associées. L’approche proposée est de n’afficher qu’un sous ensemble des données volumiques, en l’occurrence des isosurfaces, et de permettre à l’utilisateur de naviguer par une gestuelle naturelle et interactive dans l’ensemble des isosurfaces du jeu de données explorées, dans cadre de manipulation directe. Une nouvelle étude est proposée, dans laquelle l’utilisateur doit effectuer une tâche de recherche et de pointage d’une propriété locale dans un jeu de températures 3D. Cette étude a permis de choisir une méthode de rendu adaptée à l’affichage immersif d’isosurfaces et de valider l’approche interactive pour l’exploration de données.

Mots-clés : Visualisation Scientifique, Réalité Virtuelle, Interaction, Perception

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1 Introduction

Ce chapitre donne une vue générale des technologies de la réalité virtuelle et couvre de la perception dans les environnements immersifs de jeux de données complexes.

1.1 Background

Through the use of several techniques such as stereoscopic rendering, large screen display, scale 1 representation, user tracking and real-time interaction, Virtual Reality provides means to immerse one or more users in realistic environments. Virtual reality is now used in computer aided design (CAD) scenarios; it is a proven tool, which allows controlling and modifying the design. The main asset is that VR immersive techniques provide more information during the design process, compared to a desktop only situation. VR and its use in design processes, for the product, as well as the process of building it, have been developed fast in the last decade. Several big industries have integrated VR and Immersive Design into their design process to help their decision making.

The framework of this research is the use of VR for industrial design. This technology can be applied in vehicle design to help the company to make decisions before producing the real vehicle. Immersive environments allow participants to interact with a virtual concept (car interior, mechanical parts) with various models (physics, mechanics, optics) where they can modify and test their concept models with a first-person perspective as close as possible to the real world situation.

Since the last two decades, industrials show their interest for Virtual Reality (VR). Many interactive simulations have been created and developed to solve industrial problems such as product assembly and disassembly [1][2], safe and low cost staff training [3], CAD or ergonomic studies [4]. Most of current VR based solutions are industry specific solutions, For example, vehicle manufactures use a Virtual Reality Center equipped with state of the art technologies to help decision making. More and more companies are pursuing integrate VR technology into different stages of the product life cycle, in order to study assembly process, modeling design and staff training…

There is a strong demand among the industry for virtual reality interaction for more precise 3D modeling and more interaction with functional models, such as air condition models. The scientific visualization of functional models can help CAD design process in Virtual Reality environment. Thus, linking between VR technology and bidirectional communication with CAD models is very helpful to real-time model designing. The trend is to integrate Virtual Reality design environment with physical models and provide an efficient scientific visualization of the impact of physical models. This opens a new research direction for industrial modeling designing and training over the medium and long term and meets the industry's requirements.

Firstly, in order to provide more precise modeling approach in VR system and bidirectional communication with CAD models, we worked on functional models integration in VR environment, where car radio, GPS, A/C electric, have been integrated, such as project IHS10[5]. Moreover, we participated in the project MODELISAR to go investigate the problematic of integration of physics models and give more realistic experience to the users in VR design system.

1.2 MODELISAR Project

The project MODELISAR objective is to provide an open end-to end solution for automotive systems modeling, embedded software generation and integrated simulation based design and testing. MODELISAR and the FMI (Functional Mockup Interface) provide an integrated environment enabling the automotive systems to be designed through Modelica, while the associated Software of the electronic control units is concurrently generated through AUTOSAR. It is an integrated approach for the modelization of complex systems; it aims towards large industries such as car or aircraft manufacturers.

Mines ParisTech is a partner of the MODELISAR project and is in charge of the virtual reality interior design simulations with the Modelisar Functional Mock-up Interface. The goal of our work is to explore interaction and visualization methods with physics models. The title of Mines ParisTech's work package was "*Interior & HMI Design with FMI Realistic Simulation*", so it points towards interior design (mainly, but not only, car interiors), and the physics models involved in such design.

More precisely, the objective of our work package can be concluded as the following aspects. Firstly, we aim to verity the framework of a virtual reality environment with 3D interaction techniques and stereoscopic vision. Furthermore, we are pursuing to explore and understand 3D volumetric datasets stemming from physics models. Finally, we focus on providing efficient methods for 3D visualization and exploration of volumetric data, which is an important challenge of Mines ParisTech work in Modelisar and the main objective of this thesis.

1.3 VR Interaction

Virtual reality (VR) allows users to interact with computer-simulated environments. Virtual reality applications are usually displayed either on a computer screen or in a stereoscopic display system. The latter is also referred to as an immersive display system. In this section, we discuss about immersive interactive real-time VR systems related devices, interaction techniques and applications.

Immersive VR interaction is a human computer interaction in which a user's tasks are performed in a 3D spatial context. A common immersive VR system consists of following main parts: 3D display system, tracking system and interaction devices. Before considering the VR interaction techniques and their implementation, we briefly survey the three main parts.

3D display systems: The principle of 3D display systems is projection of a stereo image pair onto a large screen. The following components are commonly used in most 3D projection-based display systems: 1) a rendering system – a powerful computer with respective graphics hardware and software, 2) a projection system and corresponding glasses, 3) additional output devices, such as auditory displays, 4) a tracking system, 5) interaction devices. The most important characteristic of a display system is the technology to generate a 3D impression. In most cases, stereo image pairs are rendered, so that a user perceives a 3D virtual model using stereo glasses.

Tracking systems: Tracking systems (or trackers) provide position and orientation information of real physical objects for VR applications. Trackers can measure the motion of interaction devices, as well as user's head, hands, and sometimes the whole body or just eyes. This information is then used to calculate the correct perspective projection and auditory inputs according to the position of a user and react on users' actions. Hence, together with signaling functions of interaction devices, trackers are the primary means of input into VR application.

Interaction Devices: Interaction devices are physical tools that are used for different interaction purposes in VR, such as view control, navigation, object selection and manipulation, and system control. Sometimes the devices are integrated and supported by tracking systems. Normally they are equipped with buttons and controls. They may also support force and audio feedback. Any input device may be used for various interaction techniques. The goal of a developer is to select the most appropriate techniques for a device or vice versa, which is used for natural and efficient interaction. An interaction device may be discrete (generating events on user's request, e.g. a button), continuous (continuously generating events, e.g. a tracker) or hybrid (combining both controls). Most interaction devices belong to one of the following categories: 1) gloves/hand masters 2) mice and joysticks 3) remote controls/wands 4) force/space balls.

Some interaction techniques: 3D interaction techniques are methods for performing certain interaction tasks within a 3D environment. Typically, a user is partly or fully immersed in the 3D environment and can access its objects to control the application though 3D input devices. 3D interaction techniques are required by a number of necessary design decisions for usability performance and comfort.

Interaction tasks of complex application in 3D environments can be categorized into selection, manipulation, navigation, creation and system control [6]:

- **Selection** can be considered as the primary step of VR interaction. Normally, it is used to select a 3D object for further interaction purpose. This contains three main steps: indicating the objects, confirming the selection and receiving a feedback of selection [7].
- **Manipulation** usually refers to changing properties of previous selected objects, such as position, size, shape or geometry structure. It can be performed after selection step. A classical direct manipulation is pointing

at the desired object by using a picking ray intersection, the user can rotate it or attach the object to drag and move it in 3D space.

- **Navigation** is the process of relatively changing the user's position and orientation in a VR generated 3D environment. Navigation process is used when the generated 3D environment is larger than the real Virtual Reality Environment, where the selection and manipulation is not easy to be achieved or reached. In this case, certain techniques such as [7]are needed to allow user walking through the Virtual Environment .
- **Creation** is another process which is usually used in 3D interaction. It is a task of generating a new 3D virtual object in the Virtual Environment. In some cases, the generation of new objects needs a complex interaction, such as giving the various parameters, topological connection information.
- **System control** is an activity of system control in 3D Virtual Environment interaction. It is often referred as UI in a 3D system. It is related to spatial control of desired object or of the whole 3D scene, even executed some certain commands based on user requirement. A classical WIMP (windows, icons, menus, and pointer) standard can be seen as a popular 3D system control techniques. There are also other possible techniques for system control purpose: such as posture and gesture input (Kinect sensor), voice control and etc.

1.4 VR Perception

Our sense of physical reality is a construction derived from the symbolic, geometric, and dynamic information directly presented to our senses [8]. The output channels of a virtual reality application correspond thus to our senses: touch and force perception, hearing and vision.

1.4.1 Haptic

The haptic sense is capable of both sensing what it is happening around the human being and acting on the environment. This makes it an indispensable part of many human activities and thus, in order to provide the realism needed for effective applications, VR systems need to provide inputs to, and mirror the outputs of, the haptic system. The primary input/output variables for the haptic sense are displacements and forces.

1.4.2 Sound

According to general analysis of the way we sense the word, vision is our mean of perception, while hearing is mainly used for verbal communication, which is used to get information from invisible parts of the world or when vision does not provide enough information [8]. Audio feedback must thus be able to synthesize sound, to position sound sources in 3D space and can be linked to a speech generator for verbal communication with the computer. In humans, the auditory apparatus is most efficient between 1000 and 4000 Hz, with a drop in efficiency as the sound frequency becomes higher or lower. The synthesis of a 3D auditory display typically involves the digital generation of stimuli using location-dependent filters.

1.4.3 Visual

Vision is generally considered the most dominant sense, and there are evidences that human cognition is oriented around vision. We gather large amounts of information with vision in everyday life. High quality visual representation is thus critical for virtual environments. The major aspect of the visual sense that is commonly used in virtual reality environment is stereoscopy vision.

In humans and animals with stereoscopic vision, each eye captures a slightly different image. This difference is known as binocular disparity, or retinal disparity. The brain processes these two images in a way that lets us see slightly around solid objects without needing to move our heads [9]. It does this by essentially pairing up the similarities in the two images and then factoring the differences into our perception of a scene. These differences are usually small, but can translate into a significantly different final result.

Stereoscopy (also called stereoscopic or 3-D imaging) is often included in a VR system; it refers to a technique for creating or enhancing the illusion of depth in an image by presenting two offset images separately to the left and right eye of the viewer. The images are computed with the viewpoints offset by the equivalent distance between the eyes. Both of these 2-D offset images are then combined in the brain to give the perception of 3-D depth. Three strategies have been used to accomplish the following issues: the viewer to wear eyeglasses to combine separate images from two offset sources or filter offset images from a single source separated to each eye. It also makes the light source split the images directionally into the viewer's eyes (no glasses required).

The two images can be displayed sequentially on a conventional monitor or projection display. Liquid Crystal shutter glasses are then used to shut off alternate eyes in synchronization with the display. When the brain receives the images in rapid enough succession, it fuses the images into a single scene and perceives depth. A fairly high display swapping rate (min. 60 Hz) is required to avoid perceived flicker.

Stereoscopic vision refers to the ability that humans have to see the same scene with both eyes in slightly different ways. It results in our ability to visually perceive 3D depth and distances. Stereoscopic vision is not synonymous with depth perception, but rather leads to it. Perceiving 3D depth and distances that humans have as a result of stereoscopic vision allows us to see and assess potential threats with greater accuracy and faster response time. In our own time, this aspect of our vision facilitates many routine daily activities. A surgeon must have stereoscopic vision in order to accurately perform a procedure, and the driver of a car must be able to tell how far away his car is from other objects.

The human visual system relies on a large number of cues for estimating distance, depth, and shape of any objects located in the three-dimensional space of the surrounding. Figure 1 gives an overview of the various cues for depth perception.

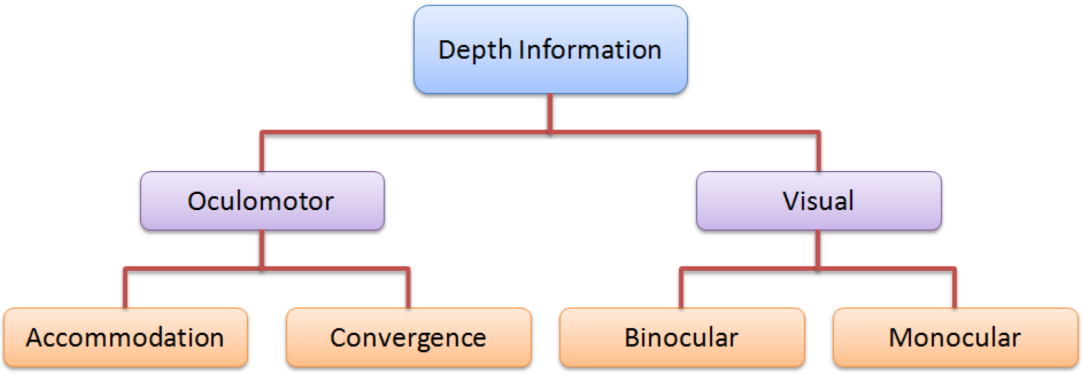


Figure 1: The source of depth information

A. Visual depth cues

Visual depth cues can be classified into monocular and binocular cues. Monocular cues are cues to depth that are effective when viewed with only one eye. The most important monocular cues are interposition, aerial perspective, texture gradient, linear perspective, size cues, accommodation, lighting/shading, and motion parallax[10][11].

- Interposition: Probably the most important monocular cue is interposition, or overlap, or occlusion (blocking the sight). When one object overlaps or partly blocks our view of another object, we judge the covered object as being farther away from us and provide information about relative distance. However, this information only allows the observer to create a "ranking" of relative nearness.

- Aerial perspective: Due to air containing microscopic particles of dust and moisture that make light scattering by the atmosphere. The objects that are a great distance away have lower luminance contrast and lower color saturation and make them look hazy or blurry.

- Texture Gradient: Suppose you are standing on a gravel road. The gravel near you can be clearly seen in terms of shape, size and color. As your vision shifts towards the distant road. The texture becomes denser and less detailed and cannot be clearly differentiated, and this information helps us to judge depth.

- Linear Perspective: Linear perspective refers to the fact that parallel lines, such as railroad tracks, appear to converge with distance, eventually reaching a vanishing point at the horizon. The more the lines converge, the farther away they appear.

- Size Cues: Another visual cue to apparent depth is closely related to size constancy. If two objects are known to be the same size (e.g., two trees) but their absolute size is unknown, relative size cues can provide information about the relative depth of the two objects. If one subtends a larger visual angle on the retina than the other, the object which subtends the larger visual angle appears closer.

- Familiar size of objects. Through experience, we become familiar with the standard size of certain objects. Knowing the size of these objects helps us judge our distance from them and from objects around them.

- Accommodation is an oculomotor cue for depth perception. When we try to focus on far away objects, the ciliary muscles stretch the eye lens, making it thinner, and hence changing the focal length. Accommodation is only effective for distances less than 2 meters.

- Lighting and shading describe that light falls on an object and reflects off its surfaces, and the shadows that are cast by objects provide an effective cue for the brain to determine the shape of objects and their position in space.

- Motion Parallax: Motion parallax appears when objects at different distances from you appear to move at different rates when one moves. The rate of an object's movement provides a cue to its distance. The more distant objects appear to move in a slower speed.

- Tilt-shift: Lens of camera projects sharp focus on a image plane. Without tilt, the image plane parallels with lens plane and plane of focus. All the objects in sharp focus have the same distance from the camera. When camera lens is titled to the image plane and all objects coincide with plane of focus, all the objects can be sharply focused; otherwise it produces different sharpness on foreground and background objects, which brings depth of field cue.

Binocular cues provide depth information when viewing a scene with both eyes.

- Stereopsis or retinal (binocular) disparity. Humans can use information derived from the different projection of objects onto each retina to judge depth. By using two images of the same scene obtained from slightly different angles, the brain can derive a depth perception from binocular disparity. If an object is far away, the disparity of that image falling on both retinas will be small. If the object is close or near, the disparity will be large. It is the stereopsis that allows people to perceive depth.

- Convergence is a binocular oculomotor cue for distance and depth perception. By virtue of stereopsis the two eye balls have their axis on the same object. In order to do that they converge. The angle of convergence is smaller when the eye is fixating on far away objects.

Of these various cues, only convergence, accommodation and familiar size provide absolute distance information. All other cues are relative they can only be used to tell which objects are closer compared with others.

B. Stereoscopic vision cues in virtual reality environment

Conveying real-world depth information in a virtual environment is done using a wide variety of real-world visual cues. In most VE systems, depth cue can be derived using motion parallax, some shading cues, and linear perspective. Shading information is always available and specular shading information is usually available. In textured environments, it is rare for the shading to take into account the information from the texture, but instead uses the information from the graphical surface to which the texture is attached.

In some cases, systems are augmented with sensors that allow for direct 3D manipulation of the virtual world. The motion tracker is a device that is able to continuously detect the position and/or orientation of a physical location in space. Tracking systems not only can be attached to the hands, allowing the user the ability to place virtual hands or directly manipulation orientation with the object in the environment, but also considerably increase the realism and degree of immersion of even desktop virtual environments because the motions of the controllers are directly analogous to motion in the environment and enhance the visual cues of 3D display systems.

3D displays are implemented either in a tracked or untracked mode. Untracked displays assume a fixed viewer position, which is reasonable for many desktop applications. Commonly, in VE systems, the graphics system renders images for the eyes and their distinct locations. An increased perception of reality is accomplished by adding tracking sensors the head, so the viewpoint can be moved in real-time. This allows the user to move, increasing stereoscopic perception beyond pure stereo vision through the addition of motion parallax.

1.5 Problematic

Virtual and augmented reality has now successful uses in the design process of large industries such as aeronautics, automotive or energy, with applications at various levels, Computer Aided Industrial Design (CAD), Computer Aided Manufacturing (CAM), and Computer Aided Engineering (CAE). VR immersive techniques are also used for scientific visualization, for example, for the purpose of design, research or communication. Scientific visualization often involves complex data and rich models which involving multi-dimensional parameters.

In the field of industrial design, a design scenario based in VR technology should provide a realistic user experience and an efficient designer experience of the simulation in VE systems to prototype design process. One example of such scenario is containing following main steps:

- The user can interact with the vehicle interior within the VR system, and also with a physical model simulation of some key aspect of car design. For example, simulate the effect of turning on the air conditioning, on both the temperature in the car and on the temperature measure displayed on the dashboard. This provides the passenger user experience of the interior of the car.
- As for the designer, during the simulation process, a parameter may be changed by the user though VR interface, such as the diameter of the air conditioning outlet or the position of air

conditioning outlet. Then the simulation system computes and provides the updated dataset for rendering propose. Finally, such simulation-modification process may be re-run for a new user experience.

- Of course, the user and the designer can be the same person.
- Once the satisfactory parameters are found, for example, position and diameter parameters of the outlets in an Air Conditioning scenario, the CAD model could be dynamically updated.

This way, in a short time frame, some of the key design parameters may be tuned and readily optimized to maximize the end-user satisfaction and design relevance.

VR environments are commonly used to represent objects and worlds. Their design is essentially driven by the needs for realistic rendering. Such design guidelines are no more available when VR is used for complex scientific data visualization. The objective in this case is not only to be realistic, but also to provide new and intelligible ways of model representation. This raises new issues in data perception. The perception issues of complex data, especially regarding visual feedback, are an open problem. It is one of the subjects of in this work.

The industrial use of virtual reality data exploration tools is to find out potential design flaws in early design steps. One of the mains important uses is to allow the user to perceive specific phenomena and have a better understanding of visualization datasets. This also challenges to virtual reality community for a novel interactive immersive representation techniques, as well as adapted interaction methods for scientific visualization propose.

Scientific visualization brings complex data into VR simulation systems, how to provide an effective and efficient interactive real-time data manipulation method in a VR based exploration system is another open issue, considering as the other subject of this thesis.

2 State of the art

L'objectif de cette partie est de dresser un état des lieux de l'utilisation des technologies de la réalité virtuelle dans les domaines scientifiques pour améliorer la perception de la visualisation scientifique de 3D données.

Virtual reality techniques have been proven to be useful in providing an interactive environment to the user and help him to get better understanding of scientific visualization. This chapter provides an overview of the current and previous research in the field of scientific visualization, a focus on human visual perception characteristics that are important to consider in the field of data visualization and finally VR interactive techniques on manipulation of various datasets. These researches will be classified by different visualization data types. A review of techniques for providing effective and efficient visualization of various data, and the challenges and issues in using virtual environment for scientific visualization is also presented.

Then we analyze these previous studies to find out the advantage points we should apply as a source of reference, and their weaknesses we should avoid of. Finally, we will address our research background and specify our visualization requirements. Based on these requirements, we propose our assumptions based on our selected data type and visualization techniques, and also clarify the potential problematic of human visual perception on our selected data type and visualization.

2.1 Previous works

2.1.1 Scientific visualization

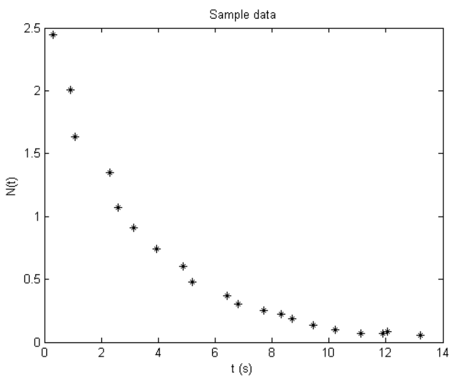
Computer graphics provides the basic functions for generating complex images from abstract data. Visualization employs graphics to give us insight into abstract data. Apparently, a large variety of techniques and research directions exist in data visualization [12]. Choosing a specific technique is mostly determined by the type and the dimension of the data to be visualized. The generally discussed research areas include volume visualization for volumetric data, scalar fields, vector data flow visualization for computational fluid dynamics, large data-set visualization for physical and natural sciences. Many visualization techniques deal with multidimensional multivariate data sets.

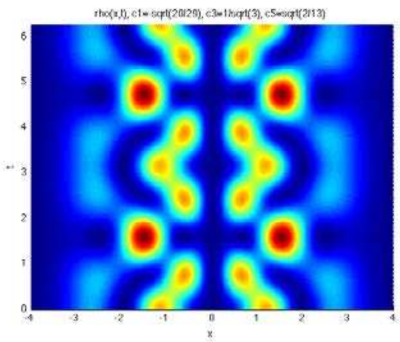
Scientific visualization is the use of computer graphics to create visual images that aid in the understanding of complex (often massive) numerical representations of scientific concepts or results. Such numerical representations, or data sets, may be the output of numerical simulation as in computational fluid dynamics (CFD) or molecular modeling; recorded data, as in geological or astronomical application; or constructed shapes as in visualization of topological arguments. These simulations or recorded datasets often contain high-dimensional data in a three (or multi)-dimensional volume. The display of the features within datasets may involve complex three (or multi)- dimensional structures. Traditional visualization systems implemented for the conventional desktop and mouse are effective for moderately complex problems [13]. Virtual reality displays aid in the unambiguous display of these structures by providing a rich set of spatial and depth cues. Virtual reality

interface concepts allow the rapid and intuitive exploration of the volume containing the data, enabling the phenomena at various places in the volume to be explored, as well as provide simple control of the visualization environment through interfaces integrated into the environment.
In the field of scientific visualization, datasets can be classified by dimension. Dimension is one of the most overloaded concepts in information visualization. If it appears unqualified, it may denote the number of spatial dimensions in the data (1D, 2D, 3D, or 4D: 3D coordinates + time), or the dimensions in the data (1D, 2D, 2.5D, or 3D), or the number of variables in a case-by-variables structure (1D, 2D, 3D□ nD)[14]. Now we are going to list the classical visualization approaches depending on data complexity.

A. Simple data

One dimensional dataset has a set of 1 dimensional coordinate points and each point has a data value associated with it, like sets and sequences: linear or sequential data types, such as text or program source code. A common representation of this data type is to put it onto a Cartesian plane with the coordinate points mapped to the x-axis, and the data values mapped to the y-axis.





Two dimensional dataset: has a set of 2 dimensional coordinate points and each point has a data value associated with it, such as maps: planar data, such as floor plans or other layouts. A common representation of this data type: the two dimensions of the coordinates are mapped onto a Cartesian plane with the coordinate points mapped to the x- and y-axes, and the data values are mapped to a set of colors. This results in a flat image of the data.

One and two dimensional representations are commonly used for statistic purpose to analysis and get insight of the experimental dataset. 3D stereoscopic visualization and virtual reality techniques are increasingly used for analysis of 3D scientific data in multi-discipline field. They provide an excellent and easily comprehensible insight into complex 3D structures. However, in many research topics in environmental and geosciences the analysis of data usually also involves data that might be better viewed in 1D/2D. Examples are maps or histograms [15].The use of virtual environments as visual information systems for the efficient communication and discussion of complex multi-attribute data sets also requires 2D data to be visualized with a high quality. Further it is often not possible to show all the relevant information simultaneously and so an interactive virtual environment is required that provides an overview and the necessary application control techniques to select additional information, e.g. from a database, to be visualized on request.

The VR systems have been primarily designed only with 3D tasks in mind, such as design or assembly studies. When geo-science data are presented in such a system, the 3D data are shown in the original form and all other information within the data need to be converted into 3D representations [16].

- Investigations in geo- and environmental sciences often contain a large number of different datasets that are spatially distributed and it is often impossible to show all this information simultaneously. Therefore, scientists frequently use Geographic Information Systems (GIS). GIS connect a spatial 2D visualization (a map) with a relation to a database that contains additional information about the objects, such as streets, dwellings or borehole location.
- If the investigation involves complicated 3D structures that cannot be presented on a map, this overall paradigm has to be extended from two to three dimensional and virtual environments become the ideal discussion platform due to the stereoscopic visualization and the direct interaction in 3D space. However, much of the additional information that belongs to objects that are shown in the virtual environment involves data which can inherently be better visualization in 2D, such as areal images, soil columns or log plots. All these data need to be at the user's disposal during discussion and accessed by making selections.
- When users are finding their way within a structurally complicated virtual model of several kilometers in size in each direction, adding 2D visualization can help orientation of the users.

Bjorn Zehner proposed such mixing of virtual reality and 2D visualization system in UFZ research center to allow user to explorer geoscience datasets.

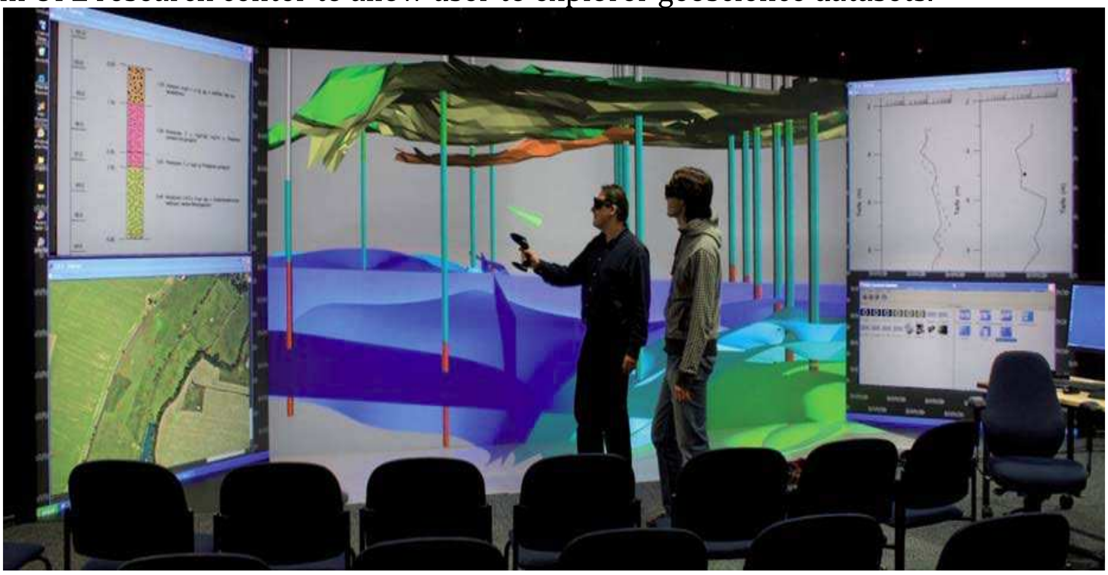


Figure 2: UFZ's visualization center used with mixed 3D/2D information.

On the rear screen and on the floor a 3D model is shown with which the users can directly interact in virtual space. On the side wings additional 2D information is shown upon the user's request, such as detailed borehole information on rock types or graphs of physical values (windows at the top of the two side wings). The users choose which information is shown by selecting the corresponding objects in the virtual model. A map (bottom left wing) always indicates the orientation of the display in the virtual world and so helps when working with data sets that show geographical information ranging across several kilometers. The tool that connects 2D and 3D visualization is a type of pick-tool. The pick-tool is a pointing ray that can intersect with the object in the main 3D visualization. Depending on the object the user intersected, the additional statistic information is illustrated in a 2D histogram or chart on the left screen. One of this functionality is shown in Figure 3.

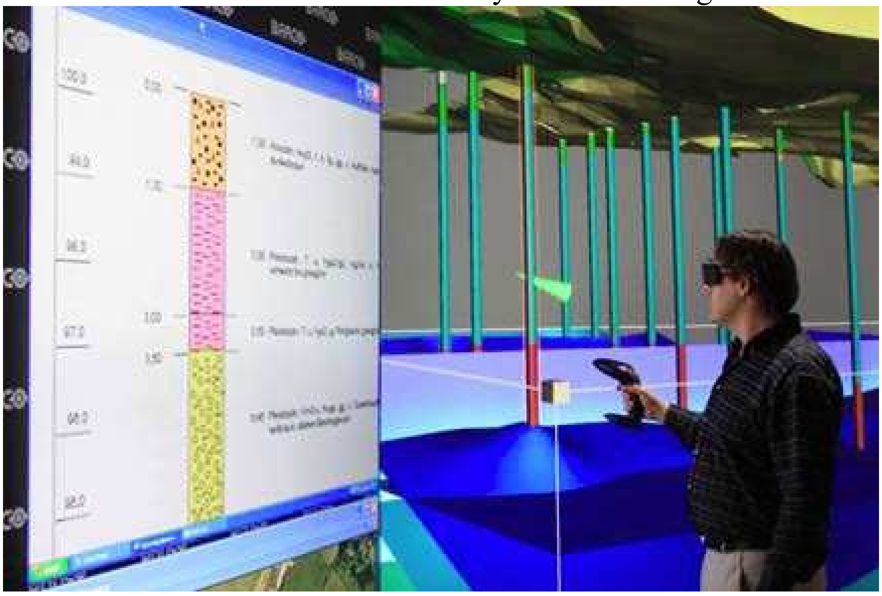


Figure 3: Example of requesting additional information on one of the objects shown in 3D space.

Current virtual environment need to be extended to be able to show non 2D data, such as maps and graphs, if they are to be used as visual information systems for complicated 3D geo-science data sets with multiple attributes, just as Geographic Information Systems are used for discussing 2D data today. It is clear that an additional 2D map view which shows the current location and orientation is a great help.

Color mapping is a function that maps (transforms) the colors of one (source) image to the colors of another (target) 2D image. A color mapping may be referred to as the algorithm that results in the mapping function or the algorithm that transforms the image colors. Color mapping is also sometimes called color transfer or, when grayscale images are involved, brightness transfer function (BTF) or opacity mapping when involved opacity of the pixels in an image. Brady et al. developed a virtual environment visualization tool for biological imaging named “Crumbs”. Crumbs provide color and opacity tools, giving the user the ability to specify the mapping of data values to color. An MRI data set, for example, is represented by cube of density values. By choosing colors and opacity mapping appropriately, the researcher can highlight specific matter within the data [17]. For example, bones, nerves, arteries, and skin all have different densities.

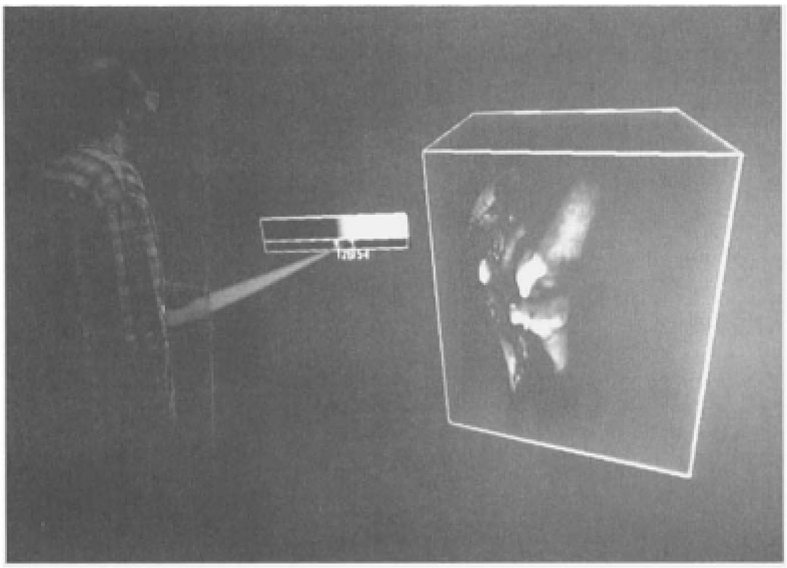


Figure 4: Adjusting the contrast allows the user to highlight a particular range of data values (*Photograph by William Sherman*).

The translucency/opacity tool is shown as a 2D graph, see Figure 4. The X axis represents data values and the Y axis is the opacity value for a particular data value. To more readily differentiate these materials, values for the density of arteries may be represented in red, whereas values for the density of nerves may be represented in blue. The representation is updated immediately as the researcher manipulates the color and opacity tool. This type of 2D data representation allows the researcher to experiment with various mapping and see the results in real time.

This type of 2D representation is widely applied in many VR systems. It not only can be used for data visualization propose, but also provide an intuitive manipulation of VR system parameters, referred as 'slide bar' control which allows the user to control the number of visualization slices[18], or 2D-curve control component to modify the shape of 3D surface [19].

Three dimensional dataset has a set of 3 dimensional coordinate points and each point has a data value associated with it, a very common example is shapes: physical objects like buildings or human body. As two dimensional dataset, visualization of this type of data can mapped three dimensions coordinates onto a Cartesian plane with the points mapped to the x-, y-, z-axes, and the data values are mapped to a set of colors.

Points are a fundamental geometry defining primitive in computer graphics, they can be seen as the raw output of 3D shape scanning and capturing or particle-based simulations. 3D point-based visualization is widely used for representation of 3D objects, geometric modeling and rendering purpose. 3D point-based visualization is different from classical graphics pipelines that mostly focus on triangles. This new way of graphics representation uses point sampled representation. [20]

Four dimensional dataset contains the basis of three dimensional data structure (x, y, z coordinate) and another axis, for example, the another axis should be time t, which describes 3 dimensional coordinate points and each point has a data value associated with it at a given time *t*, see Figure 5.

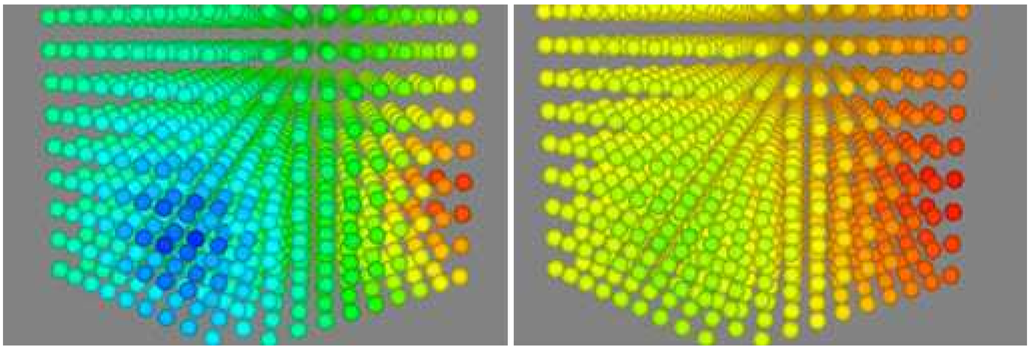


Figure 5: 3D temporal data visualization (Left image represents the data value in time *t*1, and the right image represents the data value in time *t*2).

Researchers from Earth Environmental Science analyze various data sets such as in situ, ocean, satellite, and simulation data. These data are one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D) data that include time series. Many systems have been developed already for 1D and 2D data, sophisticated tools for 3D data have not been well explored for environmental research. This is because large quantities of 3D data did not exist until recently, and analyses involving 3D data were not common before. There are many 3D visualization techniques, especially in medical science. Visualization tools are good at displaying or rendering shape of objects. However, the common 3D visualization tools are not well adapted to display targets that are non-solid, for example, express the earth environmental data proficiently. Moreover, researchers in earth environment want to view not the shape but the value of variables on a cross section along phenomena. As a result, a powerful visualization tool for earth environment science (PVES) that can accommodate 3D datasets was created.

PVES displays raw data in 3D space naively using Virtual Reality Modeling Language (VRML), which allows users to interact with [21]. Visualized results are displayed as a lattice along the axes of latitude–longitude and pressure level. It is also possible to display multiple products at the same time while utilizing the advantages of virtual reality. For example, if water vapor ratio is the size of the lattice and atmospheric temperature is the color of the lattice, the two products are displayed at the same time as in Figure 6. This is useful for analyzing correlations between the different products.

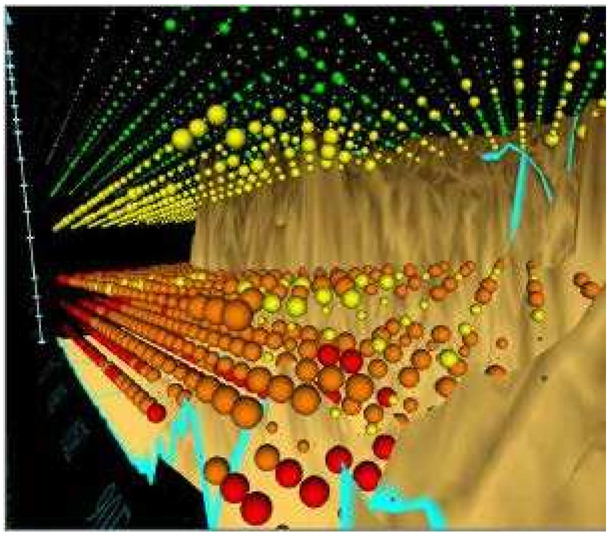


Figure 6: 3D display of Earth Environmental Science data set in PVES

To display a cross section of 3D data in virtual reality space using the PVES, users can define the cross section. They can also select the period and area of interest. They then select the data of interest by describing an arbitrary cross section by typing the latitude–longitude pairs in the text field. The server visualizes the selected data and displays the visualization result. Because the cross section and geographical features overlap, users can view and discuss the relationship between geographical features and data points visualization. Then, users can effectively view and understand changes in the time series. A cutting plane samples the 3D scalar field along a slice through the data and then renders the data by coloring it or generating 2D contour lines in the 2D slice, as shown in Figure 7.

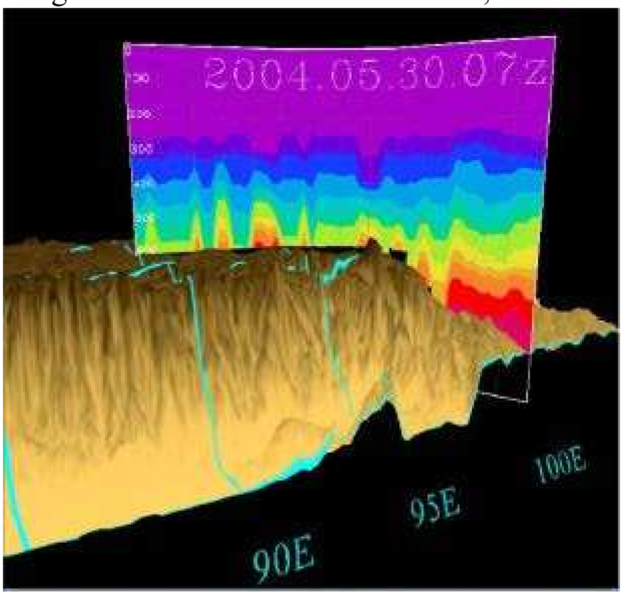


Figure 7: A cross section for water vapor ratio of 3D data that represented in 2D graph.

3D visualization is also used for temperature management. B. Lange et al [22] proposed a 3D visualization technique to analyze and mange energy efficiency from a data center, it deals with many different types of information like temperature, pressure and hygrometry. In their system, sensors are placed in a virtual room and the internal space is modeled using 3D point cloud. 3D points are located using a segmentation algorithm based on an extraction method, see Figure 8.

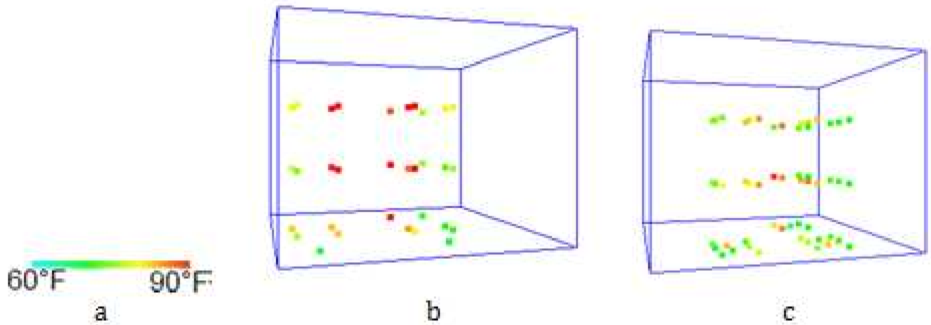


Figure 8: Data use to model the system. (a) presents temperature color scale, (b) and (c) present data features stem from capture sensors.

The room is empty and was represented by a simple shape, a box with a 4 meters length, 3 meters width and 2.5 meters height. They use point cloud visualization based on particle paradigm. Data are extracted from sensors located in the IBM Green Data Center in France. They put the same number of particles (30000) and 35 sensors distributed on three layers at 1 meter, 2 meter and on the ground. They define high and low temperature regarding the real sensors value.

B. Scalar field data

Scalar field are often represented by 3D points sampled at discrete intervals in a 3D grid. Each sub volume bounded by these sample 3D points is known as a voxel (volume element), which is analogous to a 2D pixel in a bitmap. Grids maybe stretched and curved to place more sample points in areas of interest, such as areas in which the field values change. Because 3D scalar field are not directly viewable – they consist solely of numbers in a 3D grid – we need to transform them into useful visualizations. The three techniques commonly used to visualize 3D scalar field data are: Cutting Planes, Isosurfaces, and Volumetric Rendering.

a. Cutting planes

A cutting plane samples the 3D scalar field along a 2D slice through the data and then renders the data by coloring it or generating contour lines in the 2D slice. With such a slice or cutting plane, the user can view a manageable subset of the data and can explore the field by sweeping the plane through the space. A set of volumetric data such as a deck of Magnetic Resonance Imaging (MRI) slices or Computed Temograph (CT) can be seen as modern imaging technologies that generates large quantities (approx. 100MB) [23]of three-dimensional information. But in order for this information to be clinically useful a moveable 2D cutting planes technique is used proposed by Hinckley [24], Qi [25]explore the volumetric data.

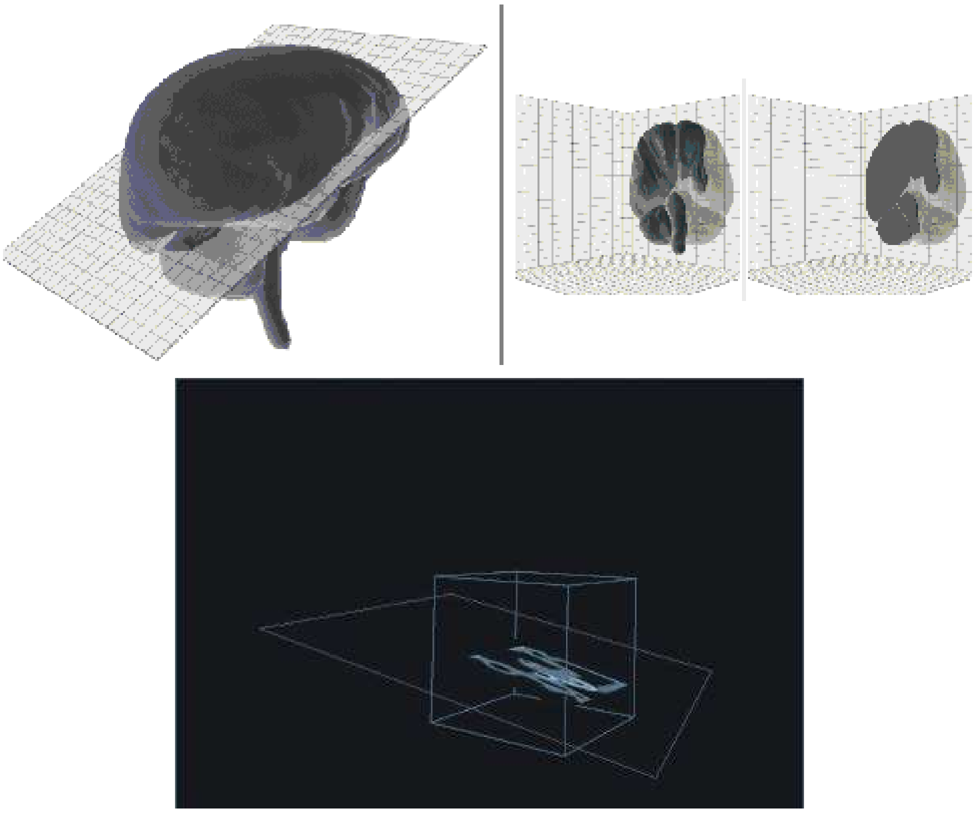


Figure 9: The Cutting-Plane used in medical MRI data set.

Such 2D cutting plane is used to cut through a 3D data set in order to explore its interior structure. This cutting plane technique can be reconstructed from a 3D volume model and visualized for diagnostic purpose or for planning of treatment or surgery and widely used in medical software platform.

b. Isosurfaces

An isosurface, the 3D equivalent of a single contour line, is the continuous surface that passes through all voxels containing a specified value. It is a surface that represents points of a constant value (e.g. pressure, temperature, velocity, density) within a volume of space; in other words, it is a level set of a continuous function whose domain is 3D-space.Isosurfacesprovide a more global view of a particular value in the field than cutting planes, but do not let the user see how quickly the data changes, as in the cutting plane technique, and also takes more computing resources (from a few seconds to a few minutes to compute).

Isosurfaces rendering are normally displayed using computer graphics, and are used as volumetric data visualization methods in computational fluid dynamics (CFD), allowing engineers to study specific features of a fluid flow (gas or liquid) around observation objects, such as aircraft wings. Isosurfaces tend to be a popular form of visualization for volume datasets since they can be rendered by a simple polygonal model to reconstruct surface shape, and they can be drawn on the screen very quickly. In medical imaging, isosurfaces may be used to represent regions of a particular density in a three-dimensional CT scan, allowing the visualization of internal organs, bones, or other structures.

A common method to generate as a polygonal surface to construct isosurfaces is using a Marching cubes algorithm [26][27].The basic principle behind the marching cubes algorithm is to subdivide a 3D space into a series of small sub cubes. Then Marching cubes instructs to 'march' through each of the sub cubes by testing for each corner points if it is inside the isosurface or not, and replacing the cubes with an appropriate set of polygons. The sum total of all polygons generated will be surface that approximates the constant value surface that the data set contains or describes.

Marching cube algorithm deals with the 8 corners of each sub-cube and therefore it must deal with a potential 256 possible combinations of corner status. However to simplify the algorithm, it reduces the complexity by taking into account cell combinations that duplicate under the following conditions.

- Rotation by any degree over any of the 3 primary axis
- Mirroring the shape across any of the 3 primary axis
- Inverting the state of all corners and flipping the normals of the relating polygons.

Taking this into account, the original 256 combinations of cell state down to a total of 15 combinations, with this number it is then easy to create predefined polygon sets for making the appropriate surface approximation. The image bellow gives an example data set covering all of the 15 possible combinations. The blue spheres denote corners that have tested as inside the shape and the green arrows denote the surface normals of the relevant triangles.

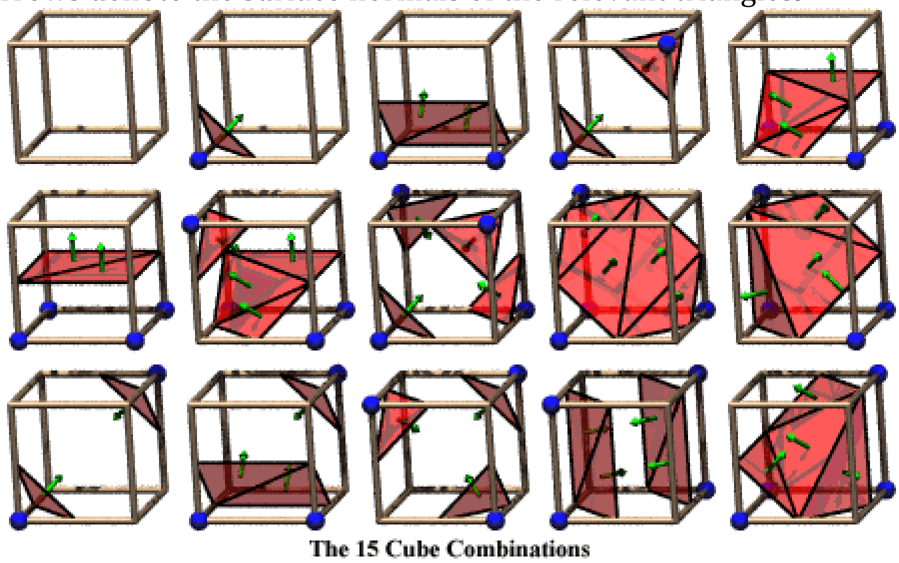


Figure 10: 15 cube corner status in marching cube algorithm (James Sharman)

Isosurface generation is commonly used for scientific visualization purpose. Oliver Kreylos et al [28]involved isosurface visualization to enable scientific workflow in a Virtual Reality environment. In the geological science, the source data are topography mode (3D height fields) and draped color image typically generated from satellite, aerial photography or laser scanners that are volumetric or 3D point cloud based. To make observations, researchers need to get data features in a very large point sets containing several million points. The techniques they use to visualize these 3D data are color-mapped planar slices, and isosurfaces computing using an incremental version of the Marching Cubes algorithm.

Figure 11: isosurface visualization in Geoscience.

Natalya Tatarchuk et al [29]have developed a technique for real-time volume data analysis by providing an interactive user interface for designing material properties for organs in the scanned volume. Intelligently combining isosurface extraction with direct volume rendering in a single system allows for surface properties as well as for the context of tissues surrounding the region and gives better context for navigation.

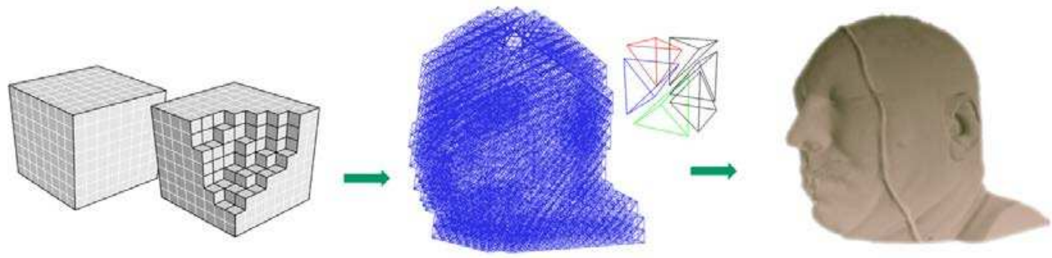


Figure 12: Isosurface extraction pipeline on GPU processing.

The isosurface extraction pipeline (Figure 12) proceeds as follows: they start by dynamically generating the voxel grid to cover their entire volume or a section of it. They use GPU processing to tessellate the volume into tetrahedral on the-fly. This allows adaptively generating and sampling the grid, based on the demands of the application. Each input voxel position is dynamically computed in a GPU shader. GPU then computes 6 tetrahedral spanning the voxel cube. Once having the tetrahedral, then they use the marching tetrahedral algorithm to dynamically extract polygonal surface from scalar volume consisting of material densities. GPU accelerated isosurface extraction is also described in papers [30][31].

c. Volume Rendering

Volume rendering visualization is a method of extracting meaningful information from a set of 2D scalar data [32]. A sequence of 2D image slices of human body can be reconstructed into a 3D volume model and visualization for diagnostic purposes. Direct volume rendering methods generate images of a 3D volumetric data set without explicitly extracting geometric surfaces from the data [33].These techniques use an optical model to map data values to optical properties, such as color and opacity [34]. During rendering, optical properties are accumulated along each viewing ray to form an image of the data using a Ray casting method.

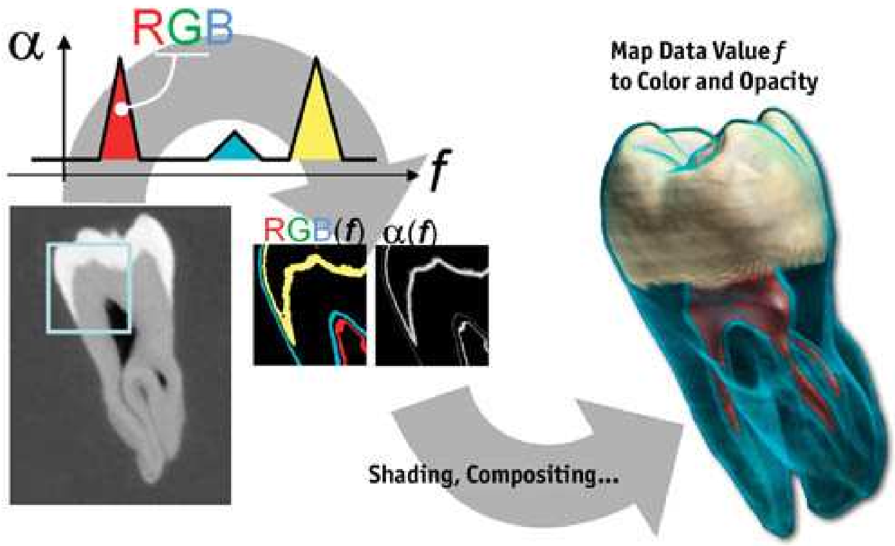


Figure 13: The Process of Volume Rendering.[32]

Ray casting with 3D texture [35] is one of the core techniques that are usually used by volume rendering. It simulates the propagation of the light traversing a colored translucent volume. Each translucent volume element contributes to the final color of the ray when it reaches the screen. This final color is usually computed by summing these contributions, see Figure 14.

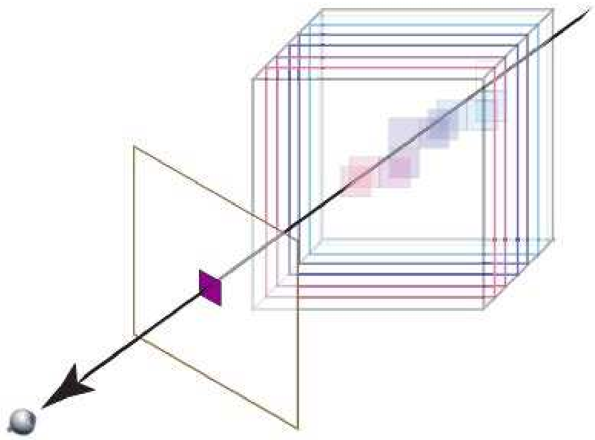


Figure 14: The ray casting integral can be approximated by summing over parallel 2D slices.

C. Vector data

Vector field is one of the major data type in scientific visualization. In fluid mechanics, velocity and vorticity are given as vector fields. This holds also for pressure or density gradient fields. Electromagnetic is another large application area with vector fields describing electric and magnetic forces. In solid mechanics, displacements are typical vector fields under consideration. Science and engineering study vector fields in different contexts. Measurements and simulations result in large data sets with vector data that must be visualized. The main challenge of vector visualization is to find ways of visualizing multivariate data set. Color, arrow, particles, line convolutions, textures, surface, and volumes are used to represent different aspects of vector fluid flows (velocities, pressures, streamlines, streamlines, vortices, etc.).

In the case of Earth Environment Science, variable such as air temperature, specific humidity, the horizontal wind, and geo-potential height are very important in water cycle analyses. Same as atmospheric phenomena research, the moisture flow data is one of the important factors influencing water resource management. Both of these data sets are 3D vector data.

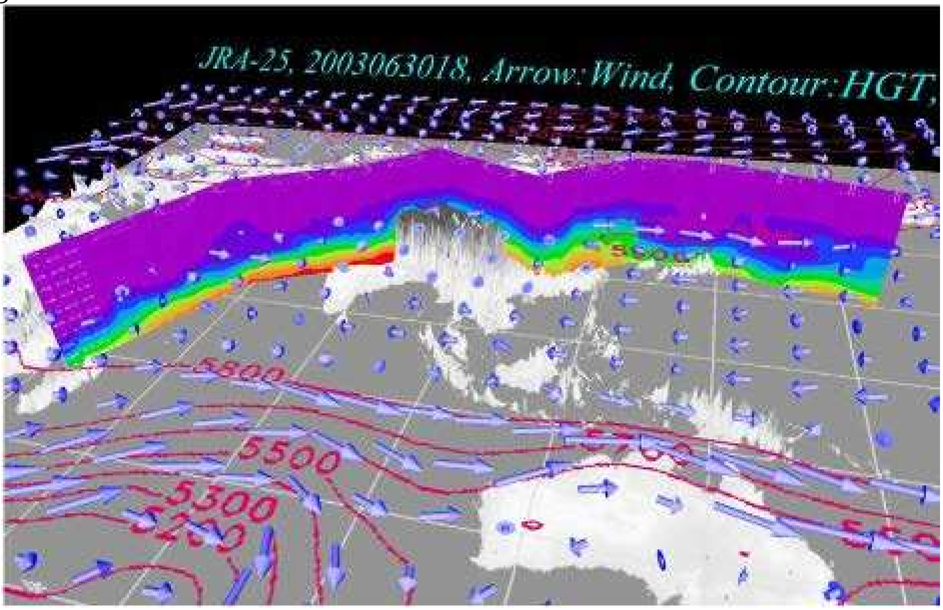


Figure 15: 3D vector data visualization using arrow.

Masaki Yasukawa et al[21]proposed, using arrow indicators, to visualize 3D horizontal wind data and moisture flow data; so that perpendicular spread of water vapor and the horizontal distribution of specific humidity at the same time can be viewed. And this type of figure is useful for understanding meteorology, reanalysis of data validation and atmospheric phenomena analyses.

Computational fluid dynamics (CFD) is becoming increasingly important for the evaluation of car body design concepts in the vehicle development process. Commonly used simulation applications are based upon the Navier-Stokes equation and use the finite volume method to numerically solve the partial differential equation. The finite volumes are organized in grids structure that fit the car body surface.

Each finite element refers to a node list support object and a physical material support object that includes the fluid physical properties (mass density, viscosity, etc.). Researchers from BMW research center used measurement probes to give the user an intuitive and easy way to analyze the data sets[36].

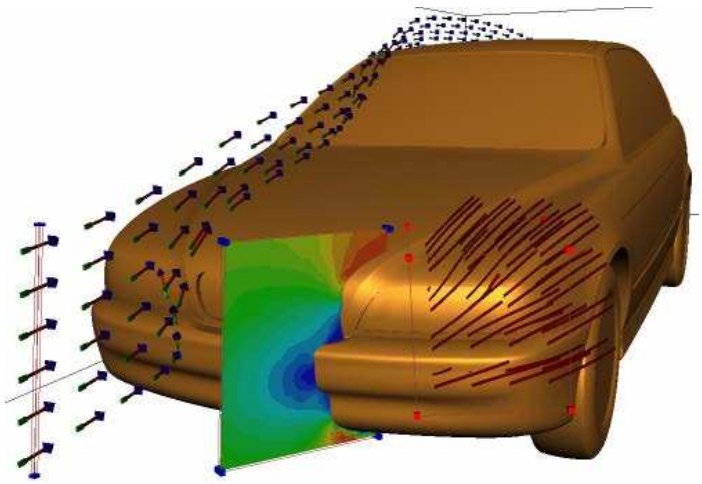


Figure 16: Measurement probes as rake, slice and arrow.

It can be seen in Figure 16, the system allows particle traces to be visualized as streaklines, ribbons, and glyphs. The ribbons show the local rotation of the flow by calculating the particle velocity. The glyph is constructed as an arrow pointing into the flow direction.

2.1.2 Human Perception

Human perception is the process of attaining awareness or understanding of the environment by organizing and interpreting sensory information[37][38]. All perception involves signals in the nervous system, which in turn result from physical stimulation of the sense organs. For example, vision involves light striking the retinas of the eyes, smell is mediated by odor molecules and hearing involves pressure waves. Because human visual channel generally can process much larger bandwidth than other perceiving senses, like auditory or haptic, it often considered the primary sense since it gathers large amounts of information in everyday life.

A. Stereoscopic visualization in VR

Virtual reality refers to a set of techniques that allows users to interact with a synthetic environment where it is possible to carry on tasks similar to the ones experienced in real contexts. In the classical conception of virtual reality, the representation of the synthetic environment is fed fairly directly to the eyes, ears, and possibly hands. The actions of the user in the environment are translated directly from typical physical activities. In a VR environment, the participant is immersed in a virtual world that replicates the main sensory communication channels—vision, hearing, and touch (the last one more technically known as a haptic feedback)—and allows some physical interactions with the virtual world. Most of VR environment are screen-based system, which generates a spatially limited virtual world, and that restrict their output to a screen display and provides interaction with the virtual world through a pointing device. The screen-based VR system provides an interface to the human visual sensory system that is represents physical reality with depth information thanks to display rendering and user head tracking.

Stereoscopic vision refers to the ability that humans have to see the same scene with both eyes in slightly different ways. It results in our ability to visually perceive depth and distances. VR environment provides a stereoscopic vision to retrieve the real world's depth and distance information.

Depth perception generates from a variety of depth cues. These are typically classified into binocular cues that require input from both eyes and monocular cues that require the input from just one eye [39]. Binocular cues include stereopsis, yielding depth from binocular vision through exploitation of parallax. Monocular cues include size: distant objects subtend smaller visual angles than near objects [40].

When we look an object in real word, our eyes rotate to meet at the desired location, this is called convergence. Accommodation is the adjustment in the focal length of our eyes, which allows correct image focusing at varying distances. Viewing an object in real word gives a zero parallax as the eyes converge at the same point.

In a typical VR system, all the virtual objects are projected on the screen. In order to render a stereo pair, it needs to create two images, one for each eye in such a way that when independently viewed they will present an acceptable image to the visual cortex and it will fuse the images and extract the depth information as it does in normal viewing. The screen can be seen as a projection screen. In the case where the object is behind the projection plane, the projection for the left eye is on the left and the projection for the right eye is on the right, the distance between the left and right eye projections is called the horizontal parallax. Since the projections are on the same side as the respective eyes, it is called a positive parallax. If an object is placed in front of the projection plane then the projection for the left eye is on the right and the projection for the right eye is on the left. This is known as negative horizontal parallax [41][42].

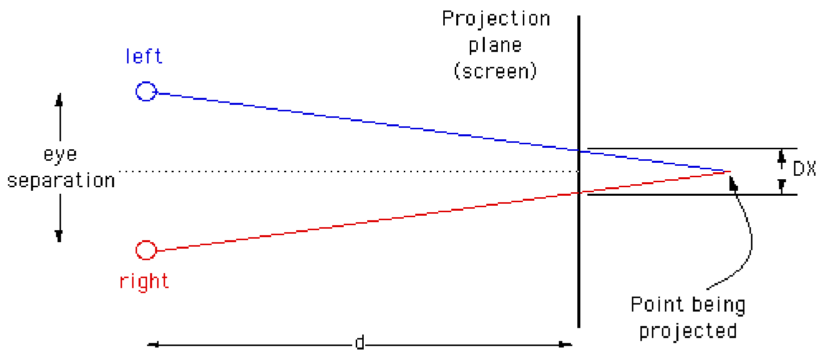


Figure 17: Common measurement of the parallax angle.

A common measure is the parallax angle defined as thea = 2 atan(DX / 2d) where DX is the horizontal separation of a projected point between the two eyes and d is the distance of the eye from the projection plane, see Figure 17. For easy fusion by the majority of people, and in order to reduce fatigue, the absolute value of theta should not exceed 1.5 degrees for all points in the scene. Theta is positive for points behind the scene and negative for points in front of the screen[42].

When we look at an object with two eyes, we perceive it as singular, like we do other parts of the visual scene stimulating points on our retina that share a common visual direction. These points are termed "retinal corresponding points" and fall on an area called the "horopter". Points outside the horopter fall on slightly different retinal areas and so do not have the identical visual direction and lead to "retinal disparity", the basis of our depth discrimination. This retinal image disparity occurs due to the lateral displacement of the eyes [43]. The region in visual space over which we perceive single vision is known as "Panum's fusional area"[44][45], see Figure 18.

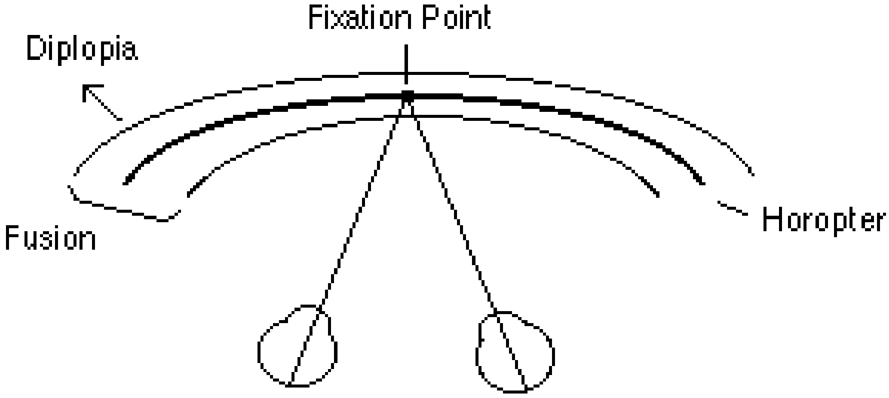


Figure 18: Panum's fusional area.

The principle of Panum's fusional area has to be preserved to create a nature and credible context to full immerse the participant in a VR environment [46].

B. Perceptual visualization

Scientific datasets are often difficult to analyze or visualize, due to their large size and high dimensionality, especially scientific simulation datasets such as results of geographic information systems, satellite images, and biomedical scans. Researchers in computer vision and cognitive psychology are studying how to visualize multidimensional datasets, in order to provide an easy understandable visualization system that also allows easy feature identification. The following perceptual features are commonly used in the literatures.

a. Color

Healey chose to use two features to visualize oceanography datasets: color and texture. For color, they conducted a number of experiments to determine how to choose colors that are equally distinguishable from one another. That is, they want to pick *n* colors which, when displayed simultaneously, allow the user to identify the presence or absence of any one of the colors. Their result shown that three criteria must be considered during color selection [47]: color distance: There is a threshold for the distance from each color to its nearest neighbor (s); linear separation: each color must be linearly separable from all the other colors, again by a minimum threshold measured in a perceptually balanced color model, and color category: each color must occupy a uniquely named color region. They found that when these rules are satisfied, up to seven isoluminant colors can be displayed simultaneously. A user can quickly determine whether any one of the seven colors is present or absent in a given display.

b. Perceptual texture elements

Healey also studied the use of perceptual texture elements (or pexels) for multidimensional data visualization. They opposed to "texture maps" (patterns that are mapped onto regions of a graphical object)[47], perceptual textures are arrays of elements with visual and spatial characteristics that are controlled by the underlying data being displayed. Their experiments are testing the use of height, density, and randomness to display multidimensional data. Their pexels look like paper strips; at each data position, a pexel is displayed. The user maps attributes in the dataset to the density (which controls the number of strips in each pexel), height, and randomness of each pexel. See Figure 19.

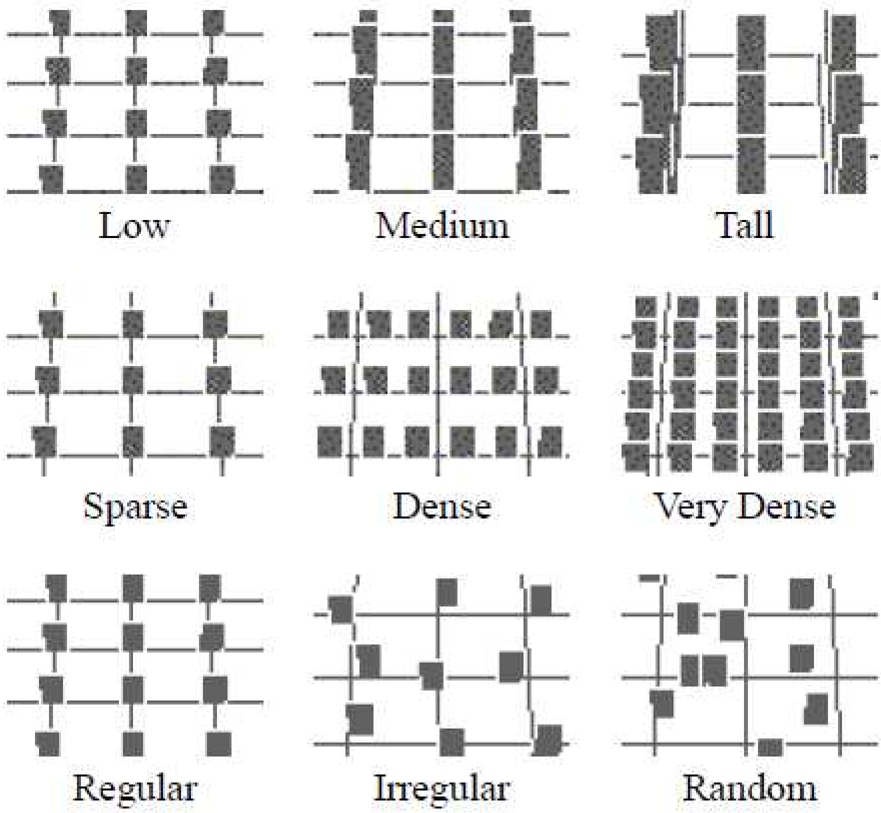


Figure 19: Different properties of perceptual texture elements.

Their experimental result has shown that:

- differences in height may be easier to detect, compared to differences in density or randomness,
- variation in height may mask differences in density or randomness; this appears to be due to the occlusion that occurs when tall pexels in the foreground hide short pexels in the background; this will be less important when users can control their viewpoint into the dataset (our visualization tool allows the user to interactively manipulate the viewpoint), and
- Tightly spaced grids can support up to three easily distinguishable density patterns; placing more strips in a single pexel (e.g., arrays of three by three or four by four strips) will either cause the strips to overlap with their neighbors', or make each strip too thin to easily identify.

These features can be used to perform certain visual tasks very rapidly and accurately. These results from their experiments allow building visualization tools that use these visual features to effectively represent multidimensional datasets.

c. Color scale

Color plays a major role inhuman visual perception for visualization design. Professional designers and scientists are aware of rules that guide the design of color palettes, not only from an aesthetic point of view but also from an attention-guiding one. Likewise, visualization is not only concerned with providing a pleasing image. So, it is important to help users gain quick and accurate insight into the visualized data.

The study of color for data visualization tasks is not new, yet it has traditionally focused on the design of transfer functions (also called color scales or color palettes) intended for the mapping of scientific or cartographic scalar data to RGB attributes. Well known for the former is the PRAVDA system [48], where authors used Blue/Yellow color mapping for color palettes according to the result of paper[49]where the author indicated that the most common default color mapping, is the rainbow color mapping, which is a hue-based scale from blue, through a rainbow of colors, to red. When this scale is mapped onto scalar data, the user is conceptually mapping a linear scale in hue onto a scalar variable. Perceptually, however, this scale does not appear linear. Equal steps in the scale do not correspond to equal steps in color, but look instead like fuzzy bands of color varying in hue, brightness and saturation. When mapped onto scalar data, this color mapping readily gives the user the erroneous impression that the data are organized into discrete regions, each represented by one of the rainbow colors. This can lead the user to infer structure that is not present in the data and to miss details that lie completely within a single color region, see Figure 20.

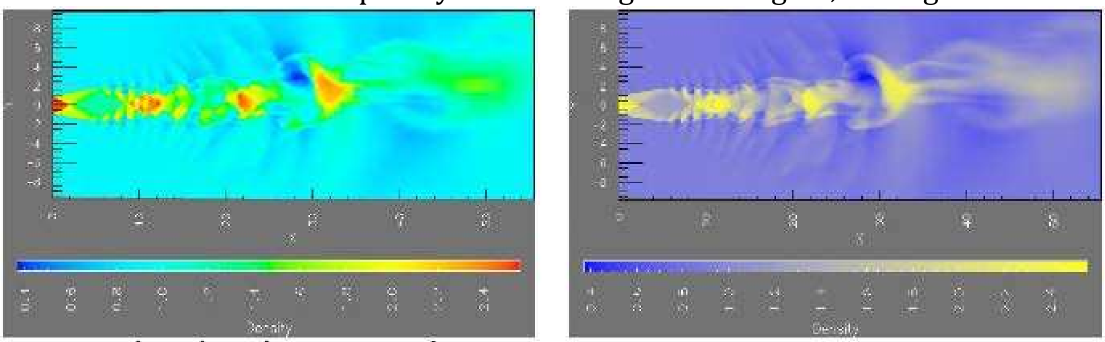


Figure 20: Comparison of rainbow color mapping and Blue/Yellow color mapping.

d. Transparency

Volume visualization is a useful technique that allows user to discover meaningful structural information in volume datasets. It relies on proper transfer function specification to deliver the expected results to user visual system for perceiving purpose. In typical scientific volumes, structures to be visualized may be layered or partially occluded by others in the rendered image. Instead of completely removing the occluding structures or exterior layers, the structure are often rendered in a semi-transparent manner to preserve the appearances and spatial information in the image.

Enhancing the perception of semi-transparent structures has been studied for decades. Gooch et al [50]proposed a non-photorealistic lighting model for technical illustration. Lighting method can emphasize volumetric data perception through the features such as shadows, highlights, and silhouettes in an image. Psychological studies [51] have identified that luminance and contrast are two major factors in transparency perception. The semi-transparent nature of direct volume rendered images is useful to depict layered structures in a volume. Ming Yuen Chan et al[52]studied a perception –based transparency optimization to obtain a semi–transparent result with the layers clearly revealed.

To study the effect of color on transparency perception, a set of Direct Volume Rendered Images (DVRI) of the molecule were generated with different color saturation values, see Figure 21. In the DVRIs, the layer of structures overlapped and the color saturation change resulted in different transparencies of the out layer.

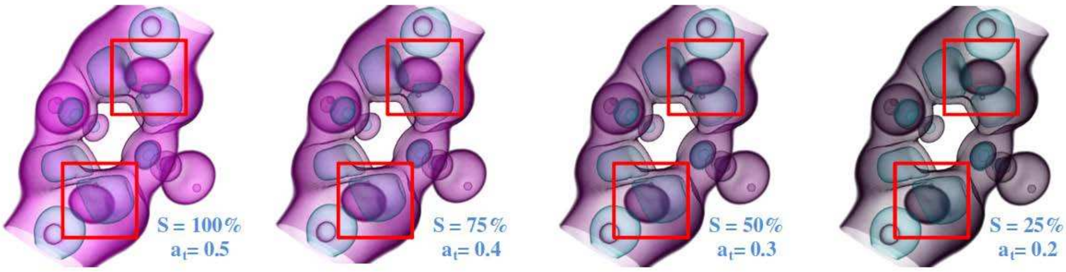


Figure 21: Molecule with different color saturation values.

The results show that the transparency perception does not only depend on visibility but also the color or appearance of the layer. To faithfully present the structures in the image, one should optimize the transparency of structures in the image in addition to the opacity of each constituent structure. In this study, the author also proposed a process of visiblity equalization. Figure 22 shows the result of visibility equalization (opacity optimization). The skin and bones of the carp were assigned with importance values of 0.2 and 0.8 and the objective was to balance the overall visibility of eachstructure based on this weighting.

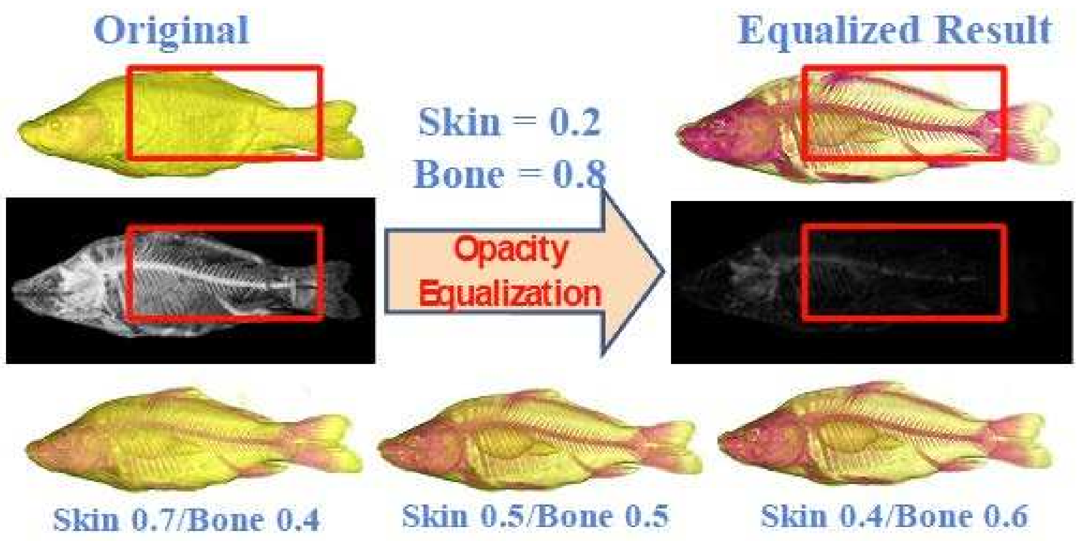


Figure 22: Opacity optimization of skin and bones rendering.

The authors conducted a user study of visibility equalization method. The subjects were asked to rate the improvement and quality of the images throughout the optimization process. The feedback from the subjects indicated that the layered transparent structures might not be distinguishable even after the visibility equalization but an improvement was observed after the shape and transparency adjustment. It indicated that a good perception of transparent structures relies not only on visibility (opacity) but also the color and lighting.

e. Transfer function

A direct volume renderer requires every sample value to be mapped to opacity and a color. This is done with a "transfer function", it assigns color and opacity to the volume based only on the single scalar quantity which comprises the dataset, it was one dimensional transfer function. Transfer functions can be categorized as data-centric or image-centric. The former determines the visual properties based on the volume data values and their derived attributes. Multi-dimensional transfer functions [53] can be defined on the local properties of the volume to reveal the target structures. Properties like curvature [54]and size [55]have also been used. Alternatively, the image centric transfer function is designed based on the rendered images. For example, transfer function can be searched based on the specific features[56]or visibility[57]of structures in the rendered image.

The author of the paper [53]demonstrated the importance and power of multi-dimensional transfer functions, which can be applied on scalar volumetric dataset (based on data value, gradient magnitude, and principles of edge detection.). The usefulness of having a second derivative measure in the transfer function is that it enables more precise disambiguation of complex boundary configurations, such as in the human tooth CT scan. The different material boundaries within the tooth overlap in data value such that the boundaries intersect when projected to any two of the dimensions in the transfer function domain. Thus, 2D transfer functions are unable to accurately and selectively render the different material boundaries present. However, 3D transfer functions can easily accomplish this.

f. Motion cues

Direct Volume Rendering (DVR) is one of the most important techniques developed to achieve direct perception of such volumetric data. It is based on semi-transparent representations, where the data are accumulated in a depth–dependent order. However, the drawback of semi-transparent representation is that it also produced images that may be difficult to understand or perceive. Boucheny et al [58] presented two perceptual studies that propose the idea to improve effectiveness of semi-transparent representation of volumetric data. First the authors questioned the ability to perceive the spatial layout of volumetric object rendered though texture-based DVR techniques and conducted an experiment in which participants are asked to decide how semi-transparent cylinders are organized in depth, see Figure 23.

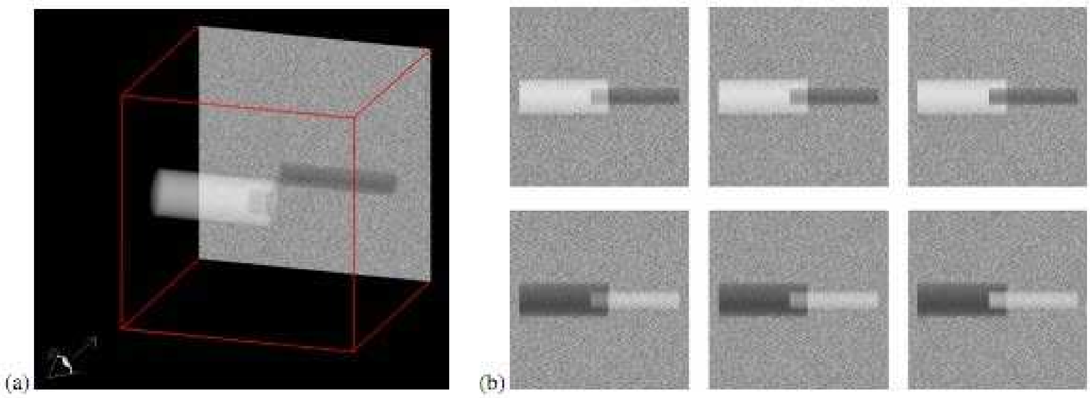


Figure 23: User study in DVR perceptual experiment.

The results collected in this experiment show that our perception of the organization in depth of overlapping semi-transparent objects is weak, and can be influenced by factors other than the sole combination of luminance. Then the second experiment was conducted to exam how volume rendering techniques can convey information about the spatial layout of the supported data in a dynamic context (motion cues added.). They tested the influence of the Transfer Function that associates opacity and a luminance to every voxel scalar value in order-dependent DVR, and compared performances to order independent methods.

The user performance results shown that by adding motion cues in volume rendering, a dynamic context DVR can lead to a strong perception of the organization in depth of volumetric data, but that this can be achieved only through a careful tuning of the Transfer Function (TF).

g. Illumination

Large datasets typically contain rough feature comprised of finer sub-features in form of shape. The perception of shape has been studied for decades. The desirable goal for visualization of multi-scale data is the user can, within a single image, attend to full range of feature scales from large to small.

Melek et al [59]proposed a display techniques for dense volumes of thread-like data that uses a local illumination model with a shadowing pass, which allow individual fibers near the domain boundaries are clearly visible, and the added shadows provide cue to the density of the fiber mass and cues to the relative depth of individual fibers toward the core of the domain. Ramnachandran found that the perception of shape from shading is biased toward a single luminary[60].Langer et al found that under diffuse lighting, the human visual system has a bias toward interpreting dark regions as 'deep' or recessed [61].

Local illumination can be understood as a solution to the usual light transport equation using vector-valued light [62]. Chris Weigle et al[63] studied a physically-based illumination. In order to address whether physically-based illumination (taken as a whole, or global illumination) influences the perception of a scene compared to local illumination and whether that effect improve task performance.

A human subject experiment to quantify the effect of physically-based illumination was conducted by measuring the participant performance for two tasks: select in the closer of two streamtube from a field of tubes and identifying the shape of the domain of a flow field over different densities of rubes.

The results shown that physically-based illumination influences participant performance as strongly as perspective projection, it proves that physically-based illumination can provide a strong cue to the layout of complex scenes. The authors also found that increasing the density of tubes for the shape identification task improved participant performance.

h. Kinetic: moving texture

Scientific visualization is often concerned with the creation of 2D visual depictions of the features found in 3D data sets with the goal of having these 3D images provide scientists with insight into their data. Unfortunately, the 3D representation can introduce ambiguities since it is merely a 3D projection of 3D data set. Time-varying sequences of 2D image are widely used in visualization as a means to provide an extra dimension of information for perception to occur. A work that deals with the use of motion as a way of providing supplemental cues to aid in the perception of these often ambiguous 3D structures found in scientific visualization have been done by Eric B.Lum et al [64]. In this paper, they presented a visualization technique, which they "Kinetic visualization" for creating animations that illustrate the shape of a static object in an intuitive manner using motion cue.

Kinetic visualization uses motion along a surface to aid in perception of 3D shape and structure of static objects. The method uses particle systems, with rules such that particles flow over the surface of an object to not only bring out, but also attract attention to information on a shape that might not be readily visible with a conventional rendering method which uses lighting and view changes, see Figure 24.

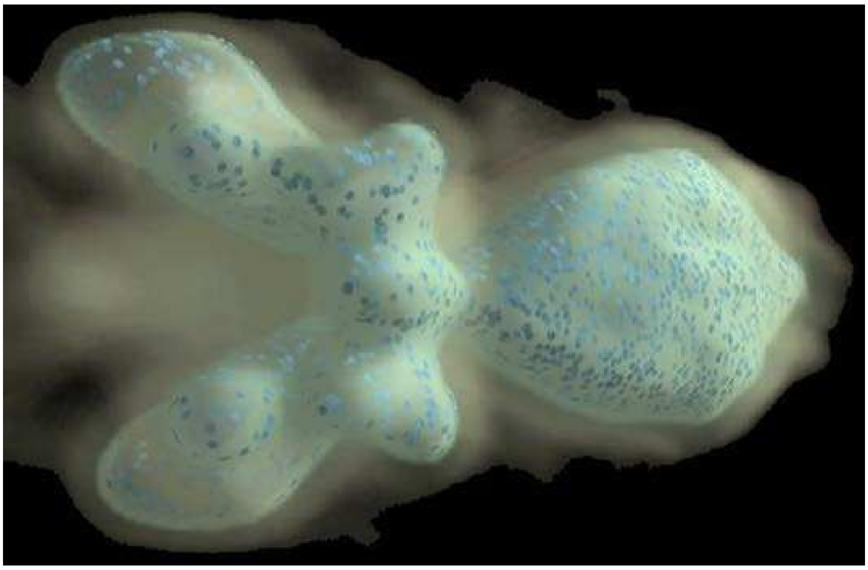


Figure 24: Kinetic visualization.

i. Ambient Occlusion and shadows

Ambient Occlusion is a shading method used in 3D computer graphics which helps add realism to local reflection models by taking into account attenuation of light due to occlusion. Ambient occlusion attempts to approximate the way light radiates in real life, especially off what are normally considered non-reflective surfaces.

Cast shadows are known to play a key role in human perception of the 3D world. To qualitatively and quantitatively understand the importance of shadows in our perception of the world, several studies and experiments have been conducted to understand how shadows shape our perception and understanding of a scene. Through these experiments, the importance of shadows has been demonstrated in understanding the position; size and geometry of both the shadow caster and shadow receiver. Hubona et al[65] discuss the role of shadows in general 3D visualization. Wanger et al[66] study the effect of shadow quality on the perception of object relationships.

Eric Penner et al[67] presented a novel method for generating approximate isosurface ambient occlusion and soft shadows to improve the perception of details of isosurface. Compared with other approaches which may require hours or days of pre-computation time and suffer from aliasing and/or quantization artifacts, their approach can load a data set within seconds, has very good performance and doesn't suffer from the aliasing of pre-computed lighting techniques.

As we kwon that regular "diffuse–plus–specular" Phong shading model [68]which is commonly used with volume rendering, A. James Stewart, author of paper [69]presents a shading model for volumetric data which enhances the perception of surfaces within the volume. The model incorporates uniform diffuse illumination, which arrives equally from all directions at each surface point in the volume. This illumination is attenuated by occlusions in the local vicinity of the surface point, resulting in shadows in depressions and crevices.

j. Visualization animation

Computational fluid dynamics, usually abbreviated as CFD, is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Having a understandable and efficient method to visualization of computational fluid dynamics (CFD) data is vital in understanding the varied parameters that exist in the solution field.

The animation of CFD data is not only computationally expensive but also expensive in the allocation of memory, both RAM and disk. Preserving animations of the CFD data visualizations is useful, since recreation of the animation is expensive when dealing with extremely large data structures. Researchers of CFD data may wish to follow a particle trace over an experimental fuselage design, but are unable to retain the animation for efficient retrieval without rendering or consuming a considerable amount of disk space.

Stephen C. Jones and Robert J. Moorhead [70] proposed in the early 20'to develop optimal image compression algorithms that allow visualization animations, captures as independent RGB images, to be recorded to tape or disk. If recorded to disk, the image sequence is compressed in non-real-time with a technique which allows subsequent decompression at approximately 30 frames/sec to simulate the temporal resolution of video. Initial compression is obtained through mapping RGB colors in each frame to a 12-bit color map image.

Over the past few year GPUs (graphics processing units) have seen a tremendous increase in performance, with the latest NVIDIA GPUs now achieving nearly one teraflops of performance, or roughly an order of magnitude higher performance than high-end CPU. In addition to this high computational performance, the latest modern graphics hardware offers increasing memory capacity, as well as support for 64-bit floating point arithmetic. Together with CUDA[71],which exposes GPUs as general-purpose, parallel, multi-core processors, GPUs offer tremendous potential for applications in computational fluid dynamics.

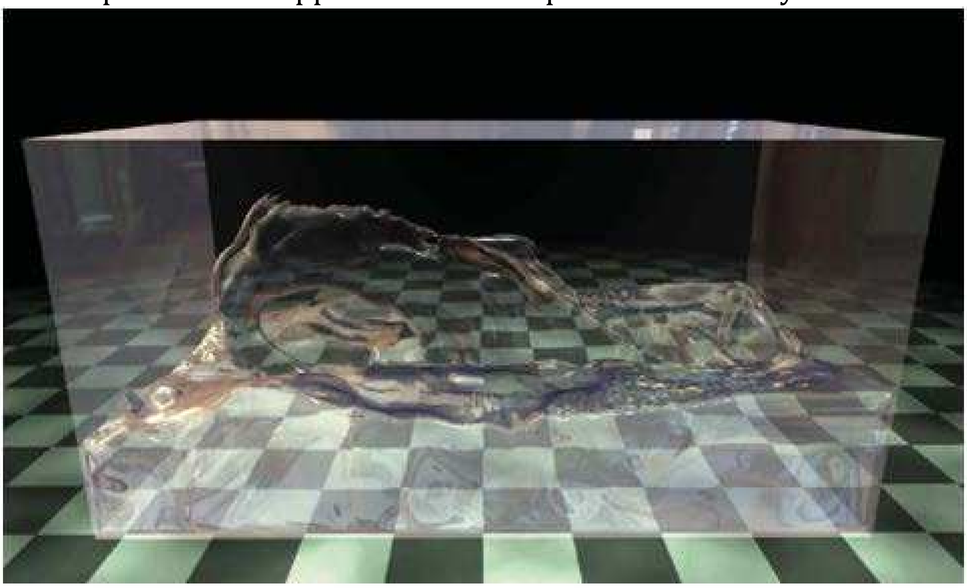


Figure 25: Water Simulated and Rendered in Real Time on the GPU

Physically based animation of fluids such as smoke, water, and fire provides some of the most stunning visuals in computer graphics, but it has historically been the domain of high-quality offline rendering due to great computational cost. Keenan Crane proposed a GPU CUDA architecture based method not only simulate animation of fluids effect in real time[72], but improve that they can be seamlessly integrated into real-time applications to help user perception of CFD data sets, see Figure 25.

k. Others

In order to visualize large-scale dataset, distribution visualization framework which combines VR technologies and remote computing resources on a high speed network is used for point-based VR visualization, so that large-scale scientific datasets can be visualized in real-time on local VR devices[73]. In this paper, the framework is designed to be a scalable distributed system with pipelined data retrieval, computation, and visualization for various datasets. The author selected point samples as an intermediate format of data which flow through the pipeline, because the conceptual simplicity and rendering performance of points make them a good choice as modeling and display for VR-end reconstruction. Different sampling, packing and rendering algorithms with different levels of computational complexity are also studied and customized to match the various visualization requirements for specific VR application.

The authors conducted a set of case studies to prove the feasibility of the proposed visualization strategy, datasets with different characteristics, such as triangle meshes and volumes, are used as customized visualization instances of the proposed framework. Several pipeline configurations, such as single server to single client, server cluster to single client, and server cluster to client cluster, are tested for different applications. The framerate is the criterion of evaluation. All experiments show that VR interaction can be improved for various visualization tasks by utilizing the visualization framework.

Kreylos et al.[74] presented an efficient method to visualize very large LIDAR datasets with the use of a multi resolution and view dependent out-of-core approach, which has been an important improvement of the existing LIDAR visualization methods.

Their rendering algorithm is focused on achieving high frame rates required in immersive stereoscopic environments. It is point based, but it does not utilize the modern graphics card’s programmable shaders, which can be used to provide the user with a better perception of depth and 3D shapes. Thus, an approach has been presented that enables a high quality visualization of large LIDAR datasets with a more sophisticated point-based rendering technique by Boštjan Kovač et al [75]. Similarly as the Kreylos' method, but with important distinctions, our method uses an out-of-core data management algorithm that retrieves data from slow bulk memory on demand and buffers it in RAM and GPU. A LOD management scheme assures that far away points are not rendered at full density. A point-based rendering method is used to render points as dynamically scaled and 3D rotated fuzzy ellipses to produce mostly hole-free and anti-aliased

3D scenes. The method also provides important 3D cues such as lighting and orientation of points.

Aravind Kalaiah et al propose a scheme for modeling point sample geometry with statistical analysis [76]. Generally, the scheme contains two steps:
They first analyzed the given unstructured point sample geometry using Principal Component Analysis (PCA): a tool that has been used successfully for analysis of empirical data in a variety of fields. The input consists of a collection of points with attributes such as spatial location, normal, and color.

The method works by exploiting local coherence with a PCA analysis and is fairly general in that it can handle other local attributes such as normal and color within this framework. The representation is quite compact and efficiently approximates the original geometry with hierarchy. This type statistical analysis of a densely sampled point model can be used to improve the geometry bandwidth bottleneck and to do randomized rendering without sacrificing visual realism.

Point-based geometry receives more attention as its advantage of simplicity and flexibility. In order to fill the visual gap between point samples, point-based models are used SPLAT (oriented 3D ellipses) representation to approximate the surface geometry [77]. Since no topological consistency conditions between neighboring splats have to be observed, Wu [78] apply an unconstrained global optimization technique and a sub-sampling algorithm which is especially designed for splat-based representations is proposed to improve output quality. Due to a desired photorealistic results of SPLAT representation, optimized ray tracing approach has been studied for the rendering of objects whose surface are represented by point clouds [79]. The authors determined a neighborhood around each point of the point cloud, estimated the surface normal at each of the points, computed splats with varying radii that cover the surface, and used the normals of all points that are covered by each splat to generate a smoothly varying normal field for each splat. Phong model is another important parameter can improve the SPLAT surface rendering. Mario [80]propose to base the lighting of a splat on a linearly varying normal field associated with it, and they show that the resulting Phong Splats provide a visual quality which is far superior to existing Phong model rendering.

C. Interactive perception

Human perception is referred as the process of obtaining awareness or understanding of the environment by organizing and interpreting sensory information comes from everywhere around us. Human perception in the broadest sense is a matter of interaction between the world and the self. At its simplest, the world gives us events; we in turn give those events meaning by interpreting and acting upon them to cognize the events. There are some obvious details here: we have sensations (input from the world, stimuli) and actions (output to the world, responses). Human perception can be seen as the most important aspect of knowledge cognition of our daily life.

As interaction plays an important role of human perception processing, the interactive perception augments the process of perception with physical interactions. By adding interactions into the perceptual process, manipulating the environment becomes part of the effort to learn task-relevant information, leading to more reliable task execution. It can be seen as an acting to improve perception and then using the resulting improvement understanding of the world.

In the field of scientific visualization, scientists not only create and implement the pure algorithms that allow the realistic the rendering of various type of data set to provide better/finer visual perception, but also using the intuitive interaction techniques to improve the data manipulation and exploration. Following interaction techniques are commonly applied in the literatures:

a. Arbitrary curved

Users also want to cut out arbitrary curved surfaces from 3D data and get desired images. Masaki Yasukawa et al[21] proposed a powered visualizer for earth environmental science which can accommodate three-dimensional dataset. In general, users do not utilize 3D data for analysis, but they use only the pats along the geographical features of interest. It is an onerous job for users to cut out the desired arbitrary cross section form 3D data. Furthermore, they must also repeat the same job on a great deal of data for time-series analyses, so that analysis time is wasted and the analysis is not efficient. Thus, an arbitrary cross-section slicer is developed. The user can specify an arbitrary curve over the 3D dataset and then visualize its cross section.

On the cross-section slicer, users view not only on kind of 3D product but also related data, and the integrated analysis is carried out while users view those data simultaneously. For example, geo-potential height, wind and specific humidity associated with the pressure level data in on the cross-section can be easily used for data analysis, see Figure 26.

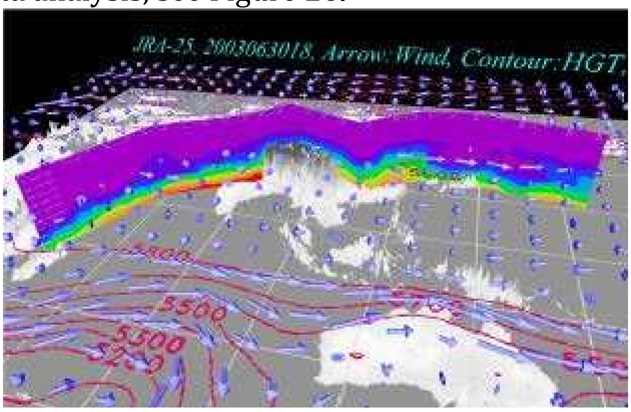


Figure 26: Arbitrary curved selection in PVES environment.

b. Interactive Clipping Planes

Bjorn Zehner in paper [81]proposed to use an interaction device (Flystick) to implement four interaction tasks:

- Navigation
- Interaction with objects in 3D space, such as translating objects or moving clipping planes

- Selection of objects for which additional information should be shown in the 2D windows
- Steering the 2D windows

The navigation is linked to the small joystick on the Flystick top. By pushing it forward, the users fly in the direction they point and by pulling it back, they fly backwards. For direct 3D interaction, tools are provided to translate objects or to move objects temporarily which then snap back to their original positions.

For 3D distribution of scalar data, multiple isosurfaces are often generated and the ones that are near to the viewer often hide the ones behind them which disturbs the view of the 3D course of the scalar field

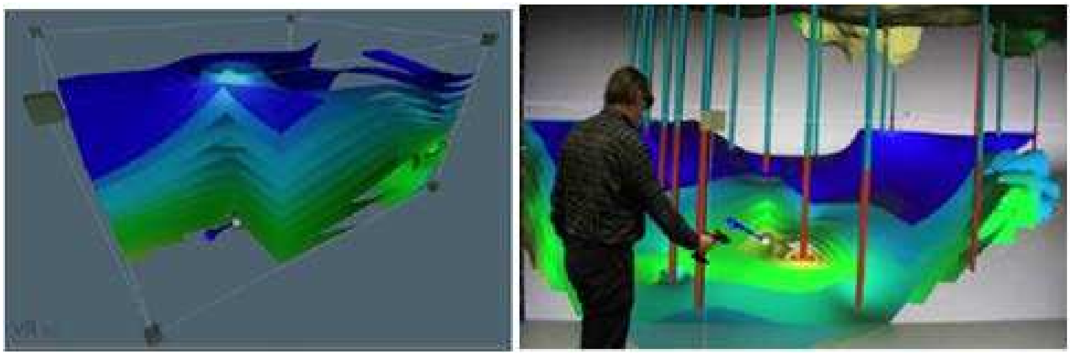


Figure 27: User defined clipping region and Region of interest selection.

The author has implemented a solution of data–analysis supporting 3D interaction: the user can use 3D tools to define a clipping region by manipulating the 3Drectangular parallelepiped that is defined by 8 cubes at its corners and represents the volume of interest. Outside of this volume the isosurfaces are clipped, and so are not visible. A small sphere can be moved within the defined volume that represents the point where 3 additional axis-parallel clipping planes inside the volume intersect, so that sub cutting area can be interactively defined within the volume, see Figure 27. The additional 2D information is shown upon the user's request, such as detailed borehole information on rock types or graphs of physical values. The users choose which information is shown by selecting the corresponding objects in the virtual model.

c. Isosurface and streamlines

Earth sciences employ a strongly visual approach to the measurement and analysis of geologic data due to the spatial and temporal scales over which such data ranges. Kreylos et al[82] proposed using 3D perception and interaction with data and models to have better perception of exploring data set in the VR environment. In geological mapping application, the main interaction is to record observations by drawing vector-based mapping elements, such as polylines, directly onto a 3D terrain model. The interaction method is straightforward: pressing a button on a 6DOF device, users can create new vertices at the projection of the position of the input device onto the terrain surface.

In a measurement application, in order to provide uses a better comprehension of the dataset, the authors in paper [28] proposed to extract features, by selecting the subset of sample points defining the surface of the particular feature. After a point set has been selected, users can request the computation of derived quantities, such as plane equations, sphere centroids and radii, or cylinder axes and radii, depending on the shape of the selected feature.

To support interactive extraction, a user can select the parameters guiding primitive (such as slices, isosurfaces, or streamlines) extraction via direct manipulation and the result of extraction is displayed immediately. For example, an isosurface can be specified not by its isovalue, but by a point on its surface. Using 6DOF input device, users can pick a point of interest inside the examined data set's domain, and the program will start extracting the isosurface containing that point starting at the picked point, see Figure 28.

Figure 28: Isosurface visualization of surface features in the Earth's mantle.

When users selected an examined isosurface, the program keeps expanding the current surface. This approach allows users to interactively understand isosurface through a data set's domain, thereby gaining a more global understanding of a data set's structure.

d. Physical interactive props

Interaction with volumetric scalar data requires a user with spatial reasoning and 3D perception skills. The traditionally interface for 3D manipulation with volumetric data is currently the computer desktop with a graphical user interface that is controlled by a mouse and keyboard. An intuitive manipulation can improve the 3D interaction process and provide a better understanding of volumetric data structure. Passive Interface Props [24] was one of the first 3D interfaces to support continuous clipping interaction in 3D space.

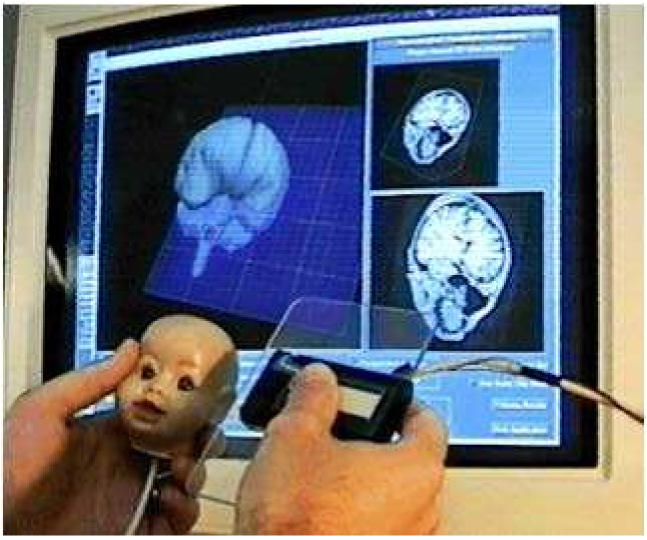


Figure 29: User selecting a cutting-plane with the props.

The Pass Props includes a head prop, a cutting-plane prop (see Figure 29) for creating intersections surface, and a pen-like prop for planning trajectories. The 6DOF movement property associated with each individual props that are tracked using trackers. Visual feedback of the user's interaction is displayed on a computer display in front of the user. The head prop is used to manipulate the orientation of the target volumetric data (such as patient's anatomy). The rendering of the volumetric data on the screen follows the rotation and the translation of the head prop. The rendering scale is controlled by the observer-to-object rendering distance, and is also controlled by moving the head prop closer to or further away from the body. The user holds the cutting-plane prop to specify the location and orientation of the slice through the 3D scalar volumetric data.

Qi et al [83] proposed a similar 3D interaction method with volumetric data sets. Instead of using props, they used tangible interaction device are wooden cubes, a metal frame and a metal pen. Three 3D types of interaction interface were designed:

- Mouse-driven clipping plane with cube: A virtual clipping plane that is controlled by the movement of the mouse. This interface divides the interactionwith3 DOF of the clipping plane into two separate operations: translation and rotation. For example, the user can hold the left mouse button down and drags the mouse with the cursor pointing to the virtual plane, the virtual plane rotates correspondingly.
- Tangible pen clipping plane: First the pen-like device is painted with linear pattern. With the detection of the linear pattern, the continuous orientation is reported and associated to the virtual plane. Usually, the non-dominant hand holds the cube that controls the volumetric data, while the dominant hand holds the pen. The virtual clipping plane has an orientation that is orthogonal to the pen, and a position that is determined by the pen tip. The user can manipulate the pen and wooden cube relatively as the user expects.
- Tangible Frame for clipping plane: A square-shaped metal frame is used to control the clipping plane. Differ from the second 3D interface, the

shape of the interaction device that control the clipping plane is a frame with five trackers. User's non-dominant hand, and grasps the frame with his dominant hand on the side. The physical cube intersects with the physical frame, and the virtual counterparts on the screen.

e. Interactive transfer function

As transfer function has an enormous number of degrees of freedom in which the user can get lost, transfer function can be seen as an important factor of direct volume rendering. Appropriate transfer function can guide the user have a better cognition of experimental volumetric dataset. Joe Kniss et al [84] proposed to resolve the multidimensional transfer function's potential complexities in a user interface.

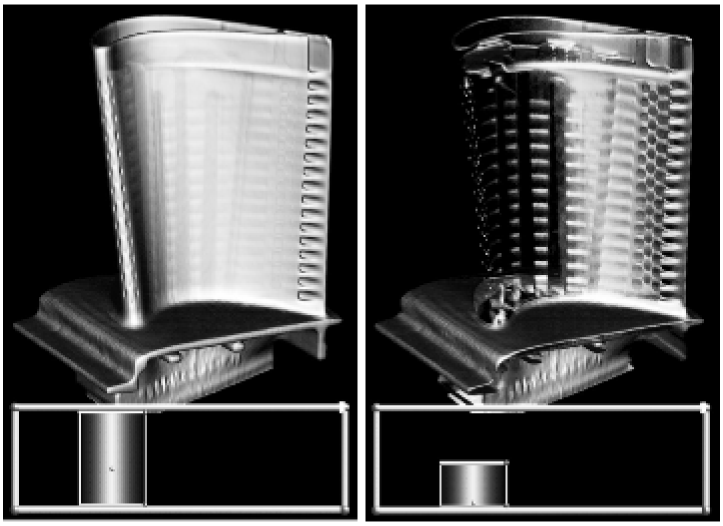


Figure 30: Volumetric rendering with 2D widget of transfer function control.

The principle of the direct manipulation widgets (see Figure 30) presented here is to link interaction in one domain with feedback in another, so as to build intuition for the connection between them. Also, the conceptual gap between the domains can be reduced by facilitating interaction in both domains simultaneously. They exploited the fast rendering capabilities of graphical hardware, especially 3D texture memory and pixel texturing operations. Together with the widgets and the hardware form the basis for new interaction modes which can guide user towards transfer function setting appropriate for their visualization and data exploration interests.

f. Dragging and interactive region of interest

Scientific visualization involves communication of simulated or measured data. The growing efficiency of today's high-performance computer enables simulation of physical phenomena with a high temporal resolution and for a long time span. Consequently, visualization system required efficient interaction techniques to navigate in the visualized time varying data.

Time-varying data, scientists often use animated visualization because they correspond to the natural perception of time. Marc Wolteret al [85] proposed a set of 3D user interface that employs direct-manipulation metaphors for temporal navigation in scientific visualization. Instead of manipulating an intermediary for time (such as slider bar or a clock-like widget) and observing the spatial changes of objects that these manipulations cause, they manipulate objects spatial properties to gain information about the temporal operations necessary to achieve those manipulation. Following mechanisms were proposed to interact with temporal visualization:

- Trajectory dragging (see Figure 31): when user selects a visualization object, the system shows its trajectory. Changing the position along the trajectory could be done by user dragging the object along its trajectory using a 3D input device using a 3D input device. The rationale behind this is that users can trace the object's path, which might result in a better understanding of the 3D trajectory.
- Region Query: the system provides the user with a box widget to describe a rectangular region. The user can create such a box region by stretching the box's diagonal while pressing the activate button. The user can select the entire box and reposition it freely. The system computes trajectories for all moving objects' spatiotemporal intersection in the specified spatial region. This allows user easily focus on time-varying phenomena in a particular spatial region.
- Reference Object: Comparing objects' velocities in relation to some object of interest requires adapting the animation speed with respect to only a single object. The system lets users select a visualization object and, using the activate button, define it as a reference object. The system adapts the flow of time to animate the reference object with a constant velocity.

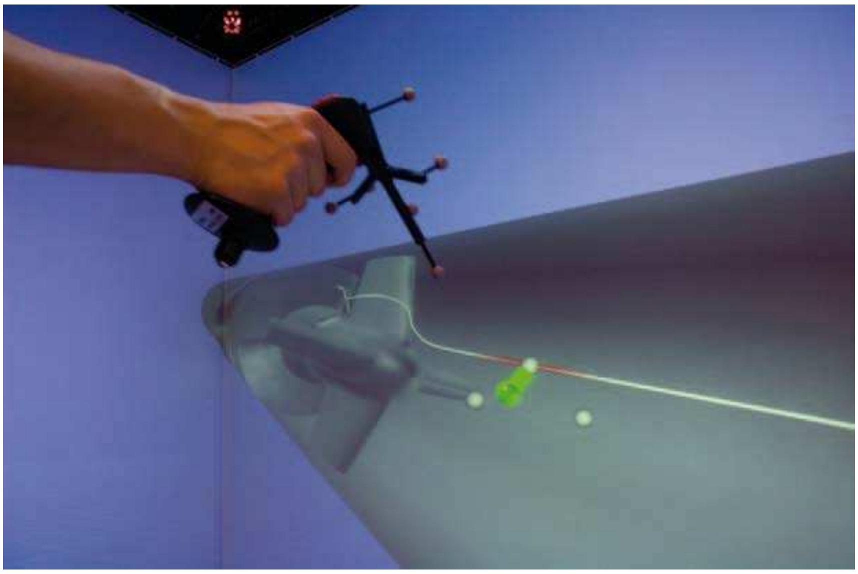


Figure 31: After 3D spatial selection of a starting point, the object's trajectory is represented.

g. CFD probes

Martin Schulz from BMW research center created CFD visualization, where user input is supported for a standard 2D mouse and for the DLR space mouse, which allows simultaneous input in six degrees of freedom in a precise manner [36].Using these input devices the user can manipulate the position and orientation of the view point or of one of the measurement probes. The measurement probes give the user an intuitive and easy way to analyze the data sets. The probes can be freely moved and oriented to defend the initial position for particle trace of the orientation of slice.

2.1.3 Stereoscopic vision

Virtual reality systems are widely used in the product design process not only because it provides the interactive manipulation of objects, but also provides a natural stereoscopic vision of manufactured objects with depth information, as we observe objects every day. Stereoscopic vision is commonly used for computer-aided design with the aim of making virtual prototypes instead of making real prototypes.

In order to study the stereoscopic perception in virtual reality environment, Laure et al [86] performed a set of experiments. First, they performed some perception tests to evaluate the importance of head tracking in VR environment. Second, they studied the effect of interpupillary distance [87] in the aspect of stereoscopic vision. In order to ensure whether normal interpupillary distance of virtual camera is the most suitable or if in some cases, a bigger interpupillary distance is need to having better stereoscopic vision. Third, they studied the issues of how to position the designed objects regarding to the screen. Whether the shaper perception is better when the object is on the screen, or it is better when the object is between the subject and the screen.

They conducted these tests in an immersive room and the results shown that head tracking has a more important effect on shape perception than stereoscopic vision, especially on depth perception because the subject is able to move around the scene. The study also shows that an object between the subject and the screen is perceived better than an object which is on the screen, even if the latter is better for the eye strain.

In order to cope with the difference between the three dimensional space in a virtual reality system and that perceived by the user from its stereoscopic images with binocular disparity, Koh Kakusho et al[88] proposed a task-oriented approach to improve objects manipulation in virtual reality system.

Koh propose to adjust the virtual space through the user's manipulation of virtual objects so that the user can succeed in executing the manipulation. The adjusted virtual space is a kind of interpretation offered by the system on the difference of the user's perception from the virtual space to explain why the user's manipulating could not be executed before adjustment. For the user's manipulation, they focus on pick and move of virtual objects using a pointer in the virtual space. They are two of the most primitive manipulations, and various kinds of manipulations of virtual objects can be realized by combinations of these two manipulations. At the same time, success of these two manipulations depends on whether the user and the system share the same evaluation of a pair of positions. When the user tries to pick a virtual object at a point on its surface with a pointer, the positions of that point and the pointer needs to be identified by the system. Conversely, when the user tries to move a virtual object from its current position to the destination position, those two positions needs to be distinguished by the system because the moving manipulation required by the user is not executable for the system unless it distinguishes the two positions.

Investigation of perceptual factors related to stereoscopic vision has recently received significant interest. De Silva et al. [10] analyzed the sensitivity of humans for different depth cues as applicable to 3-D viewing on stereoscopic displays. Mathematical models are derived to explain the just noticeable difference in depth (JNDD) for three different depth cues, namely binocular disparity, retinal blur, and relative size. And it is experimentally validated with subjective assessments.

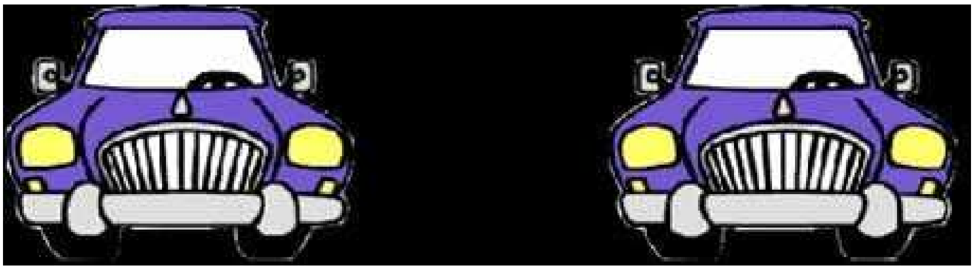


Figure 32: Subjective assessments to test perception of depth.

Subjects are asked to watch a synthetic image sequence with two objects as shown in Figure 32, both representing a synthetic image of a car. Initially, both objects are placed at the same testing disparity level. A particular depth cue of the right side object is gradually changed (increased or decreased) at a predetermined rate, while the depth cue of the left side object is kept unchanged. The subjects need to signal the coordinator, just when they sense a change in the depth level difference between the two objects. The subjects are asked if the right object moves towards the front or behind, relative to the left side object.

The results provide a quantitative model of the perception of depth that analyzes the effect different depth cues provided by stereoscopic display. The derived mathematical models of perception and experimental results indicate that with binocular disparity as a depth cue, the viewers are most sensitive to depth variations at screen level and their sensitivity decreases as the objects are reconstituted further behind and in front of the screen level. Thus, considering the sensitivity of the Human visual system(HVS) to binocular disparity, it is more appropriate to place the regions of interest at the screen level, and place objects that do not change their depth, further away from the screen level, while producing 3-D content.

Artificial image blur is a useful tool to simulate depth levels beyond the depth range that the display is capable of simulating. The sensitivity of viewers to blur does not dependent upon the base disparity level. Subjective statistics indicate that a majority of viewers perceive increasing blur to correspond to objects that move behind the sharp objects. However, in order to use image blur as a depth cue, the blurred object should not be in the region of attention.

The size of an object can be increased or decreased slightly to improve the perception of depth. All the subjects identified the relative size as a very clear depth cue that enables depth perception. In natural viewing, there is a change of object size that is perceived when the objects move forwards and backwards. In stereoscopic vision, gradual change of object size can be used as an additional cue on stereoscopic displays to improve the depth perception and the naturalness of the content. However, when decreasing the object size at the rendering system, there are dis-occlusions that arise [10].

Stereoscopic displays have a number of properties that could be advantageous in the field of human visual system improvement. Maurice H.P.H. et al[89] proposed an experiment where the effectiveness of motion-based cues and stereoscopic disparity in terms of completion time, number of errors, perceived workload and perceived discomfort are measured. This study allows getting a better understanding of the relative importance of motion based depth cues (object motion, movement parallax) and stereoscopic disparity on the performance of a path tracing task, representative of angiographic visualizations.

Results revealed that both object motion and movement parallax enhanced performance in terms of number of correct answers. However, object motion was superior to motion parallax on self-report of mental workload and visual comfort. Stereoscopic disparity significantly decreased completion times when combined with object motion or movement parallax. On accuracy, no effect of stereo was found.

As the stereoscopic vision can be obtained by various sources of information, Cutting and Vishton [90] compared the efficacy of the various sources such as: accommodation, convergence, binocular disparities, motion perspective and etc. In normal daily life, the brain combines these cues together to produce situational awareness for the human. In VR environments, some of these cues can be simulated with the use of Stereoscopic display.

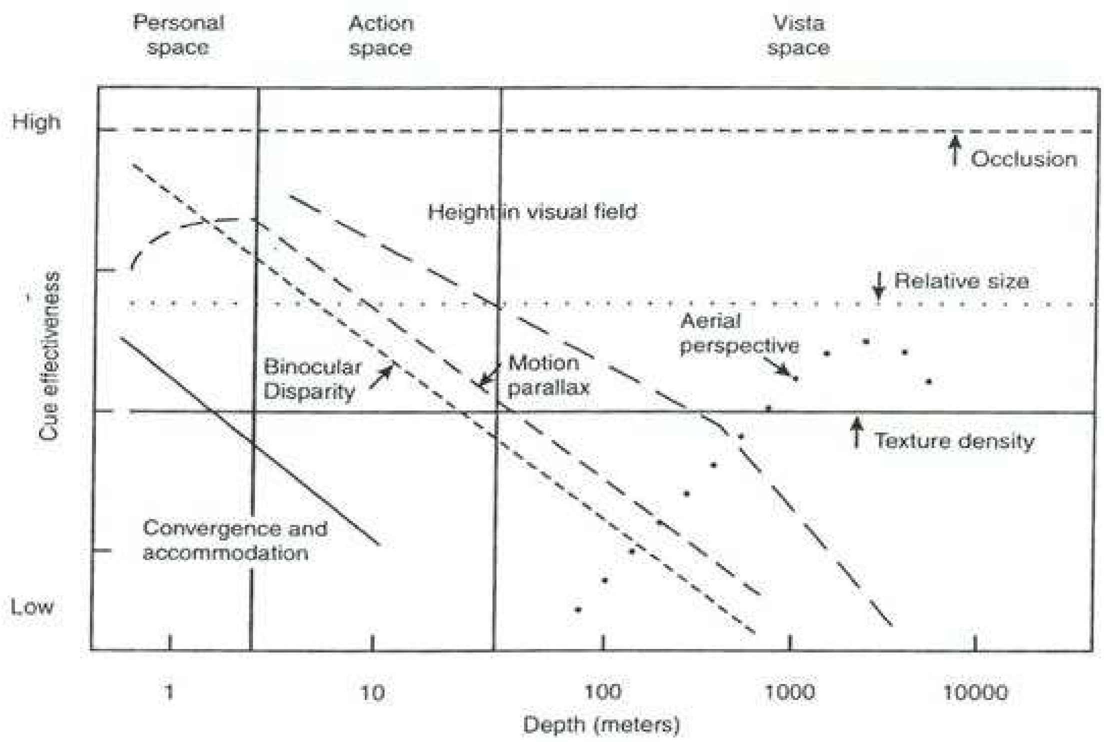


Figure 33: Normalized effectiveness of various depth perception cues over distance.

To summarize the various cues and their effectiveness at different distances, Cutting and Vishton produced a graph depicted in Figure 32 that indicates the accuracy of each cue. This figure uses a log scale for distance along the X axis, and a normalized log scale along the Y axis with the smallest distance change measurable divided by distance. A value of 0.1 on the Y axis may indicate the ability to discern a 1 meter change at a distance of 10 meters, or a 10 meter change at a distance of 100 meters. Each of these curves is based on the data from numerous previously performed user studies and demonstrates that each cue is effective at different distances, see Figure 33.

Based on their analysis of these available cues, Cutting and Vishton defined three separate spaces around the body at different distances to better categories the depth estimation available. The first area defined is named personal space and ranges from the body to up to 2 meters. Personal space is where humans perform most of their close up interactions, and so depth perception is highly refined due to its importance in daily life. From 2 to 30 meters is a second area termed action space. In this space, users may interact reasonably accurately with other objects (such as throwing a ball to hit a target), but with less cues and accuracy than personal space. Beyond 30 meters is vista space, where objects appear flat and distance estimations become quite poor compared to closer spaces [91], see Figure 33.

2.2 Resume of bibliography

From the bibliographies we studied above, we can easily realize that current works based on human perception in scientific visualization can be divided into

2 main aspects: 1) create methods/algorithms to enhance perception and 2) use 3D interaction techniques to provide better understanding of scientific datasets.

Data perception enhancement can be done by using advanced algorithms to present visually enhanced objects or simulation results in a 3D virtual scene. Most previous research progress worked to improve visual perception of datasets. They can be classified in the following aspects:

- Color issue: Color is an important factor for data visualization, since it is the main result of the rendering process. From 2D image to 3D objects, appropriate color representation can help user to distinguish objects, features and hidden characteristics.
- Luminance and contrast are two major factors in transparency perception, which the contextual information is useful to provide visual hints. Color properties, like color mapping is another important parameter for transparent objects rendering.
- As transfer function makes affection on volumetric rendering in color or opacity transformation, it has a significant influence on volumetric dataset perception. So it is important to find an appropriate transfer function.
- Lighting and lighting related attributes, like shadow, luminance, diffuse color, specular reflection and shadows can provide user referential information to improve visual perception
- Another cue proposed by in previous research work is "shape-from-motion", like Kinetic texture [64] or movement of texture can help user to reconstruct the shape details thus having better identification of shape or surface recognition.
- Motion cues [58]can help user to perceive depth information
- For 3D points rendering [47](or points cloud), point features: high point density, high height and tightly spatial distance can provide better perception of 3D point rendering scene.
- Distribution visualization framework based on remote computing resources is used for point-based VR visualization. An appropriate visualization strategy and pipeline configurations based on datasets characteristics can improve interactive frame-rate of point-based visualization tasks.
- Modern graphics card's programmable shaders can be used to provide the user with a better perception of depth, 3D shapes and large LIDAR datasets. Out-of-core data management scheme, such as memory buffer, LOD management have also been used for improve perception of point-based rendering.
- Statistical analysis method is used for modeling point sample geometry in order to improve the geometry bandwidth bottleneck and to do randomized rendering without sacrificing visual realism.

Interaction techniques proposed in the literatures of scientific visualization provide an intuitive communication with datasets and allow user perceive data comprehensively. The following techniques were proposed to improve data comprehension and perception:

- Prop or tangible based devices or objects can help the volumetric data visualization, because these provide a manual interaction with volumetric data in real world that are linked with rendering results.
- Visual Menus or Widgets to control different parameters of the rendering transfer function are useful for volumetric rendering, it can be used to compare different transfer functions and find an appropriate one.
- Request –based interaction is commonly used in 3D interaction techniques, such as user defined point, region or arbitrary curve, point or region, related rendering objects (points, shapes, curves, isosurface, etc) are represented as result.
- Pointing task can specify an object or surface, the system gives back information related to pointing object to help user understand datasets or models.

Previous works provided us a set of guidelines that can help us to set up an efficient representation of complex datasets. With the current interaction techniques the users can easily access and manipulate the experimental datasets. Some of these guidelines were designed for desktop environments; the question of whether they are applicable to a VR immersive situation is a open question.
Secondly some of these works are non-real-time, and need specific validation and developments for an interactive, immersive situation, with sufficient frame rate.

In this work, we conduct research on volumetric data simulation results that are generated continuously by a physical model simulation process. In the first part of this work, we propose to use 3D point cloud to represent a 3D scalar field in a VR environment. To our best knowledge, in paper [22], the author used point cloud representation, but only 2D application without 3D interaction and depth information perception. In order to achieve real-time rendering in VR environment, the following question should be studied:

- How to render 3D temperature field with volume 3D point cloud in read-time interactive frame rate within a VR environment?
- How to setup3D point cloud in VR environment?
- Can users perceive 3D point cloud correctly?
- What are limitations of 3D point cloud?
- How to setup a guideline for using 3D point cloud in VR environment with respect to human perception?
- How to measure the user performance in 3D point cloud representation?
- How the settings of point cloud influence the human perception?
- How size, density of the point and near clipping plane position of the camera influence human perception of volumetric data.
- Whether adding heading tracking can improve the perception of point cloud representation?

In the second part of this work, we propose to use interactive isosurface representation to render a subset of volumetric dataset in a VR environment. The following questions are discussed:

- Whether adding interactivity can improve the perception of the volumetric visualization?

- Whether only visualize subset of volumetric data can improve the perception?
- Which is the best isosurface rendering method for having better perception of isosurface, among point, mesh, semi-transparent and moving texture?
- Whether using head tracking can improve the perception of volumetric data?

3 Improving immersive volumetric data visualization

L'objectif de chapitre 3 est d'étudier les limites perceptives dans le cadre d'un rendu volumétrique de données scientifiques dans un système de réalité virtuelle offrant la vision en stéréoscopie, et le suivi du point de vue de l'utilisateur.

3.1 Cloud points visualization of 3D scalar data

Scientific visualization in VR systems can be used to present complex data combined with immersive and real time control for data exploration. The underling objective and intended benefit is to get more –whether it is information, insight, understanding or ideas- from a VR immersive working session than its equivalent on a simple desktop configuration that uses 2D classic WIMP interfaces (windows icons menus and pointers). In a VR environment the data is presented with depth perception and users can interact with the data directly in the 3D space to have a better understanding of experimental datasets. Virtual and augmented reality have now successful uses in the design process of large industries such as aeronautics, automotive or energy, with applications at various levels, Computer Aided Industrial Design (CAD), Computer Aided Manufacturing (CAM), Computer Aided Engineering (CAE). VR immersive techniques are also used for scientific visualization, either for design, research or communication purposes. Scientific visualization often involves complex data and rich models which involving multi-dimensional parameters. This challenges virtual reality community for novel immersive representation techniques, as well as adapted interaction methods. The question of perception of complex data, especially regarding visual feedback, is an open question, and it is the subject of this experiment.

VR environments are commonly used to represent objects and worlds, and therefore their design is essentially driven by the needs for realistic rendering. Such design guidelines are no more available when VR is used for complex data visualization. The objective in this case is not to be realistic, but to provide new and intelligible ways for model representation. This raises new issues in data perception. The industrial use of virtual reality data exploration tools is to find out potential design flaws in early design steps. One of the main uses is to allow the user to perceive specific phenomena, understand data values and be able to look for local maximum or minimum values of the represented data.

In this objective, researchers have proposed visualization systems meant to represent data comprehensively. Some immersive applications use 2D or 3D plots, integrated in the 3D world, as representations of functions of one or two variables. Statistical curves, data histograms, 2D/3D areas are used to represent additional information to better understand scientific models associated with 3D objects, as it has been done by Bjorn and al.[81] The authors propose to represent 2D data which can inherently be better visualized in 2D, such as pie chart, soil columns or log plots of rock types based on the user's request on 3D objects in the virtual environment.

Immersive systems provide the advantage of depth perception and intuitive real time manipulation of various parameters that makes VR more interesting for representing 3D or more complex data and models.

Representation of scalar data in a 3D space has been used in various contexts. In the medical field, volume rendering and cloud points have been used to represent medical imaging data, as a colored set of points in space, where the user can perform data exploration actions. Hinckley [24] proposed a setup where the user can manipulate real props to control a cutting plane through a visualized volumetric render of MRI data. In earth environment sciences, Bernd and al. [92] presented new ideas for the exploration of a scalar volumetric grid data from the oil and gas industry in interactive stereoscopic virtual environments. A novel input device, cubic mouse, which literally puts the seismic cube (a cube-shaped, tracked input device) into the user's hand and allows very intuitive control of viewing parameters, facilitates the exploring interaction.

For the representation of more complex data, such as 3D vectors fields and computational fluid dynamics (CFD) models, several representations were proposed:

- Moving 3D arrows: A 3D arrow proposed by Schulz and al. [36]visualization tools which incorporates virtual reality techniques for the interactive exploration of the large scalar and vector data sets is developed. Fast 3D arrows particle tracing are used to take into account collisions with the car body geometry.
- Streamlines: Tamer and Ahmed proposed [93] to integrate CFD simulations to a Virtual reality environment, CFD simulated phenomenon are represented in streamlines can help visualize the flow and its effects on the model, VR system allows natural and fast exploration and visualization of the flow that can help optimize the configuration and geometry of the designed systems.
- Isosurface: Visualization of complex grid data in geosciences is performed by Oliver and al.[82], where isosurface and streamlines are used for a numerical simulation of earth mantle flow in a stereoscopic head-tracked visualization environment.

Some studies have been proposed, that deal with the efficiency of data representation for scientific data:

- The question of how to map the values of a variable onto a color scale has been previously addressed. A commonly used mapping proposes is a color-based scale starting from blue, through the colors of the rainbow to red proposed by Rogowitzand al. [48]. They found that when a rainbow scale is mapped onto scalar data; the user is conceptually mapping a linear scale in hue onto a scalar variable. Perceptually, however, this scale does not appear linear. Equal steps in the scale do not correspond to equal steps in color. This can lead the user to infer a structure that is not present in the data and to miss details that lie completely within a single color region. Lawrence and al. proposed an architecture called PRAVDA incorporates guidance based on principles of human perception, cognition and color theory[48]. These principles are in corporate in rules which the user can select during the visualization process.

- Lum and al. [64]have presented a novel visualization technique-kinetic visualization that uses motion along a surface to aid in the perception of 3D shape and structure of static objects. The method uses particle systems with rules such that particles flow over the surface of an object; it is not only bringing out, but also describes flow information on a shape that might not be easily visible with a conventional rendering method which uses lighting and view changes.

These works focus on the perception issues on 2D images, 3D shapes and objects. In this experiment, we propose using 3D point cloud to represent a volumetric temperature field within a virtual 3D model of vehicle cabin in VR environment.

A point cloud is a set of points in a three-dimensional coordinate system. These points are usually defined by X, Y, and Z coordinates in a 3D space, and typically is intended to be representative of the external surface of an object or the field of volumetric datasets. Points are a fundamental geometry defining primitive in computer graphics, they can be seen as the raw output of 3D shape scanning and capturing or particle-based simulations [20]. Three-dimensional (3D) and time-dependent (4D) datasets becomes increasingly important scientific visualization domain, for example medicine, microscopy, and biology, etc. Such a vast amount of information implies a need for fast, accurate and cost-effective analysis in VR environment.

The 3D point cloud presents the temperature distribution within the 3D vehicle cabin and the value of each 3D point in the 3D point cloud can be influenced by physical model (in this case: air condition control model) computation in a real-time data exchange. A successful industrial usage should be: the user changes certain parameters of the air condition model, such as a diameter or spatial position of the wind outlets using VR provided interaction methods. Then the user perceives the changing results of the temperature distribution though volumetric rendering of the 3D point cloud. Based on the perceived visual information, the user could make further decision to fit the design requirements. All these features require an efficient and effective visualization of the volumetric dataset.

The objective is not only to study the limits of using point clouds for the display of scientific volumetric data, such as temperature distribution in a car interior in a VR interactive environment and to have a better visualization of volumetric data, but also study the importance of using moving parallax (such as head tracking technique) for having better perception purpose. To our best knowledge few studies are performed to address the perception issues in a scientific visualization context, in terms of complex volumetric data.

- Can we have guidelines for VR visual representation of volumetric scalar temperature data, in terms of data density, size of visualization elements?
- Another question, is the role of the size and position data volume, relatively to the user, and the physical display?

- Adding dynamic changing of point of view can improve the perception of volumetric data or not?
- Virtual reality display techniques are likely to make this question a central one. Does the user understand represented data?

These are still open questions. To our knowledge few studies are performed to address the perception issues in a scientific visualization context.

3.2 VR immersive environment characteristics

Before discussing the approach of our study, we need to define important concepts for stereoscopy and visualization in VR systems. VR immersive systems allow the user to perceive depth information classically by means of stereo glasses and a head tracking system. These are considered as the main techniques means to achieve depth perception and perspective in virtual reality. However, depth perception, stereo fusion and user comfort are depending on more parameters [86].

First, depth perception is possible in monoscopic vision, that is, vision with one eye. A number of visual cues, relying on a cognitive activity, allow the brain to reconstruct depth information.

- Size: for a given object, its apparent size is a function of its distance to the eyes, farther object appears smaller.
- Occlusion: an object that covers another is expected to be in the foreground. Shadows can give a depth clue.
- Texture gradient: closer objects represent more detail than distant objects and further objects.
- Movement Parallax: an objects image moving speed on the retina depends on its depth.

Stereoscopic perception in everyday life stems from retinal disparity. Stereoscopic images in VR environment are produced by rendering two images one for each eye, with a technique of two asymmetric frustums associated to two cameras which are separated by a distance corresponding to the user's inter ocular distance. Of course, stereo perception simulated in VR has differences and limitations compared to real life stereoscopic perception.

Accommodation is the process which the fixated point of the crystalline lens changes in order to focus at a particular depth. Convergence is the extent to which the two eyes are turned inward towards to an object. In everyday vision, accommodation and convergence are consistent and adapted the fixated object. With VR displays, there is a discrepancy between these two phenomena: convergence is still done on the objects, while accommodation stays fixed on the screen surface.

Parallax is the distance between two equivalent points in the two displayed images. The main limit for perception in VR environment is caused by unsuitable parallax, since it can impact on stereoscopic fusion. In our VR immersive environment, the objects are projected on the screen. When the point being projected is behind the projection screen, it is a positive parallax, in a contrary situation, it is negative parallax. As the object moves to the user the negative parallax goes higher.

3.3 Hypotheses and parameter chosen

Fusion limitation [94] defined a parallax limitation angle. His research indicated that, for easy fusing by the majority of people, the absolute value of parallax limitation angle should not exceed 1.5degrees for all points in the scene. In this experiment, we want to investigate fusion limits for volumetric rendering. Volumetric rendering, is a set of data points in 3D space, where the points represent a given scalar value, temperature or other properties with different colors, see Figure 34.

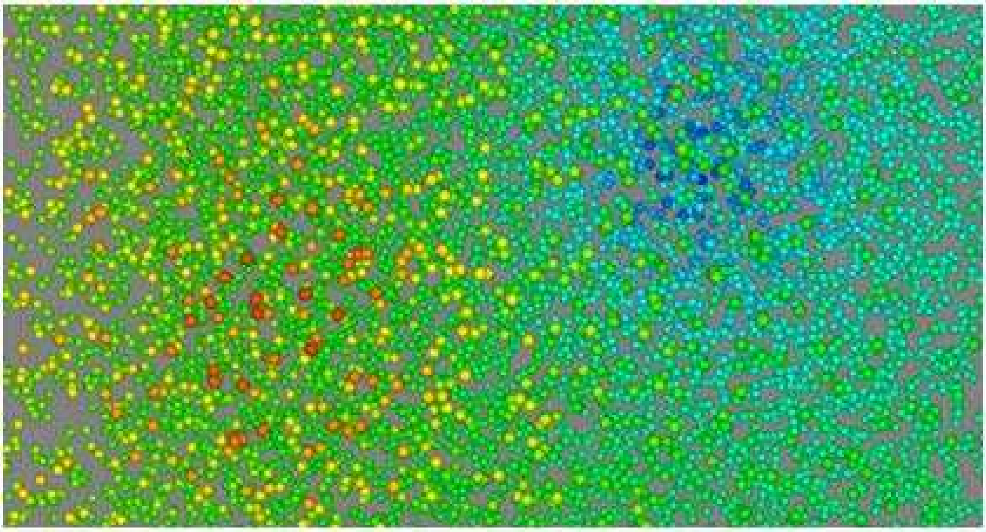


Figure 34: Cloud points in 3D space.

When using cloud point representation techniques in VR environments, consideration of fusion limits are important. The cloud point can be influenced by fusion limits in several ways:

- Too large parallaxes impede stereoscopic vision;
- If the points are too close to users, fusion is not easy to achieve;
- Large points reduce resolution;
- Point density;
- Appearance of moiré pattern, which are likely to appear in a periodic display of points can also impede visual perception of such data.

3.3.1 H1: Size of the point can influence human perception of volumetric data.

Sample point size of point cloud is the virtual size of a single 3D point. Since VR systems are calibrated to allow scale 1 representation, we can specify this size in the metric system. We have performed an informal test on various points' sizes and observed that: too large point size seem to lower resolution and comprehension of 3D scalar data representation. On the contrary, small size of point allows the user to better understand the precise position of data; however stereo fusion of small sized points seems difficult for a certain size threshold.

3.3.2 H2: Density of the point can influence perception of volumetric data.

Density, which is the number of represented points per volume unit, changes cloud point resolution. High density of cloud point brings more disparity information but occultation of background objects by foreground data can occur;

On the contrary, low density reduces the resolution and overall disparity information.

3.3.3 H3: Near clipping plane position is related to stereoscopic visual fatigue and visual comfort and can influence on perception of volumetric data.

Near clipping plane position of point cloud defines the position, actually the position of an imaginary plane on the depth axis, where the display of data starts. No data is displayed between this clipping plane and the user. Clipping plane defines the maximum parallax that the user will experience. This of course influences stereoscopic fusion, which means close to the user near clipping plane positions can impair user stereoscopic fusion and cause visual uncomfortable.

3.3.4 H4: Dynamic changing point of view (Head Tracking) can improve the perception of volumetric data.

Compared to desktop systems, a VR immersive environment not only provides natural depth information perception with stereoscopy, but also provides the designer a dynamic point of view, which can be achieved using a head tracking system. This hypothesis assumes that the human perception of volumetric data can benefit from such head tracking system.

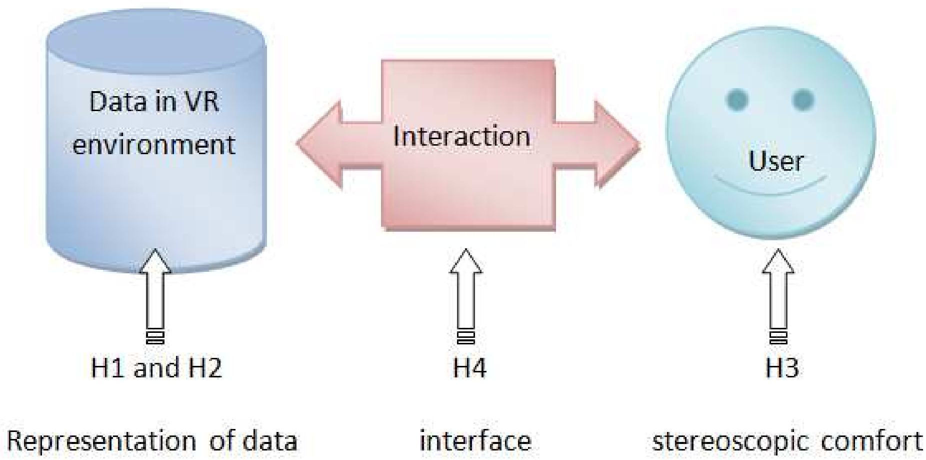


Figure 35: Our four hypotheses on perceptual vision in VR environment.

Generally speaking, our four hypotheses contain three aspects of a virtual reality simulation see Figure 35. For the data in VR environment, we have hypothesis 1 and 2, which are related to data representation; for the user aspect, we have a hypothesis regarding stereoscopic comfort and for the interaction between user and datasets in VR system, we have another hypothesis regarding to head tracking which is the interface between them.

On these assumptions, in order to assess user perception and precision, a point task is proposed to investigate the influence of these visualization parameters on perception of volumetric data.

3.4 Experiment

3.4.1 Objective

For the test we propose a series of pointing tasks. A pointing task can be considered as atypical subjective method to evaluate subjects' cognition. In a pointing task, a set of stimuli is presented, and the subjects have to point to one stimulus at a time, without pointing at the same stimulus twice. Point task is widely used in for psychologists and human factors researches [95].The results of pointing task can be used to study the performance of participants of different stimuli in the task.

As we are going to evaluate the user performance of point cloud based visualization, we conducted a pointing task in VR environment. In our pointing task, the users have to point in 3D space on maximum and minimum temperature areas represented in a colored cloud point field. This way, we assess the ability of point cloud volumetric rendering to provide a comprehension of the data. We mean to address the questions of:

- How the point size, density and near clipping plane position influence on stereoscopic vision?
- Which is the best combination of these three parameters for providing an efficient and precise enough data review tool?
- Whether human visual perception of such data can benefit from dynamic point of view through head tracking, in relation to precision and completion time, as it provides a dynamically view changing to the users.

3.4.2 Setup

The immersive VR system setup used in our study is a wall type stereoscopic display, with a 3.1m by 1.74m size screen. A Christie HD3 projector is used for rear projection on the screen with a 1920by 1080 resolution, at a 24-bit color setting. The system provides stereoscopic visualization. Image separation for each eye is achieved through Crystal Eyes active stereoscopic glasses.

The tracking of the user's head and dominant hand is performed with an optical Tracking system (AR Tracking). Dynamic point of view is computed using the classical asymmetric frustum technique, this, combined with precise calibration of the system to the user's interpupillary distance, allows the scale 1 display of virtual scenes. This is a requirement for our experiment. A wireless device, is used for application control, it is held by the user in his dominant hand, so he can press a confirmation button with his thumb. The hand tracking markers were embedded on the hand-held device (wiimote)so the user doesn't wear any device, see Figure 36.

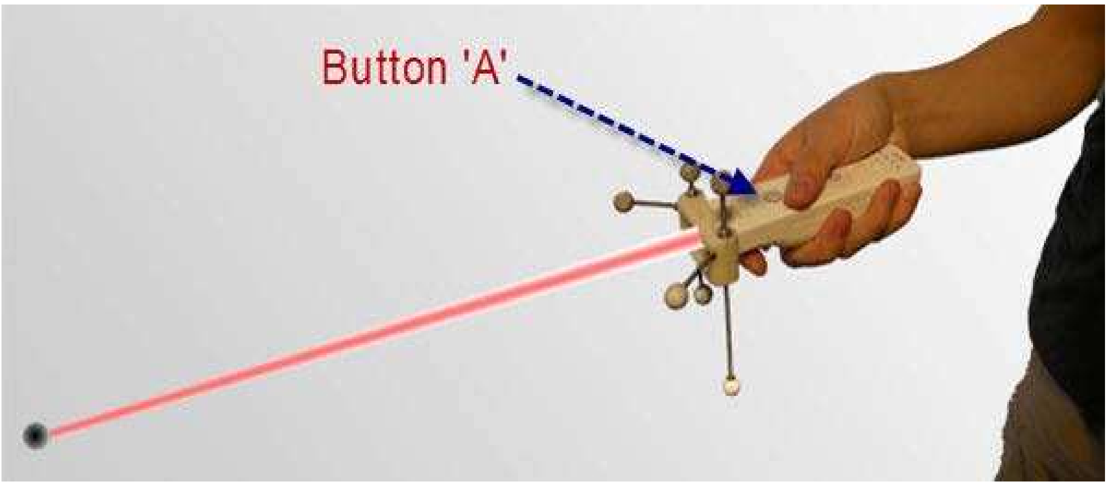


Figure 36: Control and tracking devices, with virtual cursor, used in the experiment.

The whole testing scene of the experiment is generated with an Open GL 2.0 render engine, using an Nvidia Quadro FX 5600 GPU. The refresh rate is 60Hz; active stereo is always used throughout the experiment. The users are standing approximately at a 1.2m distance from the screen but they are allowed to move freely to benefit from dynamic point of view enabled by head tracking.

3.4.3 Task description

To investigate how to provide a perceivable and understandable 3D cloud point in immersive VR system and what is the precision of user perception of the temperature distribution in 3D space, we propose a pointing task experiment.

The user has to point on two locations in space: the coldest source (0°C), and the hottest source (100°C), which are placed randomly within the point cloud volume. Again, the temperature field is represented as a cloud of points; each point is colored to represent a temperature. The color and temperature mapping is achieved by a typical rainbow color map, as the coldest point is colored in blue(R: 0 G: 0 B: 255) and the hottest point is colored in red (R: 255 G: 0 B: 0). The remaining points, which are not influenced by the cold and hot source, are set at a constant temperature (50°C) corresponding to a green color (R: 0 G: 255 B: 0). Around the hottest and coldest sources, a radiant effect is interpolated and presented as a continuous variation in temperature between the local maximum or minimum, see Figure 33.

For the pointing task, a virtual pointing cursor is displayed at the top of the handheld device; it is 100cm long cylinder, with a visual tip at the end. This tip is used for pointing coldest and hottest source. The reason for displaying at the tip 100cm further from the hand is to avoid bias due to occlusion by the users hand on the task. The users have to point at the point in space where they believed to be respectively the coldest and the hottest source, in that order, using the virtual cursor.

3.4.4 Experimental conditions

To analyze volumetric cloud point perception, we propose to focus on three important parameters: density, point size and near clipping plane position.

Density, defines how many 3D points are placed existing in cloud points along each axis (e.g. X-axis, Y-axis and Z-axis). In the present experiment, we define a cubic cloud point area which is 2.3m*2.3m*2.3m. This is a linear density that could take 3 values: 7 points/meter, 13 points/meter and 20 points/meter. See Figure 37.

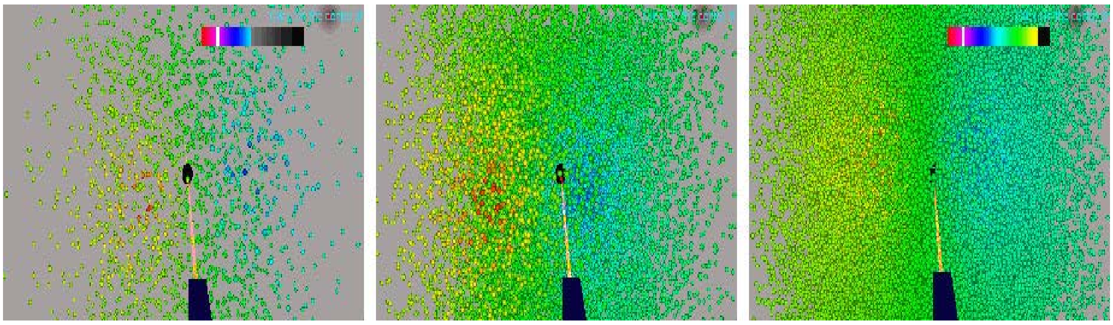


Figure 37: Different cloud point densities.

Point size is the diameter of each point. All the points are displayed using sprites with a round texture which centre colored in white and border colored in black on the alpha channel. Thus each point is not a complex spherical mesh. Three different diameters are compared in our experiment: 15mm, 20mm and 25mm. see Figure 38.

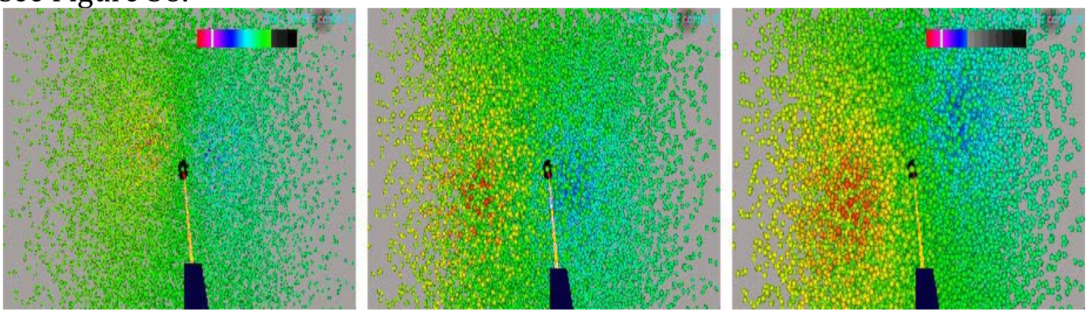


Figure 38: Different point sizes.

Near clipping plane position of cloud point defines the distance between subject's eyes and first visible point of cloud point. See Figure 39. Three different conditions we applied in our experiment are: 0.6m, 0.9m and 1.2m.

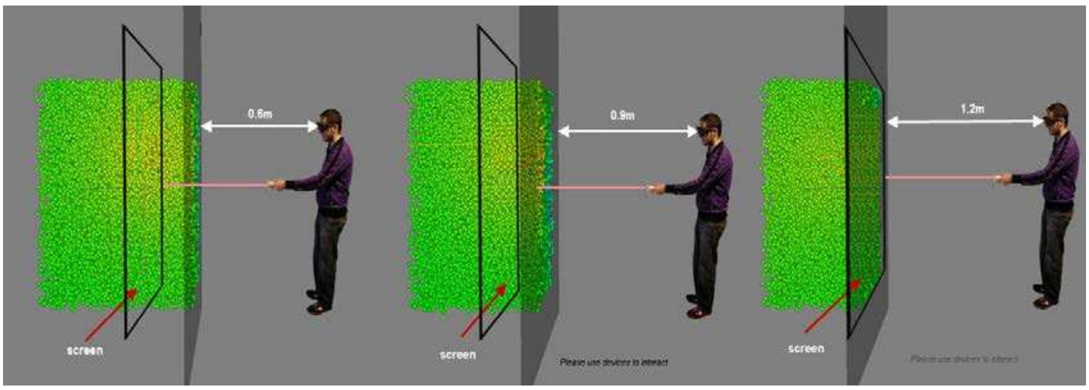


Figure 39: Different near clipping positions.

Each user was presented with all combinations of these three parameters (3 different densities*3 different point sizes*3 different clipping plane positions) yielding 27 different experimental conditions. For each user a random sequence of these conditions is generated as a pre-computed data array, stored for data analysis. For each condition, one hottest source and one coldest source are randomly placed within the cubic cloud point area. Overall in 27 different stimuli conditions, each subject performances 54 pointing tasks.

3.4.5 Implementation

Stimulus in our testing is based on cloud point, visualized in a cubic volume. In order to enhance human stereoscopic visualization we rendered the cloud point using a GPU shading computing color and size of each point:

- **Shading**: Each point has a diffuse color, but it is not uniform on its surface, a gradient is applied to increase contrast between points. This gradient was added because in a uniform temperature area the points were visually difficult to discriminate. The gradient is radically applied to each point, see Figure 40, in a set of points. All the 3D points are displayed using textured sprites (billboard [96]), thus each point is not a complex mesh and always faces the camera The advantage of using billboard is the rendering engine can process "3D sprites" much faster than other types of 3D objects.

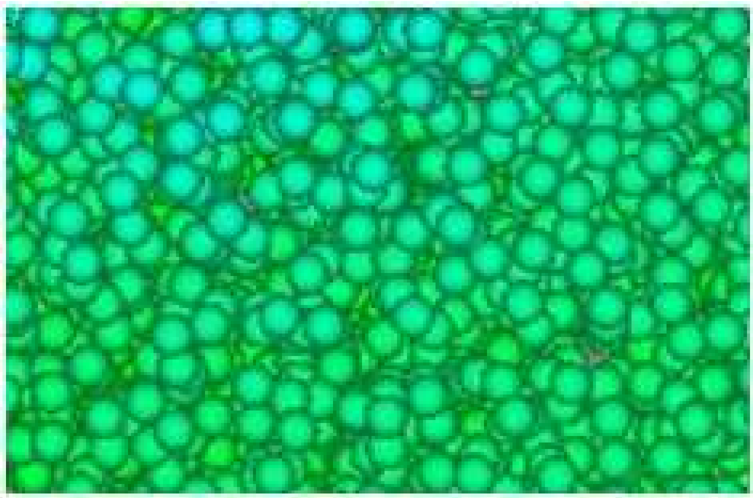


Figure 40: Gradient effect applied on each point using Shader.

- **Point size**: Attenuation defines how does the size of 3D points changing with respect to its distance from viewer. The following equation is applied to point size attenuation computation.

$$\text{ObjectSizeOnScreen} = ObjectSize * \frac{Dis(UserToScreen)}{Dis(UserToObject)}$$

- In a first test, we have observed moiré patterns, see Figure 41, in the point cloud. Moiré patterns appear when grids are overlaid, which is the case in our volumetric display method. These Moiré patterns added discomfort during visualization and we have proposed a method for cancelling the effect. It consists with adding a small displacement to each point centered on its theoretical grid position, with a direction that is randomly chosen.

The random displacement value is chosen between 0 and theoretical two neighbor intervals. Moiré patterns were totally suppressed with this method.

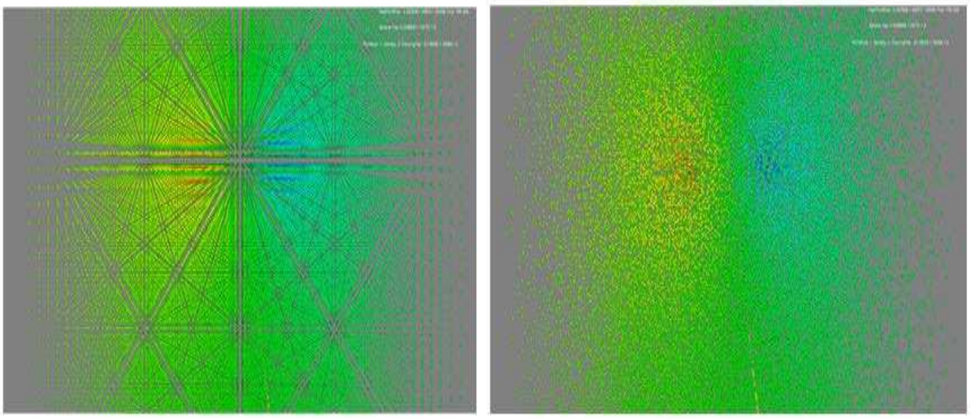


Figure 41: Left: points evenly distributed: appearance of moiré patterns. Right: adding a noise in point placement cancels the patterns.

- A Shader technique was used to deal with large amounts of graphical data. An OpenGL Vertex Shader is applied to the point cloud. The size, temperature and color mapping of each point are implemented in the GPU Shader. The temperature model is based on a linear interpolation on the grid, based on the two maximal and minimal values (hot and cold points in space): When a heat source is placed in the cloud point, the temperature of surrounding spatial point is computed by Inverse Distance Weighted Interpolation (IDW). IDW is a commonly used technique for interpolation of scalar temperature points, it based on the assumption that the interpolating surface should be influenced most by the nearby points and less by the more distant points. The following equation is used on the point cloud to map temperature on the grid and recreate a temperature distribution to be displayed in the immersive VR system. Where z(x_p) is the interpolated values at point, n is number of data point, z(x_i) temperature value of heat source, d is the distance between interpolated point and heat source, k is the distance weighting.

$$z(x_p) = \frac{\sum_{i=1}^{n} z(x_i)\frac{1}{d^k}}{\sum_{i=1}^{n}\frac{1}{d^k}}$$

- In the Vertex Shader, the position and initial temperature of source points (hot and cold) , texture of point are passed from CPU to GPU. The computation of IDW and color mapping is calculated in GPU, thus it provides us an interactive frame rate.

We evaluate human stereoscopic vision performance with the point cloud being the only object displayed, see Figure42. We had assessed with 15 subjects, ages 22-33 years old, all of them had normal or corrected visual acuity, stereo acuity was assessed using the Wirt test.

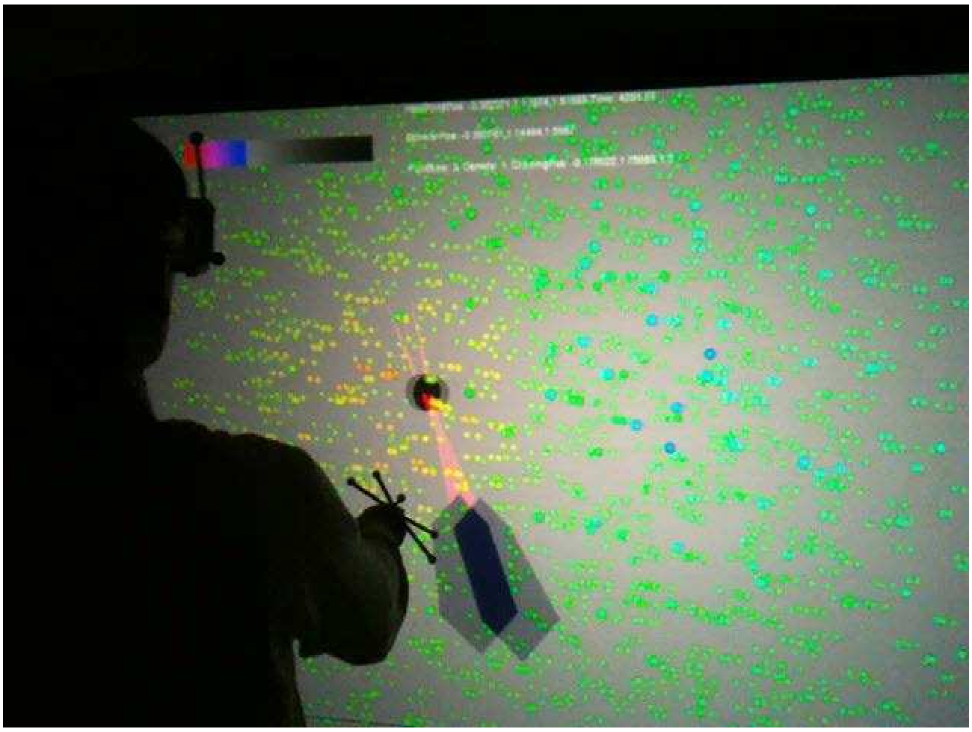


Figure 42: Experiment on cloud point.

The subjects were required to stand 1.2m away from the screen, and were free to move in the VR immersive environment. Each subject totally performed 27 (3*3*3) stimuli conditions, these conditions was randomized across subjects.

The subject has to complete the pointing task using a virtual wand which has a tip at its end (3D sphere). This tip is used to point at the position where the user believes the center of hot source and cold source located. The subjects were instructed to carry out the task as accurately and as quickly as possible.

In our study, two types of experiment were conducted: dynamic point of view and static point of view:

- In the experiment with dynamic point of view, head tracking system is used to equip with the Crystal Eyes active stereoscopic glasses. With the tracking system, a dynamic point of view is computed using the classical asymmetric frustum technique that allows the user changing the view of point cloud dynamically during the experiment.
- For the static point of view (no head tracking) experiment, the functionality of head tracking system is interrupted, we manually fix the main camera at the position -0.4, 0, 1.6 in the 3D space, so however the user head moves, the viewpoint on point cloud is fixed.

Two measured criterions in our experiment are:

- The time between target display and target pointing with the button confirmation, stopping the timer.
- For each pointing task the error distance is recorded: it is the distance between the theoretical centre of the hottest or coldest source point and the pointing sphere position at the time of clicking.

Participants training: At the very beginning of the task, the subject performs a set of tasks for training. This training part is used to familiarize the subject with the experiment environment and manipulation. We conducted two different experiments, one with no 3D environment surrounding the data, the second in a car interior environment.

The objective is to investigate if the presence of a 3D scene, affects the performance in any way. This is meant to assess the nominal use of such visualization techniques, where the 3D environment that the data is related to will be displayed. In the following we will relate to these two conditions as 'with or without 3Dscene'.

3.5 Results

3.5.1 Subjects training

In the training part, one condition is randomly chosen among the 27 possibilities; it is repeated 9 times, yielding 18 pointing tasks (hottest and coldest targets). We measured task completion time.

In Figure 43, we observe that the completion time curve decreases over the sequence of tasks, showing that users acquired experience throughout the training procedure. On the graph we compare task completion time during the training procedure and the average completion time measured in the real test. Training step is taken only one time for each subject, before the real experiment.

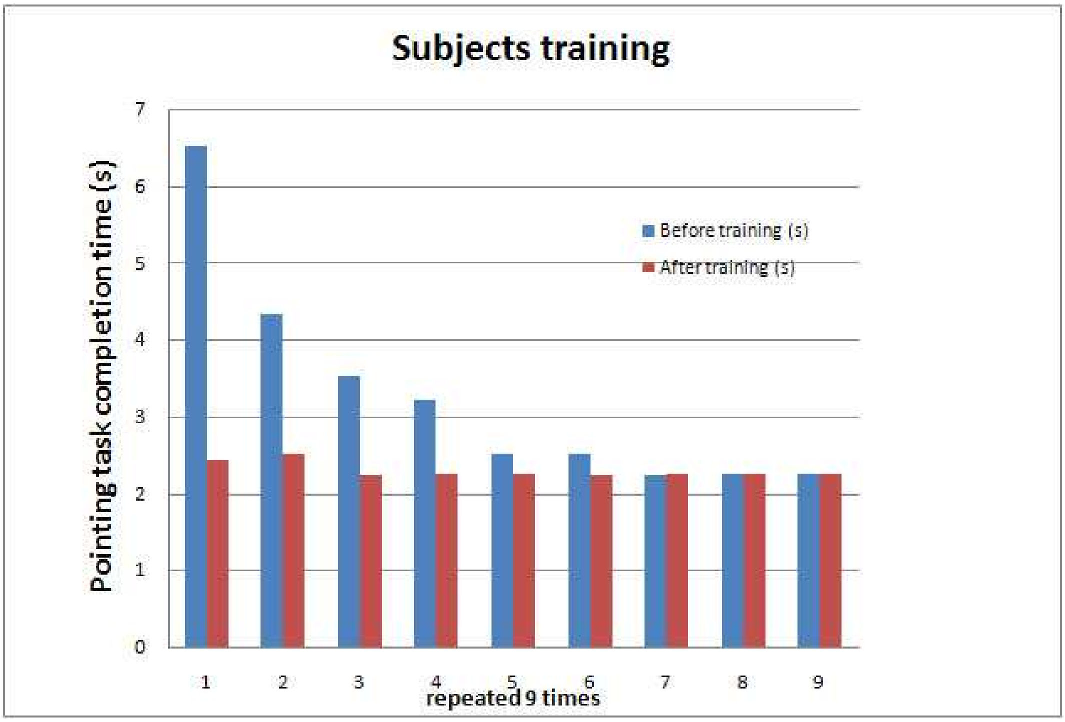


Figure 43: Subjects training results.

3.5.2 Experiment without 3D scene

In each experimental condition, we evaluate pointing time and spatial error distance by taking the average of the two pointing tasks (hottest and coldest) manipulation results. See figure 44, 45.

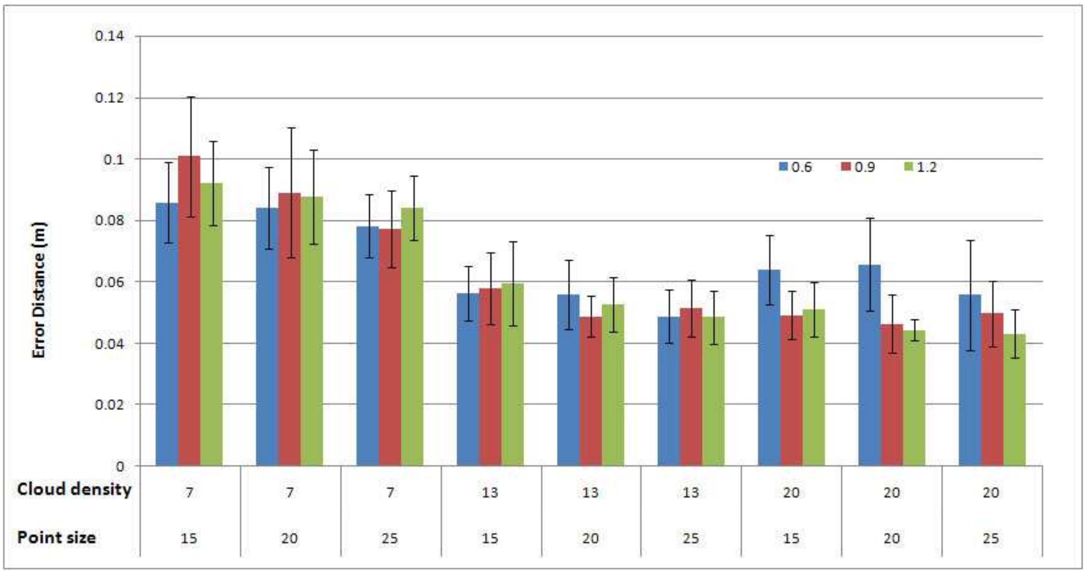


Figure 44: Pointing error (m). Experiment without 3D scene.

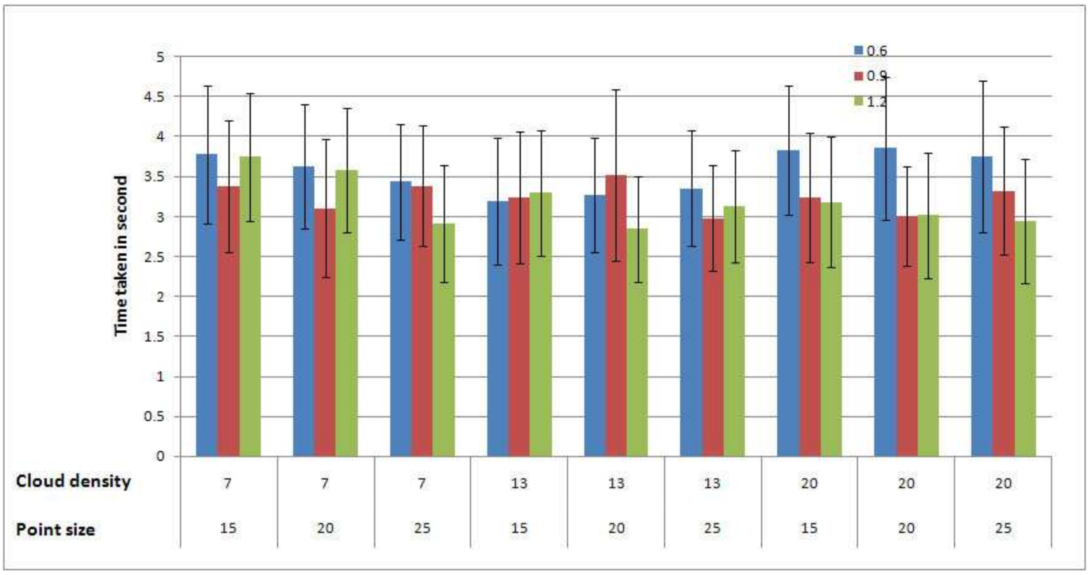


Figure 45: Pointing task completion time (second). Experiment without 3D scene.

Before doing analysis of variance, we conducted a normal test wish SPSS Kolmogorov–Smirnov (k-s) test [97] on the different combinations of 3 experimental variables of 15 subjects. See Figure 46, we can see our test results fit normal distribution.

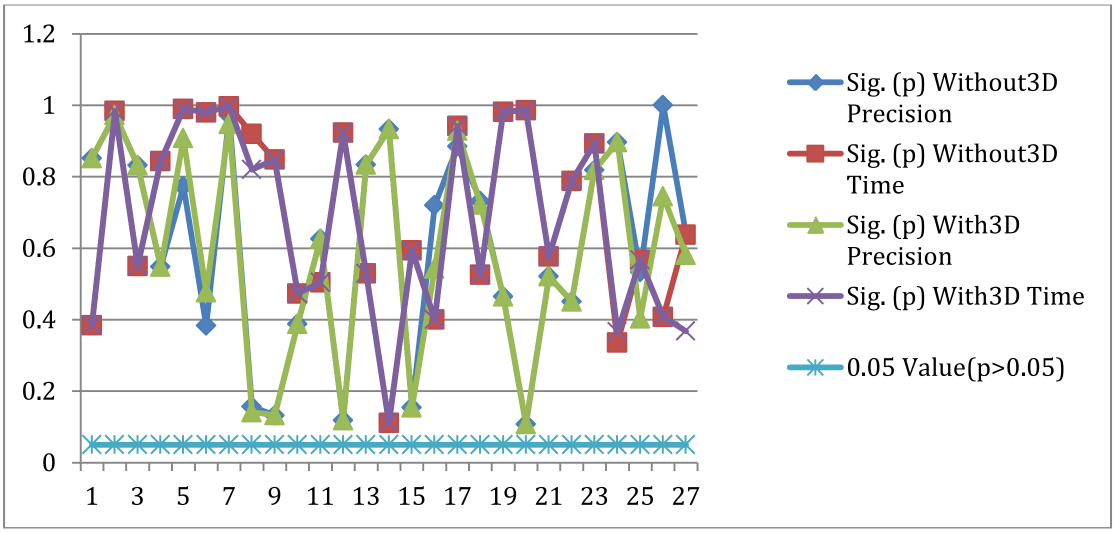


Figure 46 Normal Test results of Experiment1.

Table 1 represents the pointing error in meters, for all experimental conditions (density, size, and position of clipping plane).

Source	Sum Sq.	d.f	Mean Sq.	F	Prob>F
PointSize	0.000035	2	0.00018	5.24	0.0148
Density	0.000687	2	0.00343	101.96	0
N.C.Plane	0.00006	2	0.00003	0.88	0.4317
Error	0.00067	20	0.00003		
Total	0.00769	26			

Table 1: Experiment 1 in error distance (manova).

Table 2 represents pointing time in seconds, for all experimental conditions. We performed a multi-factor analysis of variance on the 3 experimental conditions. Results show a significant influence of Point size on error distance $F(2,20)=5.24$ $p=0.0148$. There also is a significant influence of Density on error distance, $F(2,20)=101.96$ $p<0.001$. Finally, there is no significant influence of near clipping plane position on error distance.

Source	Sum Sq.	d.f	Mean Sq.	F	Prob>F
PointSize	158874.9	2	79437.4	1.39	0.2724
Density	260744.7	2	130372.4	2.20	0.1203
N.C.Plane	762209.7	2	381604.9	6.67	0.006
Error	1144082.2	20	57204.1		
Total	2326911.4	26			

Table 2: Experiment 1 in time taken (manova).

For task completion pointing time, Clipping plane position has a significant influence on task completion time $F(2,20)=6.67$ $p=0.006$.

3.5.3 Experiment with 3D scene: car interior

In this second experiment, a vehicle interior model, with a 1:1 scale, was present in the scene. We filled the vehicle cabin with a point cloud to represent a temperature distribution within the vehicle, see Figure 47.

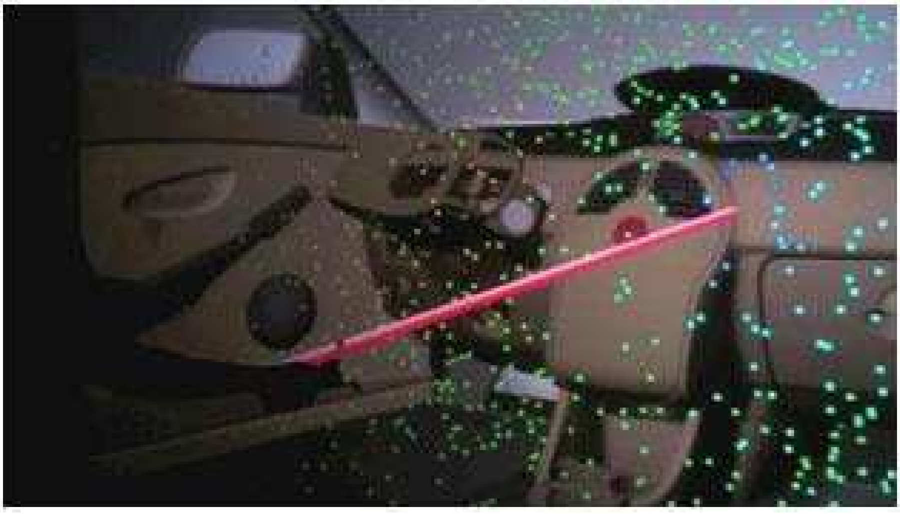


Figure 47: Experiment with 3D scene.

In this experiment, the conditions and tasks were the same as in the "without 3D scene experiment". Figure 48, Figure 49 and Table 3, Table 4 show that user performance didn't significantly change so much compared to the experiment 1: when density is low and size is small, users produced high spatial error distance and took more time for pointing.

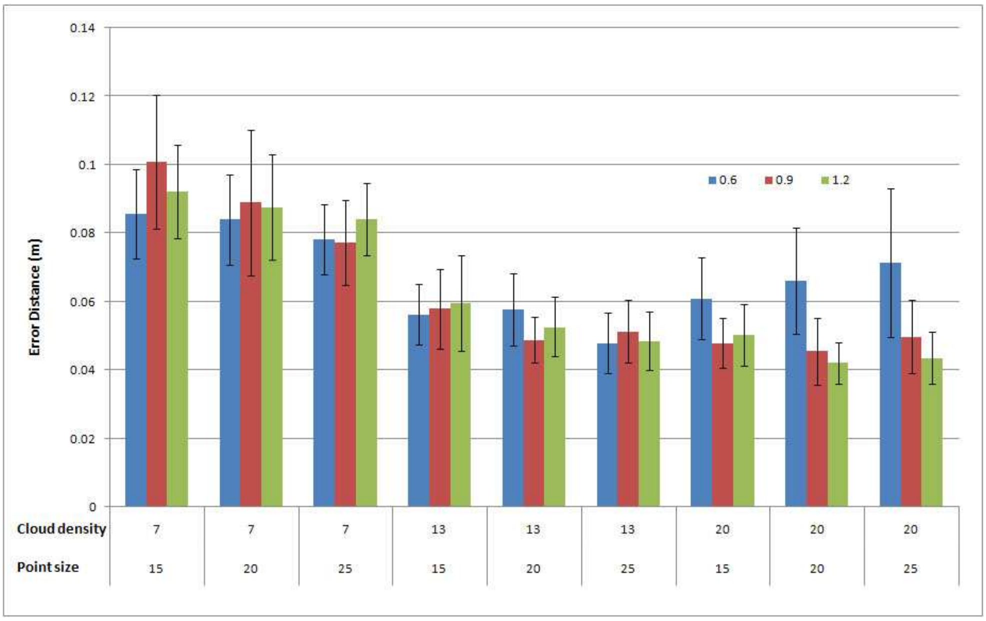


Figure 48: Pointing error (m). Experiment with 3D scene.

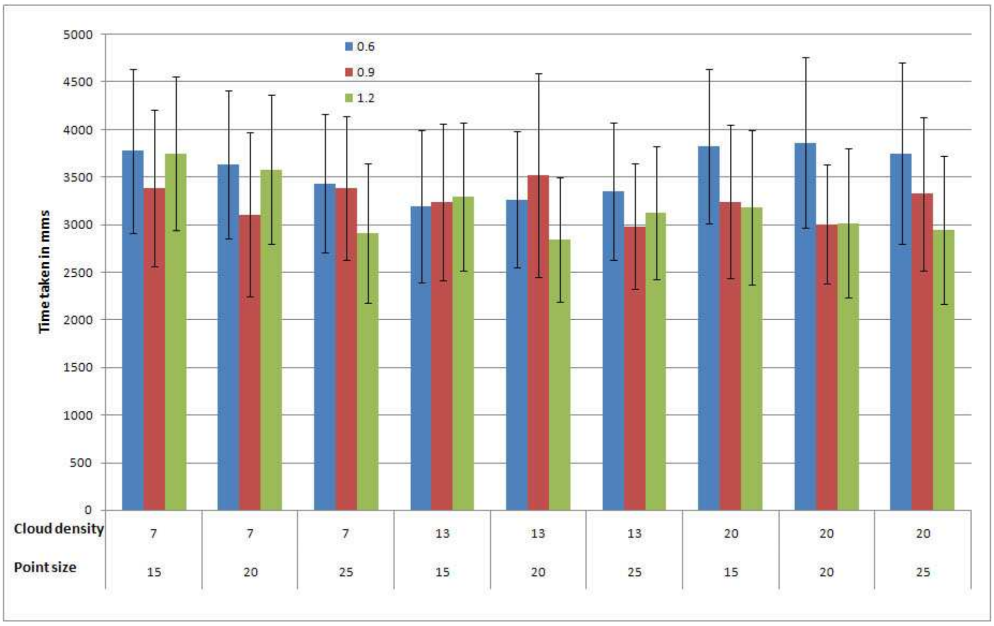


Figure 49: Pointing task completion time (second). Experiment with 3D scene.

Source	Sum Sq.	d.f	Mean Sq.	F	Prob>F
PointSize	0.0002	2	0.0001	1.83	0.1867
Density	0.00666	2	0.00333	59.89	0
N.C.Plane	0.00014	2	0.00007	1.3	0.2958
Error	0.00111	20	0.00006		
Total	0.00812	26			

Table 3: Experiment 2 in error distance (manova).

Source	Sum Sq.	d.f	Mean Sq.	F	Prob>F
PointSize	158974.8	2	79437.4	1.39	0.2724
Density	261743.8	2	130372.4	2.20	0.1203
N.C.Plane	762209.8	2	281604.9	6.67	0.006
Error	1153082.6	20	57204.1		
Total	2336011.0	26			

Table 4: Experiment 2 in time taken (manova).

We did a correlation analysis of three variables in our experiment to measure correlation coefficient between our three variables and concerning results. From Table 5, we can see the correlation coefficient between point cloud density and error distance has negative correlation (-0.79814), which means denser of the point cloud more error distance we would have. And also, the correlation coefficient between Near Clipping Plane position and task completion time is negative, which means closer to the near clipping plane we need much more time to use.

	Point Size	Density	NCP	Err Distance	Time
Point Size	1				
Density	0	1			
NCP	0	2.53E-17	1		
ErrDistance	-0.21048	**-0.79814**	-0.08244	1	
Time	-0.25846	-0.11019	**-0.53233**	0.414027	1

Table 5: Correlation analysis of Point Size, Density, and Near Clipping Plane.

3.5.4 Experiment with and without head tracking

The two following figures show a general comparison in the aspects of error distance and completion time of this point cloud experiment. From these two figures we can have a general idea of the importance of how head tracking aids in VR environments, as we see in the figure, the task with head tracking produced less error distance and less error standard deviation (0.06 and 0.02), on the contrary the error distance without head tracking goes high with a higher standard deviation (0.10 and 0.07).

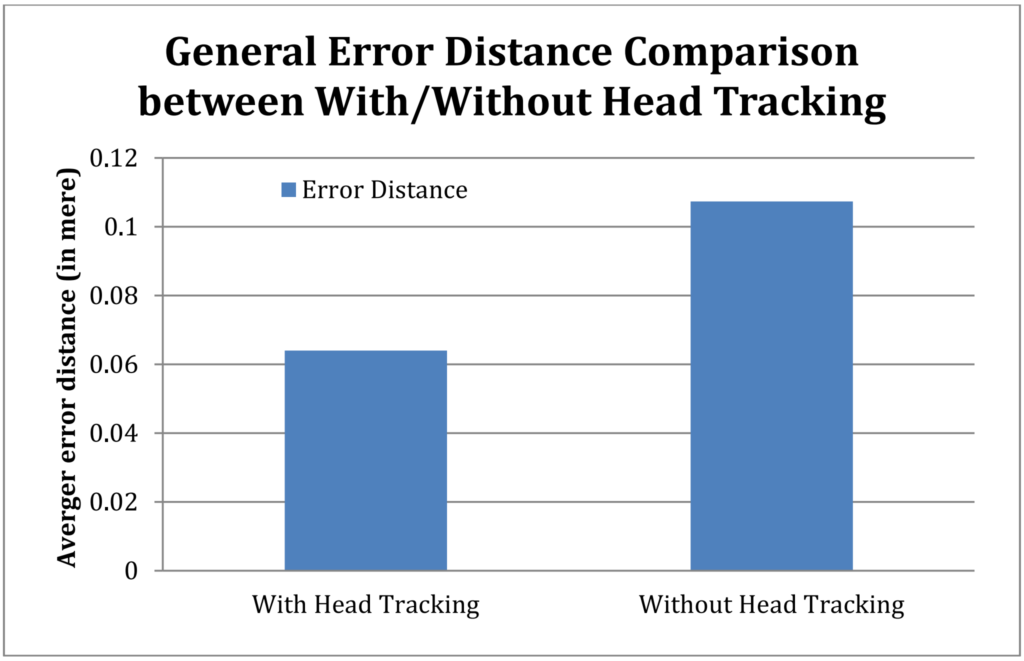


Figure 50: Average error distance in With/Without Head Tracking condition.

For task completion time comparison, the average results of the task with head tracking is 3 seconds with a small standard deviation, but the average completion time of the tasks without head tracking is 2 times more than the taskswith head tracking condition, see Figure 51.

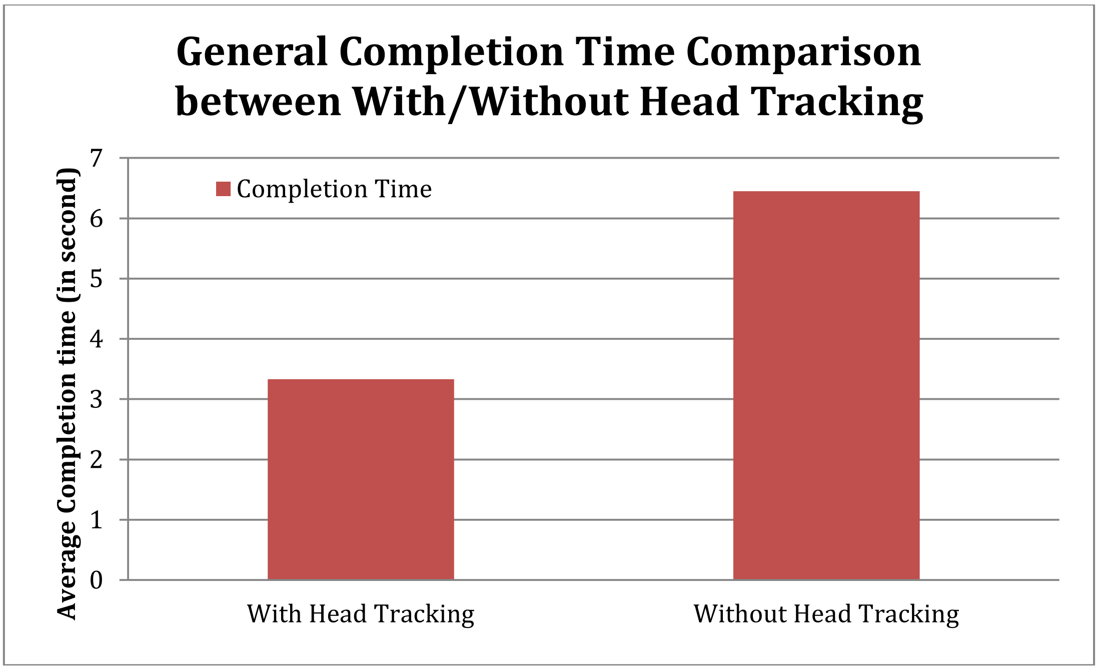


Figure 51: Average Completion Time in condition With/Without Head Tracking.

The following Figure 52 illustrates the error distance comparison in the different combinations of point density, point size and near clipping position. We can see that most of the combinations are influenced by head tracking interruption, in respect of error distance.

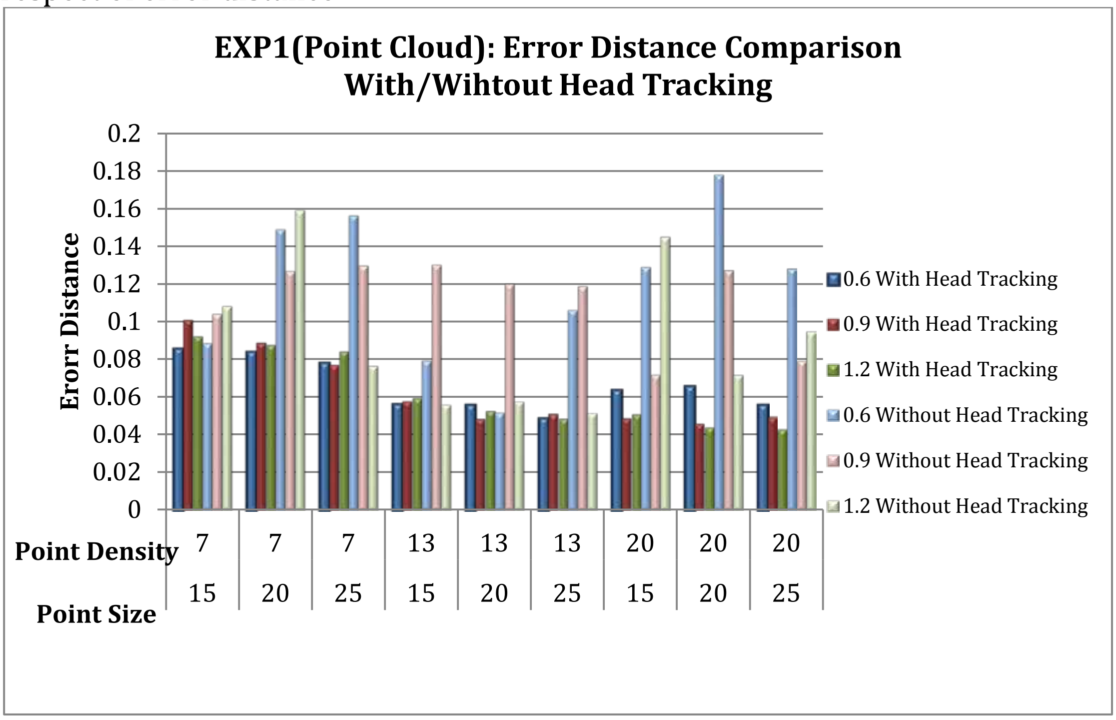


Figure 52: Error distance in each condition in With/Without Head Tracking condition.

Figure 53 shows the results of task completion time comparison of different combinations in the condition with and without head tracking. It is obvious that the task completion time can be strongly influenced by the interruption of head tracking.

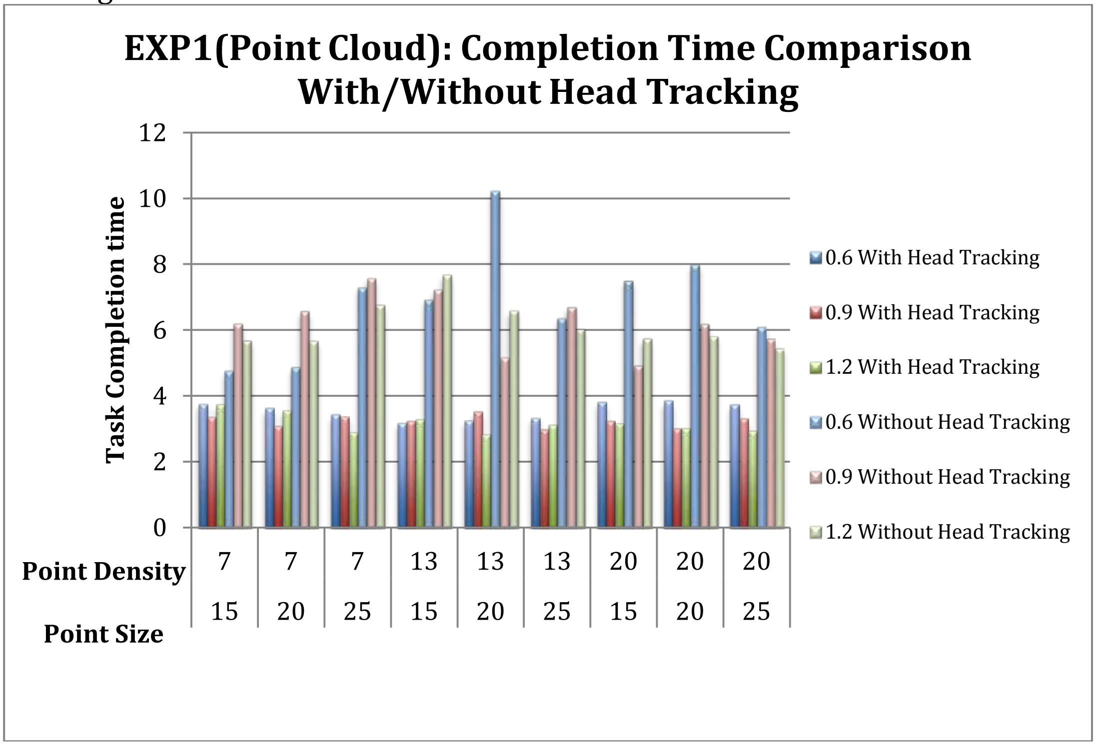


Figure 53: Completion time in each condition in With/Without Head Tracking condition.

The following two figures (Figure 54, 55) illustrate the standard deviation of different parameters in this experiment, such as point density, point size and near clipping plane position, in respect of error distance and completion time. From figure 54, we can see that the variation of error distance with parameter 'density' is high, which means the influence of point density in pointing task accuracy is obvious. Similar with figure 55, we can observe a variation of completion time with parameter 'Near Clipping Plane Position' that indicates that the influence of Near Clipping Plane Position in completion time is obvious among other parameters.

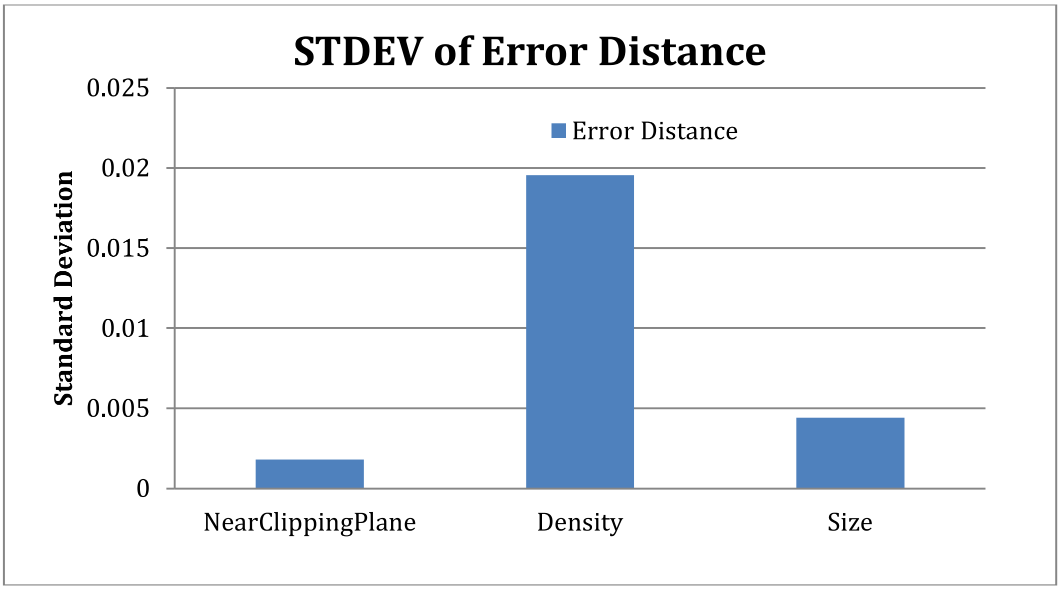


Figure 54: Std comparison in error distance.

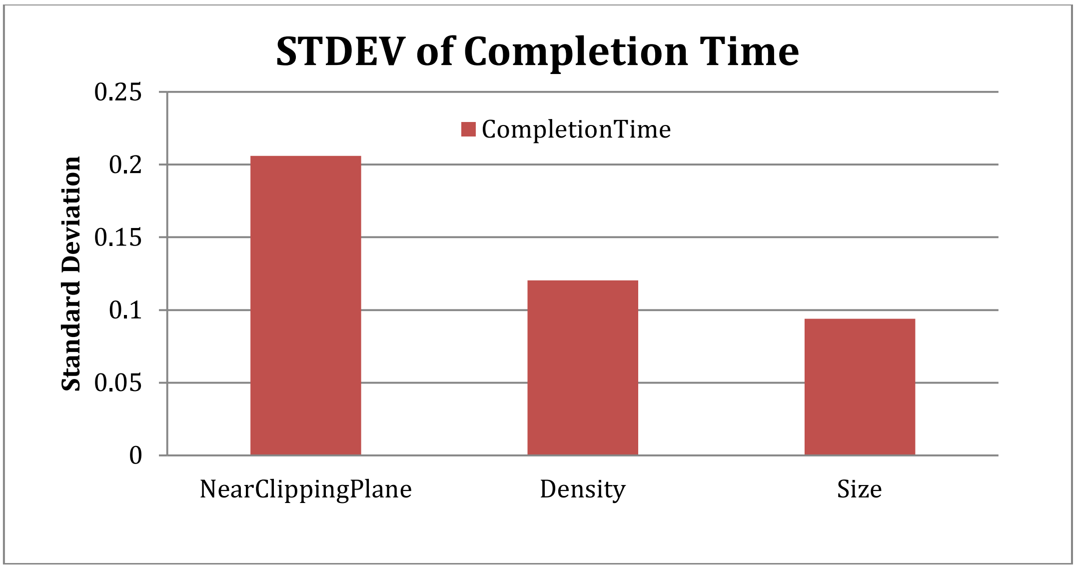


Figure 55: Std comparison in completion time.

3.6 Discussion

In our experiment, we focused on the influence of cloud density, point size, near clipping plane position and head tracking aids on human visual perception of volumetric data. We observe that:

Point size and cloud density, have a strong effect on precision and completion time.

- Clipping plane position does not have a significant influence on precision; however it has a significant influence on completion time. Our hypothesis is that situations where the clipping plane is closer to the user induce more user fatigue due to higher parallax. Hot and cold target sources where placed within an area that extends from 0.6m to 1.2m. Thus, during pointing task, user eye's convergence was performed within this area, however, when the clipping plane is close to the user, more objects with large parallaxes are displayed, this is known to induce higher user fatigue [86][94].

- One intuitive hypothesis was that an increased density would increase pointing precision; however it is not the case. We observe on Figure 56 that user precision does not get better for the high density cloud condition compared to medium density. Measured precision has also a much higher standard deviation for the highest density. A plausible explanation for this is that beyond a certain density, the occlusion effect of background point by foreground points impedes perception of far visual information and thus impedes task efficiency. We discuss in the following different display techniques meant to counter this effect.

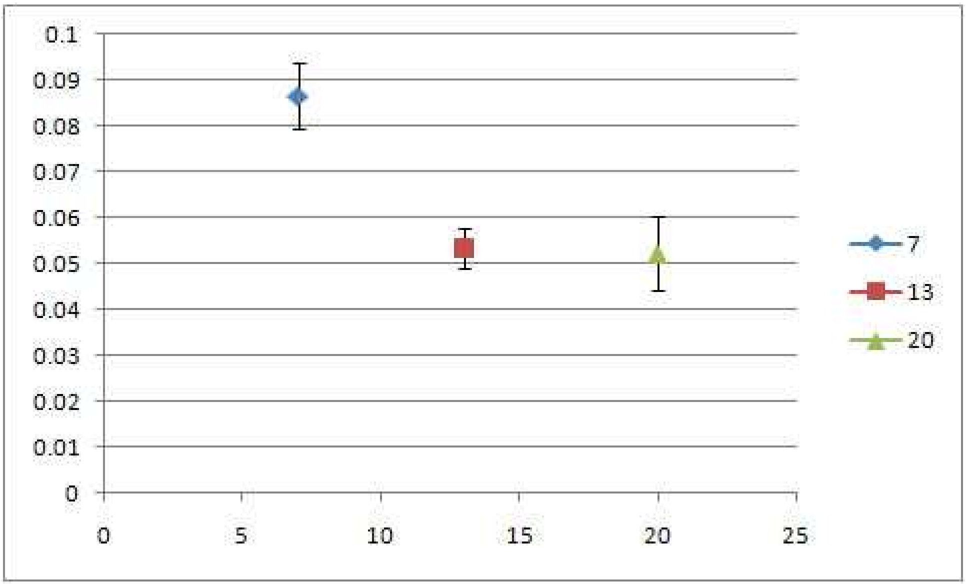


Figure 56: Comparison between high density cloud and medium density.

- Best combination: The best user performance was observed: for the farthest clipping plane position, with medium density and large point size (clip = 1.2m, point size = 25mm, 13 points per meter). The result on low density yielding low precision is intuitive. However, the experiments suggest a threshold for density, beyond which user precision does not improve.

- Experiment with 3D scene: We can observe that the addition of the 3D scene has no significant influence on user performance; it appears that comprehension of data is not impeded when the related 3D environment is added. However, this depends on background color and contrast, this issue needs more investigation, to take into account metamerism error effects that can change perception of colors depending on the background.

- Head tracking system significantly influences the human visual perception of volumetric data, not only in the aspect of pointing accuracy but also in task completion time. Adding head tracking which produces a dynamic point of view in real-time is useful for volumetric data perception.

- Point density is the most importance parameter for pointing accuracy improvement and the Near Clipping Plane Position is the most sensible parameter for task completion time. It means that if we want to set up a high accuracy point task the higher density point cloud should be used and if the completion time issue is important, a suitable Near Clipping Plane Position is important.

The result of density threshold leads us to try to propose visualization techniques that could allow increment in density, without occlusion problems. Various interaction metaphors can be proposed:

- Apply transparent textures on the volumetric cloud points in order to allow perception of far visual information. This was implemented in our setup, and in a first informal testing we observed that the stereoscopic fusion was difficult to achieve, probably because of too much similar visual stimuli.

- Adapt cloud density:

    - Manually: We could propose to the user to control the density (through any interface: sliders, analog input) to provide an adaptive visualization interface. For example, a slider bar can be displayed and manipulated by the user during the pointing task. Automatically:
    - Dynamic density of cloud point can be applied on different zones of point cloud. For example, in high gradient areas the density is set to high otherwise a low density is given.

- Increase the use of movement parallax. This could be done by simply asking the user to move around more, to gain from dynamic point of view through the head tracking system. This could be also done by providing the user with a displacement device (analog stick). Thus the user could easily get into the volume, gain from movement parallax, and reduce parallax by setting non relevant points behind the user.

- Reduce density in non-relevant areas: we propose a 'Flashlight' metaphor for visual interaction. Its principle is that the user would manually control a virtual flashlight; the point cloud density would be increased for points that are inside the flashlight cone volume. This would allow the user to actively choose high density areas.

In this work, we examined the consequences of density, point size, near clipping plane position and head tracking usage for stereoscopic perception of a volumetric representation of temperatures using a point cloud technique. Our results of the present experiment show that density and size of cloud point have a significant influence on the volumetric data perception. When the clipping plane position is close to the user, it significantly increases task completion time; this effect can be due to higher eye strain from higher parallaxes. Head tracking system can significantly help human visual perception of volumetric data.

We have observed an apparent threshold value for density, beyond this threshold the precision performance decreases. How could we push this limit in order to increase resolution without impeding correct visualization? One hypothesis is to increase the use of head tracking, for example: allow the user get into the volume, which decreases parallax, and also reduce the number of objects between the user and the target objects. Another possibility would be to allow the use to actively choose high density areas by allowing him to reduce/increase the number of displayed points. This could be done using a flashlight technique, where the density would increase inside the flashlight cone.