NRC Publications Archive
Archives des publications du CNRC

Life-Like Virtual Environments: An Introductory Survey
Parent, A.

For the publisher’s version, please access the DOI link below./ Pour consulter la version de l’éditeur, utilisez le lien DOI ci-dessous.

https://doi.org/10.4224/5763931

NRC Publications Record / Notice d'Archives des publications de CNRC:
https://nrc-publications.canada.ca/eng/view/object/?id=f5dd2089-f680-4776-ba2a-d31742871a09
https://publications-cnrc.canada.ca/fra/voir/objet/?id=f5dd2089-f680-4776-ba2a-d31742871a09

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L’accès à ce site Web et l’utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D’UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n’arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada   Conseil national de recherches Canada

Canada

Life-like Virtual Environments: an Introductory Survey

Applications and Activities, Design Requirements and Guidelines

Anne Parent
Visual Information Technology

January 1998

> The task for the production of efficient VR applications is to base the systems around design principles that enable intuitive and efficient interaction with three-dimensional structures.
> J. Wann and M. Mon-Williams, 1996

ERB-1055
NRC No. 41555

Abstract

This document reports the results of a literature review conducted in the summer of 1997 on the applications and activities, design requirements and guidelines of relevance to life-like virtual environments. Virtual environments hold the promise of simulating life experiences with such realism as to generate sensations similar if not equal to those aroused by the real world. At the heart of the promise held by the technology lies the identification and design of the life-like qualities that must be part of the virtual world in order for the user to believe in a new reality. The purpose of this report was to collect and group design requirements and principles according to the key activities performed within various applications: viewing, exploration and the manipulation of virtual objects. Eight categories of design requirements were found to drive the creation of a virtual environment. Design principles aim to support human sensory, cognitive and ergonomic requirements. Specifically, visual, auditory and haptic principles address human sensory requirements. Principles relevant to memory capacity, information load and mental models are defined under cognitive requirements. Physical and physiological guidelines aim to satisfy ergonomic requirements. Given the rapid evolution of the field, this document does not presume to contain an exhaustive survey of the literature but hopes to provide designers of life-like virtual environments with a useful frame of reference.

Résumé

Ce document décrit les résultats d’une revue de littérature effectuée au cours de l’été 1997 portant sur les applications et activités, besoins et lignes directrices reliées à la conception d’environnements virtuels naturels. La réalité virtuelle promet la création d’environnements simulant le monde réel avec un naturel tel que les sensations suscitées par l’expérience virtuelle ressemblent ou mêmes égales les sensations suscitées par l’expérience réelle. Au coeur de l’expérience promise par cette technologie repose l’identification et la conception des attributs naturels que l’environnement doit contenir afin que l’utilisateur croit en la nouvelle réalité qui lui est présentée. Ce rapport a pour but de recueillir un ensemble de besoins et principes de conception regroupés selon les activités principales réalisées dans un environnement virtuel: la visualisation, l’exploration et la manipulation d’objets. Huit catégories de besoins furent dérivées de ces activités. Ces derniers, issues des systèmes sensoriels, cognitifs et ergonomiques humains déterminent la conception de l’environnement virtuel. Spécifiquement, les principes de conception reliés aux mécanismes perceptuels, auditifs et haptiques répondent aux besoins d’ordre sensoriel. Les principes portant sur la mémoire, le traitement de l’information et les modèles mentaux résultent de besoins d’ordre cognitifs. Les principes reliés aux contraintes physiques et physiologiques du corps humain obéissent aux besoins d’ordre ergonomiques. Étant donnée l’évolution de ce domaine de recherche, ce document ne peut prétendre contenir un inventaire exhaustif des études réalisées à ce jour mais espère constituer un outil de référence utile à la conception d’environnements virtuels naturels.

TABLE OF CONTENTS

Life-like Virtual Environments: An Introductory Survey

Anne Parent
Visual Information Technology

1. Introduction

This document reports the results of a literature review conducted in the summer of 1997 on the applications and activities, design requirements and guidelines of relevance to life-like virtual environments. Virtual environments hold the promise of simulating life experiences with such realism as to generate sensations similar if not equal to those aroused by real world experiences (Langlois, 1996). At the heart of the promise held by the technology lies the identification and design of the life-like qualities that must be part of the virtual world in order for the user to believe in a new reality. The purpose of this report was to collect and group design requirements and principles according to the key activities performed in a life-like virtual environment: viewing, exploration and the manipulation of virtual objects. Eight categories of design requirements derived from the activities were found to drive the creation of a virtual environment. Design principles aim to support human sensory, cognitive and ergonomic requirements. Specifically, visual, auditory and haptic principles address human sensory requirements. Principles relevant to memory capacity, information load and mental models support cognitive requirements. Physical and physiological guidelines aim to satisfy ergonomic requirements. Given the rapid evolution of the field, this document cannot presume to offer an exhaustive survey of the literature but hopes to provide designers of life-like virtual environments with a useful frame of reference.

The first part of this report briefly introduces some of the applications for which virtual environments have as yet been intended: on-line performance, on-line comprehension, off-line learning and off-line training and rehearsal. The second section briefly describes the key activities performed within the applications: viewing, exploration and the manipulation of virtual objects. The third section of the document introduces a framework of design requirements (Parent, 1998c). This framework is believed to form the basis of the creation of life-like virtual environments. The framework is the result of an earlier review of the variables assumed to explain the sense of presence experienced in a virtual environment. The review was based on issues of the journal Presence: Teleoperators and Virtual Environments dating from 1991 to 1996. The last section of the report lists design guidelines organized according to the key activities and requirements the guidelines aim to support. The organization of the information contained in the report was chosen such as to best follow the design process of virtual environments.

2. Activities performed in a Virtual Environment

This section briefly introduces the categories of applications for which virtual environments have as yet been intended. Each category offers but a small sample of the work currently taking place internationally.

2.1 Categories of applications

2.1.1 On-line performance

On-line virtual environments provide the user with direct manipulation capabilities in a remote, or non-viewable environment. Such applications also known as telepresence have allowed the operation of an undersea robot and space shuttle arm (McKinnon and Kruk,1991), the operation of a hazardous waste handler (Sheridan, 1992; Heim, 1995), the control of a remotely piloted vehicle (McGovern, 1991) and navigation through a virtual database (Newby, 1992). A more recent application is the space rover Sojourner used by the NASA Mars Pathfinder mission in July1997. The rover is reported to have traversed 52 m in 114 commanded movements, performed 10 chemical analyses of rocks and soil, carried out soil mechanics and technology experiments and explored over 100 m^2 of the martian surface. On-line virtual environments are designed to optimize perceptual motor performance. Essentially, operator errors must be small, reactions must be fast and tracking targets must be stable. The environment must afford the operator global knowledge of the location of multiple objects within a defined space (Sarter & Woods, 1991). In Canada, the University of Toronto's Input Research Group is primarily concerned with better understanding the relationship between the motor-sensory and the cognitive aspects of interaction. Their work has included studies investigating mode errors, and testing models to characterize transactions found in direct manipulation systems (Buxton, 1993). Telerobotic systems used in advanced manufacturing applications are investigated by the University of British Columbia and Simon Fraser. Some of the anticipated benefits of this research are new methodologies for studying human hand movement in the context of specific tasks. A group of researchers in Kinesiology at Simon Fraser is currently investigating remote manipulation in endoscopic surgery. The National Research Council of Canada, Spar Aerospace Ltd., and Atomic Energy of Canada Ltd. investigated the combined use of virtual environments and a laser range imaging system for the on-line operation of remote construction equipment and robotics (Ballantyne et al. 1997).

2.1.2 On-line comprehension

Virtual environments designed for on-line comprehension aim to provide understanding, comprehension or insight regarding the structure of an environment. Applications have included exploring how molecules can be combined or docked (Brooks, 1993) and exploring the topology of a brain tumor. The CAVE VR Environment at the University of Illinois at Chicago and the National Center for Supercomputing Applications (NCSA) are engaged in the exploration of new methods of visualizing and interfacing with scientific data and simulations. The Iowa Center for Emerging Manufacturing Technology (ICEMT) deals with a variety of applications, from physiology to design to manufacturing, where visualization of complex geometry is essential to problem understanding, solution or communication. The University of Alberta's Virtual Reality and Visualization Group is interested in the visualization of large data sets that don't have an obvious geometrical structure. Partly carried out in collaboration with researchers at NEC in Japan, their interests include the structure of software systems, UNIX directory hierarchies and genetic databases. One of the two main lines of activity of the HCI laboratory at the University of New Brunswick also involves the study of scientific data and network visualization. A current project investigates the visualization and interpretation of six million lines of code representing one of the worlds most advanced digital switching systems. Another ongoing applied line of research is directed towards the development of tools to assist oceanographers and ocean mappers in their work.

2.1.3. Off-line learning and knowledge acquisition

Off-line learning and knowledge acquisition environments are designed to transfer knowledge of an abstract form. Learning applications have been reported within the military (Witmer et al., 1995) and medical fields (King, 1997), in design evaluation known as virtual prototyping (Geissen, 1996, Rowell, 1997), as architectural walk-throughs (Bukowski & Séquin, 1997), the simulation of assembly sequences and maintenance tasks (Potter, 1996; Orr, 1997), the treatment of psychological disorders (Glanz et al., 1997; North et al., 1997), education (Roehl, 1997) and marketing (Burke, 1996). The main interest of the Virtual reality group at the Centre d'optique et photonique (COPL) of the Université Laval involves the application of engineering activities. The goal of the project is to increase the transfer of engineering principles to students, at the university level as well as other levels of academic curricula, through an interactive tridimensional world. The Virtual Reality laboratory (VRL) at the University of Michigan concentrates on industrial applications of virtual environments. Research is focused on virtual prototypes of automotive and marine designs, the simulation of manufacturing processes and other engineering applications. Additional projects include architectural walk-through models, free-form design, accident simulations and educational activities. The Virtual Environments Laboratory at Northeastern University in Boston investigates virtual environments based driving simulators, highway construction zone simulations, trains crane operators in a virtual factory and models driver's spare visual capacity.

2.1.4 Off-line training and rehearsal

Virtual environments designed for off-line training and rehearsal are similar to learning environments. Their goal however, is to allow users to rehearse critical actions in a benign, forgiving environment, in preparation for a target performance in a less forgiving one. Such environments are used to practice emergency procedures (Baum, 1992; Bukowski & Séquin, 1997) or maneuver spacecrafts (Grunwald and Ellis, 1993). This environment is assumed to provide an effective transfer of training from practice in the virtual environment to performance in the real world.

2.2. Key Activities

This section offers a short definition of the key activities deemed essential to the success of many if not most applications. The key activities identified are viewing, exploration and the manipulation of virtual objects. Although the activities are not mutually exclusive, each one is defined independently. On a different level, menu usage has been added to the list of activities, given its general interest.

2.2.1. Viewing and Inspection

Viewing and inspection refer to the visual components of a task. Viewing is currently the foundation of essentially all operations exercised in a virtual environment. In order for users to view and inspect virtual objects, the quality of a virtual image must satisfy the requirements of human perceptual mechanisms. Design requirements describe the features to which an image must conform for a user to perform a given task effectively. Design principles are determined by the properties of the human visual system and by the nature of the activities required of a particular task. In spite of the wealth of basic scientific literature on human visual perception, there is currently a lack of knowledge as to the specific image features required for various tasks. One reason rests on the fact that cues for tasks such as estimating the size or distance of objects or the speed of self-motion are of a compound nature. The need to provide one cue is frequently dependent on the presence and strength of other cues.

2.2.2. Exploration and Navigation

Exploration and navigation describe the actions performed by the user leading to the discovery of the virtual space and its various aspects. Exploration is the term often found to describe a user's displacement within a small area of space. Virtual exploration simulates walking (Pausch et al., 1995) or running short distances. Navigation is used to refer to long range travel such as spacecraft, aircraft (Ellis, 1991; NASA) or sea travel. Designs guidelines allow the user to easily identify his/her current location and orientation, and provide transparent self-motion procedures (Warren and Wertheim, 1990). Designers are encouraged to capitalize as much as possible on how humans normally move through space (Warren & Wertheim, 1990).

2.2.3. Object Manipulation

Object manipulation refers to the user's interaction with the virtual objects of the environment. The manipulation of virtual objects can be done through direct user interaction, physical and virtual controls (Mine, 1996). This activity describes the user's selection of an object, a change in its position, orientation, center of rotation or scaling. Design guidelines aim to allow the user to interact with virtual objects as naturally as with objects of the real world.

2.2.4 Menu Usage

Menu usage describes a process used to select various options open to the participant of a virtual environment, be they viewing and exploration choices or procedures to manipulate a virtual object. Viewing options may involve micro or macro inspection of valuable artifacts or mining facilities. Exploration may allow a god's eye view of the Grand Canyon or scaling oneself down to a molecule of water. Menus may be used to interact with virtual objects by means of magic wands or surgical instruments.

3. A Requirements Framework

IntroductionThe proposed framework of design requirements rests on an understanding of the activities performed in a virtual environment and of the strengths and limitations of human sensory, cognitive and ergonomic systems (Parent 1998). Design principles should conform to human sensory receptors, to human mental models, memory and information processing mechanisms and should respect physical and physiological constraints.

3.1 Sensory Requirements

Sensory requirements define the parameters of human sensations and perception. Designers need to define guidelines based on the wide or narrow sensory bandwidths relevant to the performance of particular tasks. One goal of the virtual environment is to provide visual, auditory, haptic and olfactory cues appropriate to the successful completion of a task.

Table 1: Perceptual Requirements

Perceptual Requirements
Eye Geometry
Field of view
Interpupillary distance
Perception of colour
Color palette
Perception of contrast and detail
Foveal and peripheral perception
Depth perception
Binocular cues
Static monocular cues
Dynamic monocular cue
Motion perception
Object motion cues
Self motion cues

Visual fidelity defines the degree of coherence between human visual mechanisms and the display of system images. Design principles should be consistent with various human perceptual bandwidths, such as the recognition of colour variations. The literature suggests that a natural field of view (Hendrix & Barfield, 1996a ; Barfield et al., 1995; Steuer, 1992), stereoscopic cues for close viewing (Hendrix & Barfield, 1996a), depth and breadth cues for distance viewing (Barfield et al., 1995; Steuer, 1992), good image quality (Barfield & Weghorst, 1993) and light and shading realism (Barfield & Weghorst, 1993) are essential visual requirements of life-like virtual environments. According to Hendrix and Barfield, the ability to perceive spatial information about our environment is essential to one's sense of reality given its relative importance in everyday life.

Auditory fidelity defines the consistency between human auditory mechanisms and the sounds, foreground and background, produced in the virtual environment. Stereo sounds must be projected from realistic angles (Hendrix & Barfield, 1996b). This technology is still very new. Current auditory technology lacks the capability to represent sounds as being located in front of the user and to adjust sound spatialization to head movements (Youngblut et al. 1996). Olfactory technology is not expected to be available in the next few years given the difficulty of controlling the user's breathing space (Youngblut et al. 1996).

Table 2: Auditory Requirements

Auditory Requirements
Foreground
Background
Pinnae model accuracy (for spatial sound display)

Haptic fidelity defines the consistency between human tactile, kinesthetic, proprioceptic and vestibular sensations and the sensory feedback generated by the environment. Tactile feedback conveys sensations of smoothness and coarseness, of hot and cold. Few tactile interface devices are yet commercially available. Products simulate contact forces that occur when a user touches a virtual object and provide some temperature feedback (Youngblut et al., 1996). Kinesthetic sensations are tensions exerted on muscles, joints and tendons. Proprioceptic receptors indicate limb and torso positions. Vestibular mechanisms process linear and angular accelerations of the user's head thereby generating one's sense of balance. Little progress is reported in providing interfaces that allow a user to walk or run through a virtual environment. Only projection-based displays currently allow self-motion within a small area. Recently, several motion chairs have been developed that employ techniques ranging from inflatable cushions to motion bases in order to provide the user with a sense of motion (Youngblut et al., 1996). None however are expected to be available within the next few years.

Table 3: Haptic Requirements

Haptic Requirements
Kinesthetic
Proprioceptic
Vestibular
Tactile

3.2 Cognitive Requirements

Cognitive requirements define the parameters of human information processing. Designs should consider constraints on attention such as the individual's ability to process several channels of input concurrently. Fidelity to memory capacity refers to the learnability of the interactive modes and procedures provided by the environment. Constraints on working memory, such as the ability to remember where one has been when travelling in numerous realities must also be considered. Fidelity to information load limitations define the quantity of information displayed on the screen and required to accomplish the task. In order to support fidelity to human mental models the environment should offer realistic scene complexity (Welch et al., 1996). Fidelity to one's models of interaction refers to the consistency between the users actions and their expected effects on the system. Fidelity is observed when the relationship between the users' actions and their effects on the virtual objects or actors are intuitive, easy and natural (Sheridan, 1992). Users carry a large repertoire of facts and knowledge about how the world operates. Cognitive fidelity also defines the coherence between the laws of the physical world and those of the virtual world. It is assumed that 3D-realism will be greater if the relationships between objects in the virtual world conform to the individual's expectations of the world (Barfield & Weghorst, 1993; Barfield etal.,1995). For example, an object is expected to remain constant and its shape consistent unless destroyed or modified and some form of noise is expected in the background (Ramsdell, 1991). Effects must also be temporally (Barfield et al., 1995; Hendrix & Barfield, 1996a, Sheridan, 1994; Steuer, 1992; Welch et al., 1996) and spatially (Barfield & Weghorst, 1993; Sheridan, 1994) predictable. In other words, actions should lead to expected displacements within the amount of time expected by the user. Sensory modalities should be consistent to human mental models (Sheridan, 1992). A breaking sound, for example, should immediately follow a breaking object. The number (Hendrix & Barfield, 1996b; Sheridan, 1992; Zeltzer, 1992) and range (Barfield & Weghorst, 1993; Zeltzer, 1992) of sensory channels that are stimulated by the environment should be consistent with expectations. Hendrix & Barfield (1996a) report two studies showing that one's sense of presence is significantly higher when head tracking is provided.

Table 4: Cognitive Requirements

Cognitive Requirements
Mental Models
Environmental Conformity
Scene complexity
Object constancy
Object consistency
Object geometry
Background cues
Variety of sensory output
Range of sensory output
Intermodality consistency
Physical and social Interactive Cues
Range of control behaviors
Temporal predictability (head tracking, update rate)
Spatial predictability (depth, space, volume)
Memory
Ease of learnability
Information Load Capacity

3.3 Ergonomic Requirements

Ergonomic requirements define the physical parameters of the human body and its movement. Ergonomic fidelity describes natural and comfortable movement within the virtual environment. High or low levels of perceptual-motor requirement should be known with regard to a particular task. Ergonomic fidelity is observed when the position of the user is efficient and comfortable and the interactive devices provided conform to human physiology.

Table 5: Ergonomic Requirements

Ergonomic Requirements
Comfort of physical devices
Comfort of psychomotor movement

Of course, the design of a virtual environment starts with a task analysis of the applications for which it is intended. The designer must first understand how the environment will be used before specifying the requirements of the application. To guide the task analysis of a virtual art exhibit, for example, a Virtual Environment Task Analysis Tool (VETAT) for the Creation and Evaluation of Virtual Art Exhibits was developed (Parent, 1998b).

4. Design Guidelines

The following section reports on the design guidelines found relevant to the creation of life-like virtual environments. Most of the information contained in the sections is organized according to the requirements the guidelines aim to support. Some principles, however, seemed to fit less neatly within the various sections. Due to their interest, miscellaneous guidelines and research issues were therefore placed in separate tables at the end of individual sections.

4.1. Viewing

The following tables identify some design guidelines applied to the display of virtual images. Guidelines are defined with regard to visual and cognitive requirements. Although auditory and haptic requirements are likely to consolidate one's perception of a scene (e.g. noise and vibrations following an explosion) they are not reported because of their dependence on the contents of the scenes. Similarly, ergonomic considerations are not reported because of their dependence on specific virtual devices and set-ups.

4.1.1 Visual Requirements

II- 3-D Imaging

REQUIREMENTS	GUIDELINES
1. Eye GeometryA. Image Presentation	
a. screen projection Head-Mounted Displays (HMD) or Spatially Immersive Display (SID) or Head-Coupled System (HCS) or Virtual Model Display (VMD) . Screen projection	; SID rear projection is best because contrast may be better and luminance may be higher than with front projection but it is difficult to avoid a hot spot (i.e. a conspicuously higher luminance in the image centre) (Padmos & Milders 92)
b. field of view (FOV)	; the amount of the virtual environment that is viewable without moving the head or the width subtended by the viewable display surface, measured in units of visual angle - angle dictated jointly by the width of the display and the viewer's distance from the display. In the real world both are equivalent. ; the only systems that can achieve angles up to 270˚, are projection based, like Sun's Virtual Portal, in which head and body are free to move (Deering 93); ; wider fields of view clearly support greater situation awareness of surrounding objects and terrain. ; wide fields of view (unless coupled with proportional increase in viewing angle) distort the perceived distance from objects (McGreevy and Ellis,1986) ; wider viewing angles provide a more compelling sense of forward motion, given the of peripheral vision to motion, and the enhanced tracking performance that results when peripheral vision is available (Wickens,1986)
c. interpupillary distance	50-76mm (Boff & Lincoln, 1988); should allow adjustment since unadjusted IPD produces eyestrain and distorts space.
d. viewing region and distance. Viewing region and distance	; given a maximum parallax distortion of deg. ß, the minimum viewing distance is equal to the needed width or height (whichever is greater) of the viewing region, multiplied by 57/ ß. (Padmos & Milders 92)
2. Perception of colour	
a. color palette	
i. chromaticity values.1 Chromacity values	;needs 300 chromaticities at each luminance level for a realistic depiction of complicated textured scenes.

REQUIREMENTS	GUIDELINES
• chromatic colour attributes (hue, saturation)	; for simple tasks 30 chromaticities at each luminance level is sufficient (Padmos & Milders 92)
• achromatic attribute brightness (luminance)	; steps should increase by a fixed factor at each step; (Padmos & Milders 92)
ii. luminance steps	; for realistic texturing of surfaces and shading of curved objects, the maximum number of luminance steps required is estimated on the basis of the just-noticeable luminance step, which is a factor of 1.01 and a total luminance span of 20 (contrast ratio) higher luminance levels increase sensitivity to flicker, and this may put extra demands on the refresh rate. (Padmos & Milders 92) ; steps should cover the full range of luminance available (Padmos & Milders 92);
3. Perception of contrast ratio	
a. luminance	about 30 luminance steps are sufficient for simple tasks. (Padmos & Milders 92);
b. contrast ratio	**;** for most applications a contrast ratio between 10:1 and 25:1 is acceptable. ; should be determined for a white/black checkerboard pattern. (Padmos & Milders 92)
c. spatial resolution	. Spatial resolution; the power of a system to make small details visible. ; limiting resolution is defined as the number of lines per degree of a high-contrast grating input at which the observer can no longer distinguish the separate lines in the resulting display image. ; the limiting resolution should at least be equivalent to the observer's visual acuity. ; a limiting resolution of 15 lines/deg is acceptable for many applications (Padmos & Milders,1992) ; a limiting resolution of 60 lines/deg would be ideally required. (Clapp, 1985a) ; critical to reading.
4. Foveal vs peripheral perception	; perception is optimal in the central 2 degrees of the retina called the fovea.
5. Depth perception	
a. Binocular cue (stereopsis)	at less than 1m, depth differences of less than 1mm may be perceived; starts to degrade at 10 m and not effective beyond 135 m.
b. Monocular cues	at 10-20m give more accurate depth perception than stereopsis.
i. relative size and height	at greater distances objects should be shorter and smaller.
ii. linear perspective	parallel structures should converge.
iii. foreshortening	an image seen sideways should be compressed.
iv. interposition	a closer object should partly hide a more distant one.
v. gradient of object	at greater distances there should be more objects and less detail in the same angular area.

REQUIREMENTS	GUIDELINES
vi. textural gradient	; representation of the fine details on a surface. ; may play a role in spatial orientation (especially recognisable patterns of realistic sizes) (Kellogg & Miller, 1984) ; a minimum useful number of texture elements (texels) per single texture file is probably 64x64, but photo texture 512x512 texels may be desired. (Gardiner & Hadfield 90) ; current top-end systems can produce more than 200 simultaneous patterns. **;** to prevent scintillation of texture patterns at larger distances caused by aliasing and to present a realistic appearance of a given texture at both short and long distances, it is necessary to apply some form of level of detail. ; techniques include: clamping (deleting texture at distances such that texel size is equal or smaller than pixel size) or MIP mapping. ; particularly important when representing moving water (Gardiner & Hadfield 90).
vii. relative brightness	closer objects should appear brighter
viii. light and shadow effects	increase realism; important to object inspection and recognition (Barfield et al., 1988).
• cast shadows.1 Cast shadows	; can be modelled by dark, preferably transparent, polygons of the correct orientation and shape. ; particularly useful for shadows of moving vehicles.
• shading	; various techniques in order of increasing realism.
- flat shading	; flat surfaces (polygons) of an object vary in luminance depending on their orientation with regard to the sun.
- Gouraud shading	; curved surfaces of objects are represented by a limited amount of polygons through application of a graded luminance over each polygon, calculated by interpolation (Rowley, 1986).
- Phong shading	; most realistic but requires more computing power.
ix. levels of detail	essential to displaying much detail at a short distance; most systems have 10 levels of detail. **;** a feature that minimises polygons to be calculated while keeping the number of visible details on objects sufficiently high. ; not clear how many levels are required for depicting outside-world images. ; to avoid the sudden emergence of details and provide a smoother transition from a lower to a higher level of detail, the transparency feature is useful (Yan 85)
6. Motion perception	
a. Object motion cues (angular size, texture density, lateral speed of detail)	motion is perceived as continuous if the displacement between frames is limited.
b. Self-motion cues	essential to exploration.
i. motion parallax (for estimating speed)	the more objects are visible on the screen, the more accurate the perception of self-motion; allows estimation of speed.
ii optic flow (for estimating direction)	the pattern of approaching objects should expand; allows the estimation of direction.

4.1.2 Cognitive Guidelines

REQUIREMENTS	GUIDELINES
1. Environmental Fidelity	
a. degree of scene complexity	; scene realism and task performance improve with increasing number of polygons in the scene. (Lintern et al., 1987) **;** ideal scene complexity (no of poly.) will depend on the task. **;** dependent on the computing power of the generating system, the update frequency rate and pixel fill rate. **;** good texture may decrease the number of polygons needed. (Padmos & Milders 92).
b. depth of field	**;** is determined by the maximum distance at which objects must be perceived. **;** task dependent. ; a limited depth of field reduces the number of polygons displayed or enables an increase in polygon density.
c. temporal predictability	
i. update frequency	. Update frequency; frequency with which a totally new image content is generated. ; the maximum displacement per frame that gives an impression of continuous movement is 15 arcmin (Sperling 76). **;** min. required update frequency (frames/s) = object angular speed (arcmin/s) / 15. (Padmos & Milders 92) ; for many applications, an update frequency of 30 Hz will suffice. (Padmos & Milders 92) **;** the faster the angular speed of objects displayed, the higher the frequency rate required to avoid image shaking. (Padmos & Milders 92) **;** low update frequency causes shaky moving images or distortion of contours; **;** depends on: a. no. of polygons to be processed b. pixel fill rate (no. per second)-
ii. refresh rate. Refresh rate	; frequency with which a whole frame of the display is written ; low refresh rate causes luminance flicker; sensitivity to flicker is higher for larger fields at higher luminances.
iii. image delay	; sampling time of the trackers + time for calculating a change in viewpoint position + net image delay. **;** net image delay: time between new input and the display of the corresponding image frame. **;** delays probably should not be longer than for simulators - 40 to 80 ms. **;** a large image delay may cause cybersickness.

Miscellaneous Guidelines
; for object inspection and recognition, light and shadowing (Barfield et al., 1988) and motion parallax (Prazdny, 1986) play a greater role than motion fidelity, stereo and texture gradients (important in navigation travel.)

Miscellaneous Guidelines
; decisions about the level of visual realism must be based upon a task analysis of what is to be recognised, or discriminated. e.g. if texture is important, say for discriminating geological features then it cannot be sacrificed to say, speed of image updating.

4.2 Exploration

The following tables identify the design guidelines collected with regard to exploration and navigation. Visual guidelines are not reported because assumed similar to those listed under viewing activities. Auditory and ergonomic principles are excluded because of their dependence on specific events and devices.

4.2.1 Haptic Guidelines

REQUIREMENTS	GUIDELINES
1. Control-display gain	; Low gains will require a lot of displacement to obtain a given display change and therefore a lot of effort. High gains, while more efficient, lead to greater chances of instability and overcontrol. ; the best point on the trade-off function depends on the nature of the task e.g. adjustment of position requires a lower gain than does rapid travel. Also because of stability concerns, the optimal gain will depend on the system time delay.
2. Control order	; refers to the qualitative nature of the change in display state that results from a change in position of the control. ; first-order control is typically the order of choice when control is exerted by some hand manipulation- a fixed change in control position yields a constant rate of change or velocity or viewpoint. ; zero-order control is typically the order of choice when desired distances are small final position is the most important criterion (e.g. walking).
3. Time delay	; high gain systems coupled with significant time delays or lags in updating the visual world are susceptible to closed-loop instability (Wickens,1986) ; Below 6 frames per second, users choose to navigate using an overall map view requiring less intensive image updating rather than an egocentric scene view. (Airey et al.,. 1990) ; provide sufficient texture information to achieve a realistic sense of forward motion (even at the price of simplified imagery-more is not always better) (Larish and Flach,1990)
4. Travel-view decoupling	; whether to allow the direction of motion to be decoupled from the direction of gaze at the virtual environment world e.g. looking aside while walking forward. (Mercurio and Erickson, 1990) ; provide a wide field of view and allow the user to stop and hover, before inspecting right and left.

Miscellaneous Guidelines

Miscellaneous Guidelines
; forward motion must be accompanied by corresponding vestibular inputs (e.g. from walking), so that a mismatch between vestibular and visual perception does not result and cause motion sickness. (Oman, 1991)
; display gain and time lag dictate the stability of the control loop requires high spatial and temporal precision d. Travel-view decoupling

a. Control-display gain

4.2.2 Cognitive Guidelines

REQUIREMENTS	GUIDELINES
1. Modes of motion direction	
a. hand directeda. Hand directed	; the position and orientation of the hand determines the direction of motion through the virtual world.
i. pointing mode	i) Pointing mode; the direction of motion through the virtual space depends upon the current orientation of the user's hand or hand held input device. ; extremely flexible and allows arbitrary motion through the virtual world (such as flying backward when you look around). (M.Mine, 1996)
ii. crosshairs mode	; the user simply positions the cursor (typically attached to the user's hand) ; intended for novice users who are used to interacting with desktop workstations and personal computers using mice.(M.Mine, 1996) ; disadvantage: requires the user to keep the cursor in line with the desired destination and can lead to arm fatigue.(M.Mine, 1996)
iii. dynamic scaling	; advantage: provides a virtual map of the entire environment making it possible to locate your final destination.(M.Mine, 1996)
b. gaze directed and orbital mode	; in gaze directed flying the user flies in whatever direction he is currently looking (typically approximated by the direction his head is pointing). ; easy to understand and ideal for novice users (M.Mine, 1996) ; disadvantage: eliminates the possibility of turning your head to look around while you fly through the virtual world (like looking out a car window), since you continually move in the direction you're looking. ; on orbital mode , the object of interest is constrained to always appear directly in front of the user, no matter which way he/she turns his head ;the side of the object facing the user depends upon the current orientation of the user's head. Look up and you see the objects bottom, look down you see its top. ;the object orbits the user, with its position relative to your head based upon your gaze direction.(M.Mine, 1996)
c. object driven	; when direction is controlled by objects such as autonomous vehicles (e.g. elevator), attractors (e.g. a planet with a simulated gravity) or repellors. ; disadvantage: requires some additional means of controlling the position of the attractor. (M.Mine, 1996)

REQUIREMENTS	GUIDELINES
d. goal driven	; the user is presented a list of destinations which are displayed either as text or as a set of icons (virtual menu) or graphically in the form of virtual maps. The user can point to a destination transported under program control.
2. Modes of speed.3 Degrees of freedom	
a. constant speeda. Constant speed	; can be based upon the size of the virtual space the user must traverse (adjusted such that the user can traverse the space in a reasonable amount of time) ; leads to a jerky, start/stop kind of motion and a tendency to overshoot destination.
b. constant acceleration	; the user begins at a slow speed that is reasonable for short flights through the local environment. Enables speeds to grow exponentially. ; useful if the size of the environment is very large and contains lots of interesting detail that would be interesting to fly around. (M.Mine, 1996) ; the proper rate of acceleration is tricky (M.Mine, 1996)
c. hand controlled	; speed is based on how far your hand is extended in front of your body. ; linear or exponential mappings are used. ; disadvantage: fatigue from having to hold your arm at the required distance (M.Mine, 1996) ; disadvantage: fatigue from having to hold your arm at the required distance (M.Mine, 1996) ;disadvantage: limitations in the dynamic range that can be compressed into the possible range of motion of the arm and still be controllable. (M.Mine, 1996) ; speed defined by 3 zones at varying reach distances. One zone maintains the user at a constant speed, another will maintain a constant acceleration, and the third will result in constant deceleration. ; confusing, specially for novice users. (M.Mine, 1996)
3. Degrees of freedom.3 Degrees of freedom	; it is beneficial to restrict the user to changes in position and not orientation -this is like standing on a platform that can move anywhere in the virtual space, but is constrained to remain level relative to the virtual world. (M.Mine, 1996) ; in an architectural walkthrough, it is suggested that the user remain at some typical head height - excellent for outdoor simulations and landscape fly-throughs. (M.Mine, 1996) ; in some situations it is preferable to take control of the user's motion, guiding him through the virtual world under program control. (M.Mine, 1996)
4. Devices	

REQUIREMENTS	GUIDELINES
a. physical controlsc. Physical controls	; includes input devices such as joysticks, trackballs, buttons and sliders, steering wheels, handle bars. ; include keyboard input, voice control, speed controls such as accelerator pedal, dial or slider mounted on the hand held input device, treadmill. ; readily available and easy to incorporate into an application (M.Mine, 1996) ; lack a natural mapping between movement of the device and motion in the virtual world (e.g. should I twist the knob clockwise or counter-clockwise to move up?) (M.Mine, 1996) ; joysticks and dials are useful if more precise control of the orthogonal components of motion is required. (M.Mine, 1996)
b. virtual controls	; virtual steering wheels or flight sticks ; advantage: flexibility (M.Mine, 1996) ; disadvantage: no haptic feedback (M.Mine, 1996) ; potential application: control layouts in actual vehicles such as planes and automobiles. (M.Mine, 1996) ; form of virtual menus/sliders

Miscellaneous Guidelines
; capitalise as much as possible on how humans normally move through real space (Galyean, 1995; Warren and Wertheim,1990)
; travel should represent a compromise between 2 features: speed and flexibility (rapid travel to any part of the environment) on one hand and situation awareness (where I am in the overall context) on the other. (Sarter and Woods,1994)
; based on the task compromise between fully manual and fully automatic navigation; impose a constant speed or impose a logarithmically diminishing speed as the next destination approaches accompanied by a longer perceptual experience (Flach et al., 1990)
; effectiveness of a particular navigational metaphor may be a function of the type of task and of the type of virtual environment (Ware and Osborne,1990)
; provide regularly spaced texture and level surfaces to support the accurate perception of gradients, slant and optic flow (cues that humans use to judge motion and orientation in the natural world) (Lee and Moray,1992).
; make the transition from a small-scale wide angle perspective by a rapid but continuous "blow-up". This may be cognitively less disorienting. (Mackinlay et al., 1990)
; mapping of physical motion to virtual motion is very intuitive, however the range of user movement is limited by the tracking technology.
; most systems have usable working volumes of 1 to 2 meters in radius (M.Mine, 1996)
; it is likely that the size of an application's virtual space will exceed the physically tracked working volume, therefore alternate ways to move through the virtual world, independent of motion in the physical world will be required. Typically this involves some form of flying, though depending upon your application it may take some alternate form such as driving, or even teleportation. (M.Mine, 1996)
Ware evaluated 3 ways of using a hand-held 6-degrees of freedom input device in exploration, search, and viewpoint control tasks in 3 different environments and found significant differences in user preferences and user performance. The "flight vehicle metaphor in which the input device was used to control translation and rotational velocity, was the most useful in exploring a "maze", but was judged worst for navigating around a "cube" environment. The preferred strategy for the cube was "the environment-in-hand" metaphor, in which the input device was used to move and rotate the entire environment. In contrast, this metaphor was seen as inappropriate for a "road signs" environment, which was perceived to be very large -something a human could not simply pick up and move around (Ware and Jessome, 1988).

Miscellaneous Guidelines
The "virtual space effect" : the biases in perceived location of objects resulting from a display magnification (wide field view) or minification (narrow field of view) that is inappropriate given the viewing distance between eyes and the display surface. (Ellis et al., 1991)
The "2D-3D effect" which describes the perceived "rotation" of vectors towards a plane which is more closely parallel to the viewing plane than is appropriate. That is, an underestimation of the slant of a surface. (Perrone, 1982)
Display-enhancement techniques to alleviate these biases:
• inclusion of grids and posts to help identify the location of objects in an orthogonal Euclidian co-ordinate space (Ellis et al.,1987)
• the use of cubes or other known 3D objects whose parallel surface form is known a priori in the perspective scene
• the use of stereo to provide a more accurate sense of depth
• the use of a compass rose, depicted in a perspective view and in a 2d map view to facilitate the calibration of angles in the former. (Ellis and Hacisalihzade,1990).
; multidirectional treadmills would be very useful for VE navigation but are presently unavailable (Boman, D.K.,1995) ; for research in this area see Slater et al., 1993.
; virtual tricorder for navigation see Wloka and Greenfield, 1995

f. Goal Driven

4.3 Manipulation

The following tables identify the design guidelines collected with regard to the manipulation of virtual objects. Sensory guidelines are not reported because assumed similar to those listed under viewing and exploration activities. Ergonomic principles are once again excluded because of their dependence on specific devices.

4.3.1 Cognitive Guidelines

REQUIREMENTS	GUIDELINES
1. Modes.1 Modes	
a. direct user interaction	; includes hand tracking, gesture recognition, pointing, gaze direction, etc.
b. physical devices	; includes buttons, sliders, dials, joysticks, steering wheels ; well suited for the fine positioning of an object ; often lack the natural mappings that facilitate an interaction task
c. virtual controls	; lack haptic feedback and the general difficulty of interacting with a virtual object
2. Object Selection	; requires some mechanism for the identification of the object to be selected ; some signal or command to indicate the actual act of selection (e.g. a button press, a gesture or voice command)
a. techniques	
i.local	; i) Localthe desired object is within reach and the user can interact with it directly. ; objects are chosen by moving a cursor (typically attached to the user's hand) until it is within the object's selection region (e.g. a minimal bounding box) (M.Mine, 1996)

REQUIREMENTS	GUIDELINES
ii. action-at-a-distance	; fall outside the immediate reach of the user ; can be accomplished using laser beams or spotlights that project out of the user's hand. and intersects with the objects in the virtual world; also some form of virtual cursor can be moved within the selection zone. (M.Mine, 1996)
iii. gaze directed	; based upon the user's current gaze direction; the user looks at an object to be selected and then indicates his selection via a selection signal (e.g. the user turning his head to line up a target object and a cursor floating in the middle of his/her field of view. (M.Mine, 1996)
iv. voice Inputiv) Voice Input	disadvantage: mental overload of having to remember the labels of all objects. disadvantage: increased clutter in the virtual world due to the need to label all objects. disadvantage: lack of reliability of current voice systems. (e.g. voice & pointing Bolt,80) (M.Mine, 1996)
v. list Selection	; virtual selection list advantage: the user does not have to see the object to select it (M.Mine, 1996)
3. Object Displacement	3 parameters that must be specified when manipulating an object: 1. change in position 2. change in orientation 3. centre of rotation
a. change in position/orientationi) Change in Position/Orientation	
i. hand-specified	; one of the most intuitive means available to change the position and orientation of a virtual object is to allow the user to "grab" it (typically signalled by a button press or a grab gesture, and more it like an object in the real-world. ; can move in a 1:1 correspondence with the user's hand or an amplification factor can be applied to the motion of the object. ; the magnitude of the amplification factor will result in fine or gross positioning of the object. ; the amplification factor can be based upon some ratio such as the speed of the user's hand motion (analogous to the control-to-display ratio used in mouse interaction, (see Foley, 90, p.351) (M.Mine, 1996)
ii. physical controls	; joystick, slider or dial -excellent for precise positioning of objects since each degree of freedom can be controlled separately but the lack of natural mappings can make it difficult to place an object at some arbitrary position and orientation.
iii. virtual controls	; sliders, buttons and dials in a virtual menu or toolbox can be used to position objects (e.g. a virtual bowling ball could be used to knock down virtual pins). ; virtual devices such as telerobotic arms, or virtual drone like a fling tugboat can be used to grab and position objects. (M.Mine, 1996)

REQUIREMENTS	GUIDELINES
b. center of rotation	; hand-centered rotation is the scheme most directly related to the manipulation of objects in the real world (M.Mine, 1996) ; typical alternatives include rotation about the centre of an object or rotation about some user specified centre of rotation (e.g. centre of rotation of a virtual door is the centre of the hinge axis). (M.Mine, 1996)
4. Scalingc. Scaling	; used to allow a user to view some small detail by scaling up the selected object or; to get a better global understanding of the environment by scaling it down and viewing it as a miniature model. (M.Mine, 1996) ; has 2 key parameters: centre of scaling and the scaling factor ; in uniform scaling, an object is scaled along all 3 dimensions equally.- where the main purpose is to allow the user to get a close look at some fine detail or to get a god's eye-view of the scene. (M.Mine, 1996) ; non-uniform scaling allows the user to control the scale of a selected object along each dimension separately.
a. center of scalingi) Center of Scaling	; the point which all objects move towards when you scale down and all points move away from when scaling up (e.g. hand-centred scaling, object-centred scaling or a user defined centre of scaling- via remote control)
b. scaling factor	
i. hand controlled	; movement of the hand up could specify a scale-up action, movement of the hand down could signify a scale-down action, and the range of the motion could determine the magnitude of the scaling action. ; advantage: effective for uniform scaling (M.Mine, 1996) ; affordances of handles which the user can interact with can be used to control the scaling of the selected object. This is similar to the handles found in most conventional drawing programs which the user "grabs" and moves to define the scale of the selected objects; typically the vertices of the selected objects bounding box. ; advantage of handles: effective for non-uniform scaling (M.Mine, 1996)
ii. physical controls	; pressing the button on an input device can indicate the start of a scale up or down action, with the duration of the button press controlling the magnitude of the scale. ; also some form of slider or dial can be used to specify the scaling factor. (M.Mine, 1996)

. Interactiona. Direct user interaction

Miscellaneous Guidelines
; it is essential to incorporate adequate feedback; (M.Mine, 1996)
;the user must know when he has chosen an object for selection (e.g. by highlighting the object or its bounding box
; that he/she has successfully performed a selection action (via audible and visual cues),
; he/she must be able to determine the current selection state of all objects (e.g. by using colour)
; the selection of small objects can be simplified by allowing the user to work at different scales. (M.Mine, 1996)
; at 6-10 frames per second, a "whole-hand-interface" for grasping and manipulating objects is natural and effective but at 3 frames per second is difficult or impossible to use.

Miscellaneous Guidelines
; the optimum value of the perceptual motor loop must be determined by task/goal analysis e.g. if the goal is to make the user match the velocity of a moving target -in order to capture a tumbling satellite, or to travel a long distance, a first-order rate is preferable.
e.g. if the goal is to make the user reach a short distance at a precisely fixed position or location, then a zero-order control is optimal (Wickens, 1986).
; allow a switch between control orders as the task demands.
; the optimum kind of feedback on the user, whether isometric (rigid and force sensitive) or isotonic (free moving and position sensitive) depends on the control order. (Buxton, 1990)
; Isometric control is optimal for first-order dynamics and isotonic control (e.g. a sensor that responds to the position and orientation of the hand) is optimum for zero-order dynamics, given a 6 degree of freedom hand manipulator used to manipulate the orientation and location of a cursor in virtual space (Zhai and Milgram, 1993)
; using an audible click to signify when the virtual user has successfully connected with a virtual object and haptic displays, in which force information is fed back to the user through a finger apparatus or hand-grip, has been found to give a two-fold improvement in user performance over purely visual displays. (Brooks et al.,1990)
; the force cue has been demonstrated to be more helpful in grasping virtual blocks than either stereoscopic viewing or variable viewpoints. (Brooks et al., 1990)
; haptic display by itself was found to be better than visual display alone for manipulating an object in a force field. In this study, chemists who were provided with force cues reported having a better feel of the force field at the active site of the molecule and a understanding for the docking behaviour of the various drugs that were tried. (Brooks et al.,1990)
; most applications use either instrumented gloves or handheld pointing devices that include a few buttons. e.g. CAVE
; operator fatigue is a major problem since the user must keep his/her arm raised for long periods of time. (Boman, D.K.,1995)
; manipulating devices such as joysticks reduce the problem of fatigue but do not allow direct manipulation of virtual objects. Object position is controlled by a 3D cursor. (Boman, D.K.,1995)
; isotonic position control (e.g. glove) is the most "direct" interface. The major problem is fatigue. Limited output range (therefore clutch needed) is also a disadvantage. This type of devices are good for VR games, users can walk up and play without much learning. Isotonic device = when the physical resistance of the device is zero. Shumin Zhai, 1995, ETV Lab ; isometric rate control (e.g. space ball) is less fatiguing. Major problem is lack of feedback (proprioception). It takes a while for the user to acquire the skill. Once they learned, it works reasonably well for simple tasks (e.g. docking). Shumin Zhai, 19 95, ETV Lab
; isotonic devices (e.g. glove, mouse) work better in position control mode (limited output range) and isotonic devices (is more compatible with position control mode.) Shumin Zhai, 1995, ETV Lab
; an improvement over isometric rate control is ELASTIC rate control. It offers better proprioception and therefore easier to learn. The key is once again the combination of rate control with the self-centered property of elastic controller. Elastic rate control will be good for applications like CAD and data visualisation in which the user may work for hours. Elastic device = when the resistant force is proportional to the displacement of the handle. Shumin Zhai, 1995, ETV Lab
; see MacKenzie and Iberall (1994)
; see Sivak and MacKenzie (1992).

ISSUES
; the absence of constraints is one of the biggest problems in the manipulation of virtual objects. Without constraints, users are restricted to gross interactions and are unable to perform precise manipulation. (M.Mine, 1996)
; 2 possible constraints: virtual and physical. ; Virtual constraints are those in which extraneous degrees of freedom in the user's input are ignored; Physical e.g. a desktop on which the user must slide the input device. (Airey 90) (M.Mine, 1996)
; constraints should be overridable with resets e.g. picking up the mouse for out of plane translations and then replacing it on the desktop (M.Mine, 1996)

4.4 Menu Usage

The following table identifies the design guidelines collected with regard to menu usage.

REQUIREMENTS	GUIDELINES
1. Virtual Menus	; the primary difference between various menu schemes is the dimensionality of the selection mechanism - the number of dimensions specified by the user to select different menu options. ; one-dimensional menus are ideal for the selection of a single item from a limited set of options. (M.Mine, 1996) ; avoid 3-dimensional interaction at all costs with conventional menus (such as pull down menus and dialogue boxes. (M.Mine, 1996) ; principles of virtual menu design are directly related to the guiding principles of 2-D user interface design: consistency, feedback, natural mappings, good visibility.. ; placement of the virtual menu in the virtual environment. Options include: floating in space- whenever the user wishes to move the menu, he/she must grab it, and move to a new location (M.Mine, 1996). disadvantage: easy to lose track of the menus location in space disadvantage: poor image quality of HMDs makes it impossible to discern between choices. disadvantage: noise and distortion in tracking make it difficult to interact with virtual widgets.d. Menu and widget interaction

5. Conclusion

Virtual environments promise to provide the user with the experience of a life-like yet computer generated world. At the heart of the promise held by the new technology lies the identification and design of the life-like qualities that must be part of the virtual world in order for the user to believe in a new reality. In order to contribute to the conceptual framework being developed in the area, this paper reports the results of a literature survey on the applications and activities, design requirements and guidelines of relevance to life-like virtual environments. The first part of the report briefly introduced some of the applications for which virtual environments have as yet been intended: on-line performance, off-line training and rehearsal, on-line comprehension and off-line learning. The second section described the key activities performed within the applications: viewing, exploration and the manipulation of virtual objects. The third section of the document introduced a framework of design requirements (Parent, 1998). This framework is believed to form the basis of the creation of life-like virtual environments. The framework is the result of an earlier review of the variables assumed to explain the sense of presence experienced in a virtual environment. This review was based on issues of the journal Presence: Teleoperators and Virtual Environments dating from 1991 to 1996. The last section of the report lists design guidelines organized according to the key activities and requirements the guidelines aim to support. Given the rapid evolution of the field, this document cannot presume to offer an exhaustive survey of the literature but hopes to provide designers of life-like virtual environments with a useful frame of reference.

The creation of a virtual environment rests on an analysis of the sensory, cognitive and ergonomic requirements of likely importance to a given application, be it the performance of a task or the exploration of a pleasurable space. The more informed our analysis, the better our design choices are likely to be.

Sensory requirements (visual, auditory and haptic) determine good hardware designs and/or the most appropriate display one's purse and current technology can offer. A better understanding of human sensory mechanisms makes it possible to design and implement (Zelter, 1992), or simply buy and use more effective devices. With regard to viewing, empirical studies are required to determine which cues to include so that users may best discriminate objects, colors, shapes, details or sizes relevant to a particular class of applications, such as military target training. It is important to develop a taxonomy of tasks in terms of sensory input. For a given task, which sensory cues are necessary and which are accessory but improve performance (Zelter, 1992)? Other unknowns in need of guidelines include: What is the nature and role of background noise given a particular class of activities? What cues are needed to avoid simulator sickness? What is the best function to use between a change in the user's orientation and an update of the display? How can time delay problems be addressed (e.g. maintain low gain, reduced imagery). Is stereo viewing required for the user to feel present and for the environment to appear life-like (Sheridan, 1992b)?

With regard to exploration, research is needed to determine the perceptual cues most relevant to the judgment of motion. How can regularly spaced texture and level surfaces best support the perception of gradients and slant? Other research issues need investigate: Which perceptual and auditory cues best indicate a collision with the user given a particular set of objects? How are sounds best distributed given a sequence of events? What is the most efficient acceleration function? With regard to manipulation, studies are required to determine the perceptual cues most relevant to the judgment of distance and object motion. What cues best support the perception of object collision ? Other issues also include: Which auditory cues best convey collision between the particular objects of a virtual world? What is the most appropriate function to use between the user's device or orientation and a virtual object's movement?

Cognitive requirements determine the most appropriate scene content and structure, and most efficient procedures to view, explore or manipulate the virtual world. Cognitive unknowns in need of guidelines include: What level of scene realism is appropriate (Sheridan, 1992b)? What features of reality are essential or desirable to a specific set of activities? Is greater realism related to greater levels of user satisfaction? To better performance? To better training? When? What procedures allow the most efficient inspection of art work in a virtual museum? In a gold mine? Which procedures are easiest to remember? What number of degrees of freedom are desirable for novice Vs experienced users exploring a virtual space? What speed is most natural? What procedure most naturally allows easy and transparent travel? What procedure most naturally allows easy and transparent manipulation? What maneuvers are most natural? Given a set of activities, what mode of feedback is best? Sound? Image? Text? Or all three?

Ergonomic requirements determine the most physically comfortable and efficient devices to use in order to view and explore a virtual world or manipulate virtual objects. Issues to be addressed include: What devices most naturally convey a sense of walking or running? What devices most comfortably allow the manipulation of objects? What devices best simulate haptic feedback? What is the most ergonomic position a user may take, given a specific set of activities?

Tools and metrics are needed to support task analyses and usability evaluations. Comparative studies are needed to determine better displays, better devices, better and most cost effective performance and training approaches.

Acknowledgements

I am grateful to Louis Trudel for helping to collect the research material for this report and to my colleagues for comments on an earlier draft.

ReferencesReferences

Airey J. M., Rohlf, J.H., Brooks, F. (1990). Towards image realism with interactive update rates in complex virtual building environments. *Computer Graphics*, 24(2), pp. 41-50.

Aretz,A.J.(1991). The design of electronic map displays. *Human Factors*, 33, pp.85-101.

Ballantyne J., Greenspan M., and Lipsett M.(1997). Virtual environments for remote operations, *Proceedings of the ANS 7th Topical Meeting on Robotics and Remote Systems*, Augusta, Georgia, April 27 - May 1. NRC 40190.

Barfield, W., Sanford, J., and Foley, J. (1988). The mental rotation and perceived realism of computer-generated three-dimensional images. *Int. J. Man-Machine Studies*, 29, 669-84.

Barfield,W., Hendrix, C., Bjorneseth, O., Kaczmarek, K.A., Lotens, W. (1995). Comparison of human sensory capabilities with technical specifications of virtual environment equipment. *Presence*, 4(4), pp.329-356.

Baum, D.R. (1992). Virtual training devices: illusion or reality? *Proc. of the 14th Annual Interservice/Industry Training Systems and Education Conference*, Nov.

Boff, K.R., & Lincoln, J.E. (1988). *Engineering data compendium - Human perception and performance*, Vol. I, Sensory process and perception. New York: John Wiley.

Bolt, R. (1980). Put-that-there, *ACM Computer Graphics: Proceedings of SIGGRAPH 80*, pp. 262-270.

Boman, D.K. (1995). International survey: virtual-environment research, *Computer*, June 1995, pp. 57-65.

Bostrom M. et al., (1993). Design of an interactive lumbar puncture simulator with tactile feedback, *Proc. of IEEE Virtual Reality Annual Int. Symp. (VRAIS),* September 18-21, Seattle, WA, pp.280-6.

Brooks, F.P.(1988) Grasping reality through illusion: Interactive graphics serving science. *Proceedings of CHI'88*, May 15-19, Washington, D.C, pp.1-11.

Brooks F.P. et al.(1990). Project GROPE - haptic display for scientific visualisation. Proceedings of SIGGRAPH '90 August 6-10, Dallas, TX, in *Computer Graphics*, 24, pp.177-85.

Brooks F.P. (1993) Keynote address presented at the IEEE Symposium on Visualisation, October 27-29, San Jose, CA.

Bukowski, R., Séquin, C.H. (1997). Interactive simulation of fire in virtual building environments, *SIGGRAPH 97 Conference Proceedings Annual Conference Series*, pp. 35-44.

Burdea, G. and Coiffet, P. (1994). *Virtual reality technology*, New York, N.Y: John Wiley and Sons.

Burdea, G. Richard, P., Coiffet P. (1996). Multimodal virtual reality: input-output devices, system integration, and human hactors. *International Journal of Human-Computer Interaction*, 8(1), pp. 5-24.

Burke, R. R. (1996). Virtual shoppings breakthrough in marketing research. *Harvard Business Review*, March-April, pp.120-131.

Buxton, W. (1993). HCI and the inadequacies of direct manipulation systems. *SIGCHI Bulletin*, 25(1), pp.21-22.

Chapman D. and Ware C. (1992). Manipulating the future: predictor based feedback for velocity control in virtual environment navigation. *Computer Graphics 1992 Symposium on Interactive 3D Graphics*, 25(2), pp. 63-66.

Clapp, R.E. (1985a). Problems of the visual display in flight simulation. in image quality: an overview. *SPIE Proceedings Series 549*, pp. 64-70..

Darken, R.P. Sibert, J.L (1993). A toolset for navigation in virtual environments. *Proceedings of ACM User Interface Software & Technology*, 1993, pp.157-165.

Deering, M. (1993). Making virtual reality more real: experience with the virtual portal, *Graphics Interface '93*, pp.219-226.

Deering, M.F. (1993). Explorations of display interfaces for virtual reality. *Proceedings of the Virtual Reality Annual International Symposium VRAIS'93*, pp. 141-147.

Ellis, S.R. and Hacisalihzade, S.S.(1990). Symbolic enhancement of perspective displays, *Proc. of the 34th Annual meeting of the Human Factors Society*, Santa Monica, CA: Human Factors Society, pp. 1465-9.

Ellis, S.R., McGreevy, M.W., and Hitchcock, R.J. (1987). Perspective traffic display format and airline pilot traffic avoidance, *Human Factors*, 29, pp. 371-82.

Ellis, S.R., Tharp,G.K. Grunwald, A.J., and Smith, S. (1991). Exocentric judgements in real environments and stereoscopic displays. *Proc. of the 35th Annual Meeting of the Human Factors Society*, Santa Monica, CA: Human Factors Society, pp.1442-6.

Flach, J.M., Hagen,B.A., O'Brian,D., and Olson,W.A..(1990). Alternative displays for discrete movement control, *Human Factors*, 32, pp.685-96.

Galyean T.A. (1995). Guided navigation of virtual environments. *1995 Symposium on Interactive 3D Graphics*, pp. 103-104.

Geissen S.(1996). Driving to new heights in the auto industry. *Iris Universe*, Fall 37, pp. 58-60.

Glanz K., Durlach, N.I. Barnett, R.C., Aviles, W.A. (1997). Virtual reality (VR) and psychotherapy: opportunities and challenges, *Presence*, (6) 1, pp. 87-105.

Golovchinsky, G.and Chignell, M. (1993). Queries-r-links:graphical markup for text navigation, *Interchi '93*, pp. 454-60.

Green, M., Shaw, C. and Pausch, R. (1992). Virtual reality and highly interactive three dimensional user interfaces, *CHI '92 Tutorial Notes*, New York: ACM.

Grunwald, A. J. and Ellis (1993). Visual display aid for orbital manoeuvring: experimental evaluation. *J. Guid. Contr.Dyn.*, 16, pp. 145-50.

Harrington, T.L., Harrington, M.K., Quon, D., Atkinson, R. Cairns, R., & Kline. (1985). Perception of orientation of motion as affected by change in divergence of texture, change in size and velocity. *Perceptual Motor Skills*, 61, pp. 875-886.

Harwood, K. and Wickens, C.D.(1991). Frames of Rreference for helicopter electronic maps:the relevance of space cognition and componential analysis,. *Int. J. Aviation Psychol.*,1, pp.5-23.

Heim M.(1995). VR for real-world ecology, *Virtual World Special Report*, September/October, pp.50-57.

Henry, D. and Furness, T. (1993). Spatial perception in spatial environments. *Proc. IEEE Virtual Reality Annual Int. Symp. (VRAIS),* September 18-21, Seattle, WA, pp. 33-40.

Hochberg, J. (1986). Representation of motion and space in video and cinematic displays. In K.R. Boff, L. Kaufmann & J.P. Thomas (Eds), *Handbook of perception and human performance (Vol.1).* New York: John Wiley.

Hofer, E.F. and Palen, L.A.(1993). Flight deck information managements:an experimental study of functional integration of approach data, *Proc. of the 7th Int. Symp. on Aviation Psychology*, Columbus, OH: Dept. of Aviation, Ohio State University.

Holloway, R. & Lastra, A. (1996). Excepts from virtual environments: A survey of the technology, *SIGGRAPH Tutorial.*

Hood, D. C., & Finkelstein, M.A. (1986b). Sensitivity to light. In K.P. Boff, L. Kaufman, & J.P., Thomas (Eds), *Handbook of perception and human performance (Vol. 1, chap. 5).* New York: John Wiley.

Jacoby, R.H. and Ellis,S.R.(1992). Using virtual menus in a virtual environment. *Proc.of the SPIE Technical Conference*, 1666, San Jose, CA.

Kalawsky, R.S. (1993). *The science of virtual reality and virtual environments.* Wokingham, UK: Addison Wesley.

Kelly, D.H. (1961). Visual response to time dependent stimuli I: amplitude sensitivity measurements. *Journal Optical Society America*, 51, pp. 422-429.

Kennedy, R.S., Lane, N.E., Berbaum, K.S. & Lilienthal (1993). A simulator sickness questionnaire (SSQ): A method for quantifying simulator sickness. *International Journal of Aviation Psychology*, 3(3), pp. 203-220.

Kennedy, R.S. and Stanney, K.M. (1996). Postural instability induced by virtual reality exposure: development of a certification protocol. *International Journal of Human-Computer Interaction* Jan.-March 8(1), pp. 25-47.

King, C.F. (1997). Medical volume visualization: the doorway to the future. *Iris Universe*, 40, Summer, pp.40-48.

Kuchar, J.K. and Hansman, R.J. (1993). An exploratory study of plan-view terrain displays for air-carrier operations. *Int. J. Aviation Psychol.*,3, pp. 39-54.

Lampton, D.R., Kolasinski, E.M., Knerr, B.W., Bliss, J.P., Bailey, J.H. and Witmer, B.G. (1994). Side effects and after effects of immersion in virtual reality environments. *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting*, pp. 1154-1157.

Langlois, G. (1996). La science de l'illusion: La réalité virtuelle. *Interface*, 17(6), pp. 40-49.

Larish, J.F. and Flach, M. J. (1990). Sources of optical information useful for perception of speed of rectilinear self-motion. *J. Exp. Psychology.: Human Percept.Perform.*, 16, pp. 221-37.

Lee, J.D. and Moray, N. (1992). Trust, control strategies and allocation of function in human-machine systems. *Ergonomics*, 35, pp.1243-70.

Leibowitz, H.A. (1952). The effects of pupil size on visual acuity for photometrically equated test fields at various levels of luminance. *Journal of the Optical Society of America*, 42, pp. 416-422.

Levine, M.D. (1985). *Vision in man and machine.* McGraw-Hill. New York.

Lintern, G.D.C., Thomley-Yates, K.E., Nelson, B.E., and Roscoe, S.N. (1987). Content, variety, and augmentation of simulated scenes for teaching air-to-ground attack. *Human Factors*, 29, pp. 45-59.

Lintern, G. (1991). An informational perspective on skill transfer in human-machine systems. *Human Factors*, 33, pp. 251-66.

Mackinlay, J. D., Card, S. K. and Robertson, G. G.(1990). Rapid controlled movement through a virtual 3D workspace. *ACM Computer Graphics*, 24(4), August 1990.

MacKenzie, I.S. (1995). Input devices and interaction techniques for advanced computing. In Barfield W. and Furness T.A (Eds), *Virtual environments and advanced interface design*, New York, Oxford University Press, pp. 437-470.

MacKenzie, C.L. and Iberall, T. (1994). *The grasping hand.* Amsterdam. North-Holland (Elsevier Science).

McGovern, D.E. (1991) Experience and results in teleoperation of land vehicles. In S. R. Ellis et al., (Eds), Pictorial communication in virtual and real environments, London:Taylor and Francis, pp.182-95.

McGreevy, M.W. and Ellis, S.R. (1986). The effect of perspective geometry on judged direction in spatial information instruments, *Human factors*, 28, pp. 439-56.

McKinnon,G.M. and Kruk,R.V.(1991). Multi-axis control in telemanipulation and vehicle guidance. In S.R. Ellis et al., (Eds), *Pictorial communication in virtual and real environments*, London:Taylor and Francis, pp.247-64.

Mercurio, P. J. and Erickson, T. D. (1990). Interactive scientific visualisation: an assessment of a virtual reality system, *Proc. of INTERACT.*

Mine, M. (1996). *SIGGRAPH '96 Tutorial Notes*.

Mykitshyn, M. and Hansman, R.J.(1993). Electronic instrument approach plates:the effect of decluttering on flight crew performance. *Proc. of the 7th Int. Symp. on Aviation Psychology.*, Columbus, OH: Dept. of Aviation, Ohio State University.

Newby,G.(1992). An investigation of the role of navigation for information retrieval, *Proc. of ASIS*.

North, M.M., North, S.M., Coble, J.R. (1997). Virtual environments psychotherapy: a case study of fear of flying disorder, *Presence*, (6)1, pp. 127-132.

Oman, C.M.(1991). Sensory conflict in motion sickness: an observer theory approach. In S.R. Ellis et al., (Eds), *Pictorial communication in virtual and real environments*, London: Taylor and Francis, pp. 362-76.

Orr, J. (1997). The virtual plant. *Iris Universe*, 41, Fall, pp. 36-42.

Padmos, P. and Milders, M. (1992). Quality criteria for simulator images: a literature review. *Human Factors*, 34(6), pp.727-748.

Parent, A. (1998c). Designing life-like virtual environments, submitted to *Presence: Teleoperators and Virtual Environments.*

Parent, A. (1998b). *A virtual environment task analysis tool for the creation and evaluation of virtual art exhibits*. Technical Report, ERB-1056, NRC-41557, in press.

Pausch, R. Burnette T., Brockway D. and Weiblen M.E. (1995). Navigation and locomotion in virtual worlds via flight Into hand-held miniatures. *SIGGRAPH 95 Conference Proceedings*, pp. 399-400.

Perrone, J.A. (1982). Visual slant underestimation: a general model. *Perception*,11, pp. 621-54.

Potter, C.D. (1996). Digital mock-up tools add value to assemblies. *Computer Graphics World*, November, pp. 9-13.

Prazdny, K. (1986). Three-dimensional structure from long-range apparent motion. *Perception*, 15, pp. 619-25.

Regan, D. & Beverly, K.I. (1978). Looming detectors in the human visual pathway. *Vision Research*,18, pp. 415-421.

Regan, D. & Beverly, K.I. (1983). Visual fields for frontal plane motion and for changing size. *Vision Research*, 23, pp. 673-676.

Reichlen, B.A.(1993). Sparchair: a one hundred million pixel display, *Proc. IEEE Virtual Reality Annual Int. Symp. (VRAIS*), September 18-21, Seattle,WA, pp.19-1-19-46.

Roehl, B. (1997). Virtual archeology. *Iris Universe*, 40, Summer, pp. 28-35.

Rolfe, J.M. & Staples, K. & J. (1986). *Flight simulation.* Cambridge, England:Cambridge University Press.

Rowell, A. (1997). The design benefits of group VR, *Computer Graphics World*, February, pp. 21-28.

Sarter, N. and Woods, D.D.(1991). Situation awareness: a critical but ill-defined phenomenon. *Int.J. Aviation Psychology.*, 1, pp. 45-58.

Sarter, N. and Woods, D.D.(1994). Pilot interaction with cockpit automation II.: an experimental study of of pilots, model and awareness of the flight management system (FMS). *Int. J. Aviation Psychol.*, 4(1), pp. 1-28.

Sheridan, T.B. (1992). *Telerobotics, automation and human supervisory control*, Cambridge, MA:MIT Press.

Sivak, B. and MacKenzie, C.L. (1992). The contributions of peripheral vision and central vision to prehension. In. D. Elliot and L. Proteau (Eds.), *Vision and motor control.* Amsterdam: North-Holland, pp. 233-259.

Slater, M., Steed A., and Usoh M. (1993). The virtual treadmill: a naturalistic method for navigation in immersive virtual environments. *First Eurographics Workshop on Virtual Environments*, pp. 71-83.

Surdick, R.T., Davis, E.T., King, R.A., Corso, G.M., Shapiro, A., Hodges, L. Elliot, K. (1994). Relevant cues for the visual perception of depth: is where you see it where it is? *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting*, pp.1305-1309.

Takahashi, T., and Kishino, F. (1991). Hand gesture coding based based on experiments using a hand gesture interface device. *SIGCHI Bull.,* 23, pp. 67-73.

Tversky, B. (1991). Distortions in memory for visual displays. In S.R. Ellis et al., (Eds), *Pictorial communication in virtual and real environments*, London:Taylor and Francis, pp.61-75.

Ware, C. and Jessome, D.R. (1988). Using the bat: a six dimensional mouse for object placement, *IEEE Computer Graphics Appl.*, 8, pp. 65-70.

Ware, C. and Osborne, S. (1990). Exploration and virtual camera control in virtual three-dimensional environments, Proc. of the 1990 Workshop on Interactive 3D Graphics, March 25-28, Snowbird, UT, in *Computer Graphics*, 24, pp. 175-83.

Warren, R. and Wertheim, A.H. (Eds) (1990). *Perception and control of self-motion.* Hillsdale, NJ: Erlbaum.

Wickens, C.D. (1986). The effects of control dynamics on performance. In K. Boff et al., (Eds*), Handbook of perception and performance, vol. II*, New York: Wiley, pp.39-1-39-60.

Wickens, C.D.(1992a). Virtual reality and education. *Proc. of the IEEE Int.Conf.on Systems, Man, and Cybernetics*, 1, New York:IEEE, pp.842-7.

Wickens, C.D. and Backer, P. (1995). Cognitive issues in virtual reality. In Barfield W. and Furness T.A (Eds), *Virtual environments and advanced interface design*, New York, Oxford University Press, pp. 515-541.

Walraven, J.(1990). Color basics for the display designer. In *Coulour in electronic displays*, Tech. Report AC/243 Panel 8, RSG 13 TR/5). Brussels: Defence Research group, NATO Headquarters.

Witmer, B., Bailey, J. Knerr, B.W. (1995). *Training dismounted soldiers in virtual environments: route leraning and transfer*, Technical Report 1022, U.S. Army Research Institute for the Behavioral and Social Sciences.

Wloka M.M. and Greenfield E. (1995). *The virtual tricorder.* Technical Report CS-95-05. Brown University.

Yallow, E. (1980). *Individual differences in learning from verbal and figural materials.* Aptitudes Research Project Technical Report No. 13, Palo Alto, CA: School of Education, Stanford University.

Yan, J.K. (1985). Advances in computer-generated imagery for flight simulation. *IEEE Transactions on Computer Graphics and Applications*, 5(8), pp. 37-51.

Zhai, S. and Milgram, P. (1993). Human Performance evaluation of manipulation schemes in virtual environments. *Proc. IEEE Virtual Reality Annual Int. Symp. (VRAIS*), September, Seattle, WA.