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COMPARATIVE ANALYSIS OF VIRTUAL 3-D VISUAL DISPLAY SYSTEMS -- CONTRIBUTIONS TO CROSS-FUNCTIONAL TEAM COLLABORATION IN A PRODUCT DESIGN REVIEW ENVIRONMENT

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ABSTRACT

The application of virtual environments to the product design process has intrigued researchers and practitioners in industry, government, and academia. Using virtual environment tools, design teams can evaluate future designs in synthetic environments before building physical prototypes, thus creating a unique capability that reduces cost, shrinks time to market, and improves product quality. However, a proliferation of visual display devices used to generate 3-D stereoscopic information is forcing organizations to decide which tools to use to enhance product design activities.

This study evaluated, through comparative empirical testing and data analysis, how several commercially-available virtual 3-D visual display systems contribute to cross-functional team collaboration in a product design review. A 4x4 Graeco-Latin Square experimental design assessed the value of a Helmet Mounted Display, a Binocular Omni-Orientation Monitor, stereoscopic glasses with monitor, and traditional monoscopic CRT monitor technologies for use in a concept design review process. The experiment was conducted using personnel from several functional elements of the U. S. Army Tank-automotive and Armaments Command. Team performance measures, questionnaires, and observer evaluation aided the assessment of tested display systems.

Empirical evaluations revealed that design teams detected more errors when using the stereoscopic glasses and monoscopic CRT monitor systems, detected errors fastest when using the HMD system, and found no differences between the display

systems for the time to resolve design problems. Subjective data were used to evaluate participant perceptions of each technology and user preferences.

Based on these findings, the best method for integrating virtual 3-D displays is a combined technology approach. It begins with clearly defined design review objectives, individual member evaluation of the proposed design using a HMD device, and team evaluation using stereoscopic glasses to stimulate cross-discussion and identification of design errors. Lastly, natural face-to-face communication should be used for teams to resolve design problems. This study's results strengthen the premise that virtual environments improve the effectiveness and efficiency of the design review process. They also lead to a better understanding of the trade-off required when selecting a visual display system and provide insight into future virtual environment interface designs.

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CHAPTER 1

INTRODUCTION

The traditional product development process can be described as a sequential. linear process. Phases include concept development, system-level design, detail design. testing and refinement, and production ramp-up (Ulrich & Eppinger, 1995). Shu and Flowers (1994) characterize this activity as a sequence of "throw it over the wall" processes where functional groups make contributions to a project sometimes independent of other elements. As a result, critical decisions that can significantly impact overall product design and development are frequently made without regard to the effect on and consequences to other functional elements.

Some process improvements are evolving. The need to shorten the development cycle (Cooper & Kleinshmidt, 1994; Cordero, 1991; Iansiti, 1993; Vesey, 1991), to achieve higher quality (Ali, Krapfel, & LaBahn, 1995; Cordero, 1991), and to solicit direct customer feedback (Larson-Mogal, 1994) have stimulated the need for changes to traditional product development methods. As a result, numerous organizations are investigating the use of concurrent cross-functional teams coupled with emerging computer technologies to create more robust, collaborative virtual design environments.

This chapter provides an overview of a contemporary virtual environment-based design review process; a transition in methodologies. Also it addresses the need for the research study, identifies statements of problems, and defines terms used in the research.

Overview of the Contemporary Product Design Environment

In the past, products were designed on drawing boards using pencils and two-dimensional (2-D) paper drawings. The product design process, using these drawings, involved serial reviews by various functional representatives, and manual drawing revisions -- a very time intensive process. Once designs were complete, product manufacturers often created physical or functional prototypes so design teams (and maybe their customers) could see, touch, and generally experience a product (Larson-Mogal, 1994).

The onset of computer technology has had a positive impact on the product design process, which has caused a paradigm shift in the way products are designed. Today, the process is initiated by developing 2-D and three-dimensional (3-D) solid models of alternative designs on Computer Aided Design (CAD) stations -- sometimes saving up to 70% of total manual design time (Barfield, Chang, Majchrzak, Eberts, & Salvendy, 1987). This technology has provided expanded capabilities for the development and timely revision of new product designs. However, while these enhanced the productivity of a single designer, their use is not very effective in a collaborative, concurrent design or team review environment. To overcome this limitation, new tools and approaches are needed.

Emerging technologies that have the potential to significantly impact the product design process are virtual environment (VE) systems. By their nature, these systems are capable of stimulating the human senses of sight, sound, and touch. They allow a person to experience life-like domains and objects that appear to be real but only exist in a computer-based environment. In the eyes of a designer, immersion in such a near-realistic environment can provide visualization of the final product from various perspectives. Figure 1 depicts the described evolution of product design capabilities. As is shown, design has evolved from traditional 2-D hand drawings to 3-D CAD on flat screen computer CRT monitors. Beyond flat screen technologies are individual and collaborative stereoscopic VE systems. The use of VEs is projected to be the next major step in the product design evolution and that movement will incorporate collaborative design environments (Gadh, 1994; Gottschalk & Machlis, 1994; Kalawsky, 1993; Kitfield, 1994; Larson-Mogal, 1994; Pratt, 1994).

Potential benefits exist in VEs capabilities to allow product design team members to simultaneously view a virtual product, and jointly evaluate design issues, ideas, and parameters from various viewpoints. These visualization techniques have the potential to clarify information and enhance collaboration between representatives within an organization at various levels to make more informed decisions which can result in lower final development costs.

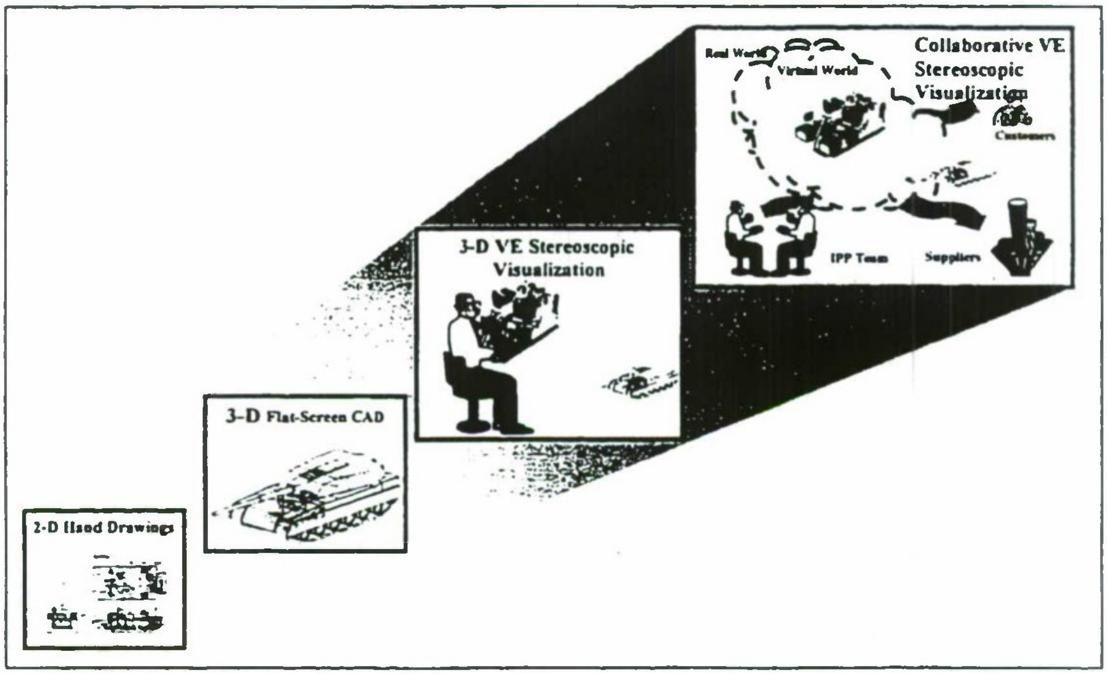

Figure 1. Design Evolution

Some work has explored the benefits of 3-D displays for a variety of applications. Evaluating pilot operations, Sanders and McCormick (1993) found that pilot decision times were faster when using 3-D displays. In another study, Wichansky (1991) concluded that 3-D stereo views are better suited for applications involving viewing of complex and abstract objects. Similarly, McWhorter, Hodges, and Rodriguez (1991) determined that 3-D stereoscopic displays were superior for visual search tasks and for spatial judgment tasks. Wickens (1992) contends that 3-D displays should be used to represent 3-D information because they are more compatible with the operator's mental model of the 3-D world then traditional 2-D displays.

There are, however, several important challenges that exist in integrating VE visualization technologies into the product design and evaluation process. Issues include determining appropriate 3-D visual display devices and managing the simultaneous use of these technologies by multi-functional design teams.

Need for the Study

Global competition, shortened product lives, rapid technology growth, declining resources, flattening of organizations, downsizing, loss of valued employees due to attrition, and shrinking budgets are forcing organizations to do more with less. Improved product design processes are required if organizations expect the same or improved effectiveness and efficiency from current product design and development practices. While product development organizations recognize the need to improve the product design process and realize that cross-functional collaboration and computer technology are keys to achieving that goal, they do not fully understand how to integrate the two into a single collaborative virtual design environment. There is a need to gain insight into these tools and processes in order to develop improved design practices.

Decisions made in the early stages of product design effect time to market and product cost. A National Research Council report on National Design Strategy concluded that 85% of product development costs are determined before the product design is released to manufacturing (Will, 1991). For this reason alone, there is a need to develop tools that will help organizations make better, more informed decisions early in the design process thereby reducing cost, shrinking development time, and eliminating unnecessary risks associated with traditional product development methods.

Many in the VE community believe that the use of a collaborative virtual design environment will have a positive impact on the effectiveness and efficiency of the product design process (Ashley, 1995; Hedberg, 1994; Keebler, 1993; National Research Council, 1995). They believe that collaborative virtual environments have the capability to promote communication interchanges across all individual organizational functions. The voice of the virtual design community, as articulated by Ellis (1997), echoes the belief that VEs are powerful communication tools. Indicating that enhanced visualization has solved some fundamental communication problems for General Motors design teams, which included people with diverse backgrounds and skills -- designers, engineers, manufacturing engineers. Ellis (1997) quotes an interview with Randy Smith of GM's R & D Center, where he said:

> It turns out that in many cases these people don't understand a simple model, like a drawing on the wall, in the same way and they may not all understand a color picture on a flat graphics tube in the same way. There's still some subjective interpretation. But give them a full-scale model with depth that is as close as we get can get these days to physical parts, and they can all communicate about it in the same way; they all understand it immediately. So this becomes a very powerful communication tool. (p. 32)

Enhanced visualization allows design team members to simultaneously enter a virtual product design world and jointly evaluate design issues, ideas, and parameters -- each from their own experience, perspective, viewpoint, and functional responsibility.

The functionalism of visualization is supported by Barkan and Iansiti (1993) and Horton and Radcliffe (1995) who believe that a VE environment would offer a common focus for multidisciplinary (managerial, technical. marketing, and manufacturing) teams to resolve design issues by sharpening their viewpoints in support of collaborative design evaluation. However, there is a need to empirically evaluate the use of VE technologies on the collaborative design review process.

In summary, there is a need to investigate the value of various commercial visual display systems combined with cross-functional team collaboration in the product design review environment. The reasons are that this marriage has potential to improve:

1. Product design efficiency by decreasing the design cycle time,

2. Product design effectiveness by improving design quality, and

3. Multi-functional team design by providing a mechanism for enhanced communication and better decision making.

Statement of the Problem

The application of emerging VE technologies, to the product design and development process has intrigued many researchers and practitioners in industry, government, and academia. Using VE tools, design teams can assemble to evaluate future designs all in a synthetic environment before any physical prototypes are built. This technology creates a unique capability with the potential to reduce cost, shrink time to market, and improve overall product quality. However, a proliferation of visual display devices in the commercial market, used to generate 3-D stereoscopic information, has provided an incentive for organizations to make decisions about which tools to use to optimize their design processes. Today, most organizations do not have the resources to conduct a comparative study of these 3-D visual display devices to make appropriate trade-off determinations. As a result, their decisions are often arbitrary.

The purpose of this study was to evaluate, through comparative empirical testing and data analysis, how several commercially-available virtual 3-D visual display systems contribute to cross-functional team collaboration in a product design review environment. Several product design issues that need to be addressed are: Which visual display devices help design teams detect more design problems? Which help design teams find these design problems faster? Which visual display technologies assist in resolving design problems? Do these tools actually assist the design team in accomplishing improved design reviews, thereby, yielding better quality solutions and products? Does this environment improve communication and reduce the number of design iterations and changes? Is the overall productivity of the design team enhanced? Which technologies are best under certain circumstances?

Definitions are presented to facilitate reader comprehension of words and phrases used throughout the study. Appendix A offers a list of abbreviations and acronyms.

Definitions of Terms

Asynchronous. Mode of interaction where things occur at different times.

Binocular Omni-Orientation Monitor (BOOM). A viewing device mounted to a stand that allows movement with 6 degrees of freedom. Using mechanical tracking, the stand sends position and orientation information to the computing system, and the user, who holds the viewer to his face, can use it to view a 3-D environment. (Stuart, 1996, p. 237)

Cave Automatic Virtual Environment (CAVE). A projection based virtual environment system that surrounds the user with four screens. Wearing stereoscopic shutter glasses the viewer perceives 3-D images.

Cathode Ray Tube (CRT). The most common display technology used in computer monitors. The technology uses a sealed glass vacuum tube that contains an electron beam emitter, or gun, a deflection yoke that focuses the beam, and a phosphor-coated screen that glows for a fraction of a second when struck by a beam. (Peddie, 1994, p. 230)

Color Monitor. Color monitors use three primary additive colors: red, green, and blue. The final screen color on the video screen is created by the combination of these primaries. The strength of the beam, as it strikes the phosphor, causes it to illuminate with brightness to match. The combination of all three phosphors creates color in a picture element (pixel). (Peddie, 1994, p. 231)

Computer Supported Cooperative Work (CSCW). Collaborative work between individuals that is carried out with the support of communications and computing technology (Stuart, 1996, p. 237). It is a multi-disciplinary field of study that performs research in the area of automation on group activities.

Computer Aided Design (CAD). A CAD system is a precision drawing tool that speeds up the design process by automating the work of a designer.

Cycle Time. The interval from the start of product definition until that product is available for purchase by consumers. (Sansone & Singer, 1992)

Field of View (FOV). The part of space you can see immediately, without moving your head or your eyes. In terms of a visual display, the FOV is the visual angle subtended by the display (Stuart, 1996, p. 239).

Haptic. Refers to all the physical sensors that generate a sense of touch at skin level and force feedback information for our muscle and joints. (Pimentel & Teixeira, 1995, p. 411)

Head Mounted Display (HMD). A headpiece or head-held brace with viewing or optical devices located or suspended in front of the user's eyes. These optical devices generate images seen by the wearer as 3-D. (Larijani, 1994).

Latency. The total delay time between a user action and the system responding to this action. This is sometimes referred to as lag.

Liquid Crystal Display (LCD). LCD screens are made up of liquid crystal sandwiched between two glass plates. They're typically small and flat, requiring very little power for operation. (Peddie, 1994, p. 240)

Mental Model. A model that a user forms of how a computer system or program works. It can be conceived as the users' understanding of the relationships of between the input and output of an interface design. (Eberts, 1994, pp. 140-141)

Monoscopic. Seeing with one eye. (Sekuler & Blake, 1994, p. 513)

Monoscopic Display. A display system that is based on viewing the same 2-D image with both eyes.

Prototype. A variety of means that are used to produce preliminary embodiments of a product, and/or its subsystems. (Barkan & Iansiti, 1993)

Spatial Resolution (Monitors). The combination of the number of vertical and horizontal lines or pixels in a raster display device, referring to how sharply an image can be defined on the screen of a CRT. Generally, the higher the numbers are equivalent to the finer the display.

Stereoscopic. Binocular depth perception based on retinal disparity. (Sekuler & Blake, 1994, p. 519)

Stereoscopic Display. A visual display that presents different images to two eyes in order to produce the effect of stereopsis to the viewer.

Synchronous. Mode of interaction where events occur at the same time.

Tactile. The sense of touch or pressure applied to skin (Pimentel & Teixeira, 1995, p. 416)

Virtual Environment (VE). A high-end user interface that involves real-time simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, and tactile. (Burdea & Coiffet, 1994)

Virtual Prototyping. A computer-based simulation of systems and subsystems with a degree of functional realism comparable to a physical prototype that facilitates immersion and navigation. Virtual prototypes are used for test and evaluation of specific characteristics of candidate design. (Garcia, Gocke, & Johnson, 1994, p. 154)

Virtual Reality. See Virtual Environments.

Methodology

Product design reviews are conducted periodically throughout the product design and development process, to identify problems, formulate solutions, and develop a consensus among design team participants. The research plan of this study emulates the traditional design review process except that multi-functional design teams identified and solved design problems with the assistance of four VE visual display technologies. These technologies are a helmet-mounted display (HMD), binocular omni orientation monitor (BOOM), stereoscopic glasses and monitor, and for comparison a traditional CAD-based computer monitor.

Participants for the study were 12 male personnel from the U. S. Army Tank-automotive Command (TACOM). Tests were conducted at TACOM's design lab in Warren, Michigan. Test participants were grouped into three person design teams from the following functional organizations: new equipment training, human factors, logistics and maintenance, configuration management, quality assurance, and design. Test teams were purposefully balanced with similar years of work experience, computer knowledge, education, and design review experience. Participant data was collected using several survey instruments and independent observation.

An exploratory concept vehicle was developed as the test model for experimentation and data collection. This concept was a 600-gallon Tracked Fuel Trailer System (TFTS) vehicle, towed behind an Abrams M1A1 Main Battle Tank to provide a continuous fuel supply until exhausted. Four TFTS subassemblies were used as the focus of the design review task. These were the fuel transfer, fuel container, suspension, and towing. The four subassemblies contained design problems and potential design issues related to mechanical, ergonomic, maintenance, and operational functions.

A 4x4 Graeco-Latin Square experimental design was selected for its appropriateness to the research proposed in this study. The treatments that were compared were the four visual display technologies. The three blocking factors were four design teams, four different TFTS subassemblies, and four experimental orders.

The design methodology sought to provide insight into how commercial visual display systems are used during a concept design review (CDR) process and what value they added. Answers to the following questions were sought:

1. Error Detection. Do design teams detect and identify more design errors when using 3-D visualization tools?
2. Time to Detect. Do design teams detect and identify design errors more quickly when using 3-D visualization tools?

3. Time to Resolve. Do design teams resolve design problems more quickly when using 3-D visualization tools?
4. Perception of individual visual display systems. What is the perceived impact on the design process, the quality of the design process, and the physiological state of the design team members after using various 3-D visualization tools?
5. Preference of visual display systems. What are preferences of usefulness, difficulty, practicality, stimulation for group interactivity and development of team consensus when comparing the four display technologies?

This study employed several human-computer interaction and usability evaluation techniques to collect data to assess the research questions. These approaches were empirical evaluation of the task, Likert-like questionnaires, human interface comparisons, and open-ended questions.

Empirical evaluation of the task captured data for the following dependent measures: (1) the number of design errors detected, (2) the average time to detect a design error, and (3) the average time to resolve a detected design error. An independent test observer documented design team performance by taking continuous time measurements of the start and completion times for each problem identified and solved by the design team.

A VE assessment questionnaire was administered to each test participant after completion of each treatment condition. The questionnaire was designed to assess the strengths and weaknesses of the technology-training period, the design review process, the quality of the design review process, and the physiological effects of exposure to the visual display systems.

After each team had completed experimentation with all four visual display systems, participants were asked to compare the technologies by ranking them from the best to worst. The factors assessed were the usefulness of the technology, the difficulty of using the technology, the practicality of using the technology for CDRs, how helpful the technology was in stimulating team activity, and how beneficial the technologies were for team consensus.

Limitations of Study

The following limitations can be applied to this study:

1. The study was limited to team interaction in a concept design review environment.
2. A single conceptual model was used.
3. The study was restricted by the technical parameters and capabilities of the commercial visual display devices (equipment) used in the study.

The study was limited to the performance of design teams during a CDR task. Individual participant performance was not addressed in this study. However, perception and preference results were based on each participant's responses to VE assessment surveys.

Another study limitation was that the design teams only evaluated a single concept model for the study. This required that the TFTS model be separated into four specific subassemblies and that test participants had to focus on only one subassembly at a time.

Differences between the technical specifications of the visual display systems (FOV, resolution, and type of optics) studied were also not the focus of this analysis. The purpose of this study was to ascertain the value of typical commercial visual display systems on the collaborative, CDR process.

Assumptions

The following assumptions were made concerning the conduct of the study:

1. Test subjects are unbiased towards conventional 3-D CAD and emerging VE technologies, and
2. The knowledge of TACOM test subjects was representative of the general population within the area of military vehicle design in the U.S. Army.

The first assumption for this study was that test participants were not biased towards conventional CAD and emerging VE technologies. User interface evaluation techniques often incorporate comparative analysis methods between status quo and alternative interface designs (Nielsen, 1993). It is assumed that test subjects are open-minded during the evaluation of new technologies and how they are used in a product design review environment.

The second assumption presupposes that the study's test participants represent a cross-section of the population at TACOM and others involved in vehicle design reviews in the U. S. Army. Study participants were randomly selected from several functional organizations within TACOM for assignment to design teams. Each of the four teams was composed of one designer and two non-designers. It was impractical to test the entire population or all possible combinations of functional organizations team membership. The sample population adequately represented the total population. Demographics data was collected and assessed to verify this assumption on the representativeness of design team participants.

Summary

The purpose of this study was to conduct a comparative analysis of four commercial 3-D visual display devices and to determine the value of these systems to a multi-functional collaborative team design environment. It has been hypothesized that VE visual display devices can offer a common focus for multidisciplinary teams to resolve design issues by sharpening their viewpoints in support of collaborative design evaluation (Barkan & Iansiti, 1993; Horton & Radcliffe, 1995). Supporters also believe that VEs are very powerful communication tools (Ellis, 1997). When these technologies are applied to product design it is hypothesized that these systems can help reduce design cycle time, decrease cost, and minimize risk.

The methodology for this study was a 4x4 Graeco-Latin Square design. Testing was conducted at an U. S. Army development facility in Warren, Michigan. Participants were assembled into three person design teams and were asked to conduct a design review of a TFTS concept vehicle system. The data analysis was based on the performance of 12 test participants. Three methods were used for data collection:

1. Measurement of test team performance,
2. Administration of questionnaires, and
3. Observer evaluation

The study was limited to the performance of design teams during a CDR task, the use of a single model for evaluation, and to the technical specifications of each visual display system evaluated. Assumptions of the study are that the design team participants were not biased towards conventional CAD tools or emerging VE technologies and were representative of U. S. Army vehicle design review personnel.

The original contribution of the research conducted in this study is a comparative analysis of four commercial visual display systems used during a design review. Specifically, the study assessed the value and differences between the four commercially available visual display technologies. Quantitative data collected included the number of errors detected, the average time to detect a design error, and the average time to resolve detected design problems. Supportive qualitative data were collected assessing the perceived value of each visual display system and preferences between them.

CHAPTER 2

LITERATURE REVIEW

The purpose of this study was to evaluate, through comparative empirical testing and data analysis, how several commercially-available virtual 3-D visual display systems contribute to cross-functional team collaboration in a product design review environment. This chapter presents the results of a literature review of relevant topics important to addressing the research issues and identifying design process improvements. These topics are product development, the concept design phase, product design reviews, design performance measures, the collaborative nature of design, and computer assistance in design--emerging technologies.

Current product development methodologies and industrial trends are important indicators of today's business environment, assisting in the identification of more effective and efficient product development processes, a critical goal of today's organizations.

A significant amount of resources are expended in the early phases of the product development process, in early concept design. For this reason, concept design is investigated in terms of its function, how visualization plays a major role, and how product prototyping influences the design process.

Design reviews are important milestones conducted periodically throughout the product design and development process. It is during these reviews that functional groups collectively evaluate the progress and determine the fate of the product development effort. Design review methods, advantages, and disadvantages are discussed.

It is also important to know when a product has reached a level in the design that provides product managers with more surety of success. This is critical to stability in today's volatile global environment. Definitions of design performance in terms of effectiveness and efficiency are reviewed.

Today, the process of design is becoming a team-orientated activity. An activity that requires teams of individuals to share information, discuss options, formulate consensus and execute decisions. Therefore, concepts of collaborative work in product design are explored. Two bodies of knowledge are reviewed: concurrent engineering and CSCW. The first offers insight into the impact of organizational teaming on the product design process and the later offers insight into the automation of group work.

Overtime, the product design process has evolved as it has been integrated with computer and communication technologies. One emerging technology are virtual environments, they have the potential to impact the design process for they offer an approach which maximizes the human visualization capability and allows multifunctional teams the ability to simultaneously interact in the same design environment. A description of VE systems is provided. Also, the value of VE immersion, 3-D display research, current multi-user systems and applications to collaborative virtual design were investigated.

Product Development

The product development process has been characterized as a systematic method of evolving a product from idea conception to product release to customers. Pugh (1991) defines product development as a systematic activity necessary to produce a 'total design,' from the identification of the market/user need, to selling of the successful product, process, people, and organization. Also identified in his total design activity model, is an iterative process based on a progression through specific core activities: market, specification, concept design, detail design, manufacture, and sales. He emphasizes the iterative nature and flexibility required in design.

Ulrich and Eppinger (1995) identify a structured methodology for the product development process. The methodology begins with concept development, and progresses through system level design, detail design, testing and refinement and production ramp-up. These researchers have identified five specific dimensions to assess the performance and success of a product development effort: product quality, product cost, development time, development cost, and development capability. Their belief is that product development is an interdisciplinary activity involving marketing, engineering, design, and manufacturing.

Modern society is reliant on the fast paced movement of technology. This rapid growth has forced manufacturers to produce products that incorporate these ever-evolving technologies. Customer expectations, more than ever, are forcing developers to produce products that have shorter life cycles. Ohmae (1995) notes that the model life for audio components is about 6 months and for early facsimile machines a mere 4 months. To remain competitive it has become essential for producers to keep pace with technology changes and live with shorter product development cycles.

Emphasis has been placed on speeding up the time from product idea or conception to product launch because being first offers a great competitive advantage. Vesey (1991), in a study of high-technology products, reported that if the products were six months late in entering the market they earned 33 percent less over a five year period than they would have earned had they been introduced on time. A conclusion reached is that the resultant potential for market loss makes timeliness of product introduction a critical success factor.

Cordero (1991) surveyed several techniques for reducing product development times. He indicates that by better managing product development speed, an organization can achieve the following benefits: a faster response to market needs, reduced product cost, and increased product quality. He categorized four distinct management strategies: organize product development, organize product manufacturing, use miscellaneous techniques, and use computer-aided techniques. Of particular importance to this study are two of these strategies: organizing product development and use of computer aided techniques.

Organizing the product development structure can be further broken into four approaches -- some better than others. The first, a traditional phased approach in which functional representatives are gathered into project teams. In these teams, representatives may work autonomously from each other and frequently at different times and locations. Cordero (1991) identified several disadvantages of this approach. They are: much time is wasted when physically separate functional representatives need to communicate, time is also lost when there is a need to conform to policies and rules, and decisions have to go through several layers of functional and project approval. The second, a faster phased approach, achieves acceleration by integrating functional members and bringing them physically closer together thus encouraging open, cooperative communication. With this approach, control is normally delegated to project teams. The third, a concurrent approach, occurs when functional representatives are closely integrated into project teams and make decisions based on shared information about market needs, technical feasibility, and product costs. In this way the team ensures that product development simultaneously considers all interfunctional requirements. This concurrent approach saves time and conflict downstream by spending time up-front, however this approach introduces risk by reducing managerial control. The fourth, a contingency approach, is dependent on the type of product being produced. Cordero (1991) postulates that this latter faster phased approach appears more appropriate for minor product changes and the concurrent approach is more appropriate for cases of incremental product innovation and multiple product solutions.

Cordero (1991) also indicates that computer-aided techniques can help speed a company's product development strategy. These techniques include computer-aided design (CAD), computer-aided engineering (CAE), computer-aided process planning (CAPP), and computer-aided manufacturing (CAM). In his research, Cordero found that computer-aided techniques facilitate functional cooperation because they increase the rate of information dispersion and that they can also improve quality and reduce cost.

Eisenhardt and Tabrizi (1995) studied data from 72 new product development projects and concluded that accelerated product development can be attributed to a strategy that relies on improvisation, experience, flexibility, multiple design iterations, extensive testing, frequent milestones, a powerful team leader, and a multi-functional team. Interestingly, they also found that planning and rewarding for schedule attainment are ineffective means of accelerating the pace of product development.

Brown and Eisenhardt (1995) conducted a product development literature survey and identified three approaches: product development as a rational plan (financial performance of a product), communication web (effects of communication on performance), and disciplined problem solving (effect of the product, team and suppliers on the process). These investigators concluded that all three demonstrated that effective group processes increase the flow of information and are essential for high performing product development processes. Their research concluded that for a stable, mature product use of extensive planning and overlapped development stages are appropriate. In contrast, when there is uncertainty in the design process, more experiential tactics are more productive, including frequent iterations of product design, extensive testing, and short frequent milestones.

Throughout the product development literature review one-theme surfaces -- one which guides successful product developers in achieving a goal of decreasing the time to market. The theme is that the use of multi-functional and empowered teams, frequent design iterations, extensive testing, short product milestones, and flexible leadership has proved to be successful predictors in the attainment of a minimized product development cycle. It can also be reasoned that streamlining any phase of product development will improve the overall process. In particular, the product concept design phase is a significant contributor to final product cost, form, reliability, and market acceptance. Any strategy or methodology that offers potential to decrease or improve concept design time merits further investigation.

Concept Development and Product Design

The time to market and product cost are dominated by decisions made in the early stages of the design process. Will (1991) reiterates results identified in a National Design Strategy report that indicated that 85% of product development costs are determined before the product design is released to manufacturing. In a related study, similar findings were shown. Garcia, Gocke, and Johnson (1994) indicate that by the time 10% of total funds of a project are spent, approximately 90% of a product's development costs are established. In other words, the most cost-determining element in the product development effort occurs early in the product development cycle as planning and design decisions are made. These decisions are attempts to identify and reduce risk and improve product development efficiency.

Concept Generation

Ulrich and Eppinger (1995) describe the concept development phase of the product development process. They believe that the process begins with initiated customer requirements that are translated into functional specifications. These functional specifications are then used to generate product concepts. Selection methods are then applied to the product concepts to systematically select the concept that best meets customer's needs. Concept generation involves the actual creation and development of product alternatives. It embraces conceptual thinking, requiring both the logical and creative sides of the human brain (Goel & Pirolli, 1992). To develop a more efficient, effective concept design process one must understand the human aspects of the concept design process itself.

Mitchell (1994) describes three characteristics of design: a problem solving activity, a knowledge-based activity, and social activity. Mostow (1985) further categorized design as a special kind of problem solving activity, and a complex problem-solving event. In a process where the parameters and goals are not easily defined and the variables are often qualitative rather than quantitative, complex interrelationships between variables exist (Mostow, 1985; Derrington, 1987). The conceptual generation process involves a mental formulation of future state of affairs where the products of the design are external representations of such possible states (Goel & Pirolli, 1992). These investigators also believe that the design problem solving activity involves the following sequence of steps:

1. An exploration and decomposition of the problem,
2. An identification of the interconnections among the components,
3. The solution of the subproblems in isolation, and
4. The combination of the partial solutions into the problem solution (p. 397)

This is a systematic, logical approach where incremental development of design ideas are generated, retained, messaged and developed until they reach their final form. All associated knowledge is brought into the design space.

Design as a knowledge-based activity, implies that good human designers are extremely knowledgeable about the domains in which they operate. Mitchell (1994) discusses that to be able to creatively develop new solutions and designs a good knowledge base of product characteristics, materials, relationships, and past product development experiences needs to be present.

The process of design is becoming more reliant on team structures and dynamics. causing the process to be more of a social activity because there is a need to maintain a shared understanding amongst all participants in the design process (Holt & Radcliffe, 1991). These multi-functional teams proceed by exchanging proposals, arguments, ideas, and seek to form a consensus. Knowledge is transformed into a common pool of information where interaction and conflict resolution can take place (Mitchell, 1994).

Concept Selection

Concept selection is part of the design process where various product concepts are analyzed and sequentially eliminated to identify one preferred concept. Ulrich and Eppinger (1995) believe that:

> Concept selection is a process of evaluating concepts with respect to customer needs and other criteria, comparing the relative strengths and weaknesses of the concept, and selecting one or more concepts for further investigation or development. (pp. 106-107)

Concept selection is a critical phase in the product development process because it is at this stage that important decisions are made regarding the design and eventual production of the product. Kmetovicz (1992) describes product alternative analysis as a phase where ideas that were synthesized and prototyped are subject to evaluation and analysis by a cross-functional team. It is at this point that decisions that help shape the future are produced. However, evaluating teams must ensure that promising concepts are not eliminated prematurely, thereby missing market opportunity and that poor choices are not made, which could lead to potential failure. Decisions that are made in the earliest stages of the design process will impact the entire development effort. Spending time up-front where mistakes are cheaper and easily fixed is crucial to developing products within budget and schedule. These activities are often referred to as a divergent-convergent process. Divergent because within the selection process a set of concepts under consideration is narrowed. Convergent because evaluations may produce additional concepts as concepts are combined or improved.

Kmetovicz (1992) describes four decision-making approaches used during the conceptual, analysis stage of product development. These are odds-based, intuitive, analytical, and a combination of all three approaches. An odds-based style is based on the probability of being right. The researcher believes that this decision making approach should be used when the quantity and quality of information is low and the error tolerance is high. He further explains that the intuitive style should be used when the information is limited and the decision-maker is a good reader of the environment and possesses good information. These decisions are made based on instinct and feeling. In the third type, using the analytical decision style, the decision-maker relies on accurate information. Here the information needs to be of high quality and quantity. Kmetovicz (1992) believes that analytical methods should be used when the decision has little or no margin for error. The last approach involves a combination of all three methods. The researcher implies that there is no specific approach and that sometimes decision-makers must consider the benefits from all the methods.

Nippani (1994) offers a thorough evaluation of several existing analytical techniques that have been proposed for the evaluation and selection of conceptual product designs. These are: weighting techniques, Pugh concept selection, two-stage methodology, electre methods, fuzzy methodologies, utility theory, and Analytical Hierarchy Process. The advantage of using these approaches is that they are structured, theory-based methodologies. Some of these techniques force product development teams to interact and develop evaluation criteria in the earliest stages thus propagating team synergy yielding improved concept selections.

Mental Imagery, Visualization, and Design

Mental images, physical images and virtual images all play a role in aiding the human in the product design process. First, the relationship between mental imagery, visualization, and design will be examined in a historical perspective. Secondly, an examination of physical and virtual product prototyping methods will be presented.

Liston and Stanley (1964) summarized effective methods for conceiving, describing, proving and communicating new product ideas. Creative engineering, a term coined by the researchers, means the part of technology which uses discoveries of scientific research to fashion ideas for products useful to man. They also identify creative product design as a non-routine processes that is a mental process that is directed at envisioning or imagining solutions to problems. Designers often describe the way they deal with engineering design problems, by their use of these mental images. Mental images are analog representations that permit information to be processed in a holistic, parallel way. Mental images include a great amount of information about the objects being presented, which can be used when solving design problems.

Ideas or solutions to a problem must be translated into a picture or as referred to in the current literature as a mental model. Alabastro, Beckmann, Gifford, Massey, and Wallace (1995) maintain that humans constantly develop mental models of the world around them, and that these models are internal mental replicas which have the same relation-structure as the objects they represent. As more detail is accumulated in the mental model it becomes increasingly more difficult to keep all the information in sharp focus. There is a limit to the size and complexity of mental images that can be sharply focused in the conscious mind.

External assistance in the form of pictorial sketches assists the designer by providing visual stimulus and offers a feedback mechanism which assists the conscious mind in keeping details in focus thus stimulating the subconscious mind to further complete the mental model. Ullman, Wood, and Craig (1989) studied the effects of drawing and sketching on the mechanical design process. Five mechanical design engineers of varying experience were given initial specifications for a simple industrial design problem. The engineers were asked to solve a problem. During the experiment their verbal reports, drawings, and gestures were video and audiotaped for 6-10 hours. Analysis of the data concluded that 86% of the design actions was in sketching, drawing, or drafting. According to the researchers, it appears that drawing was done by engineers to aid their cognitive ability to visualize and solve the problem.

The field of human computer interaction has embraced the concept of mental models as it offers insight into computer system design. Eberts (1994) discusses the use of mental models for the development of computer-user interface designs. A mental model is a representation that users form of how a computer system works. This model assists the user in understanding the current state of a system and provides a context for predicting future events.

Eisentraut (1995) identified the importance of mental images in the design process in the following way: the pictorial knowledge base serves as a source for searching possible solutions, design solutions can be enlarged, and the images can stimulate the evaluation of alternative solutions. A conclusion reached is that a limitation of mental imagery is the capacity of human memory. Sketching and drawing play an important role in relieving this human capacity limitation. The use of physical or virtual prototypes can add more clarity for filling in the details of ideas for complex products.

Physical and Virtual Prototyping

Lanz (1985) defines prototyping as a functional form of a new type of design. The author indicates that creation of a prototype: pleases users, reduces development costs, decreases communication problems, slashes calendar time, produces the right system the first time, and cuts manpower needs. In the past, product manufacturers created physical prototypes and mockups so people could see, touch, and generally experience a product (Larson-Mogal, 1994). Products evolved from paper-based descriptions of product concepts, to partial prototypes, to full prototypes, and eventually to a complete product. Cost and risk are dependent on the level of testing with a complete product being at the high end.

Horton and Radcliffe (1995) have investigated a current understanding of the role of prototyping during the design process. These investigators created a four-faceted view of the prototyping effort: problem solving (solving problems by testing a solution), exploration and serendipity (uncover unexpected problems and questions), process (build a better understanding of the design), and sharing (design participant can converge, express, negotiate). From their perspective, the physical aspects of prototypes help materialize a design, and offer a common focus for multi-disciplinary groups to resolve design issues by sharpening their viewpoints.

Prototyping is an integral part of the product design process, and has become a key enabling technology in reducing the time to market for new products by identifying design flaws before tooling and manufacture begins. According to Barkan and Iansiti (1993), the physical nature of prototypes offers two benefits: they provide designers and design teams with a mechanism for product visualization, and function as a real platform for collaborative design evaluations. Managerial, technical, marketing, and manufacturing can also derive benefits from prototypes because they can serve as a basis for rapid learning, team unification, and consensus building.

Barkan and Iansiti (1993) also indicate that all forms of prototypes are a powerful means of resolving crucial questions quickly, can help to provide a common understanding of the product which they model, and serve as an integrating force for all members of a multi-functional organization. Early prototyping reduces the risk associated with innovation because problems are detected and corrected early.

Prototyping can also contribute to a reduction in product development time because problems can be reconciled earlier in more flexible stages of design -- at a point when there are less cost and difficulties associated with design changes.

However, the benefits of physical prototyping can be overshadowed by their expensive, repetitive nature. Physical prototypes frequently require manual tooling, skilled assembly, delicate testing instrumentation, and excessive time spent interpreting test data. The prototyping process can become a revolving sequence of events: identifying problems, applying lessons learned, revising physical prototypes, and finally performing re-evaluation of the entire prototype. All of steps are time consuming.

Application of advanced computer simulation technology in the prototyping process has resulted in the development of a concept called virtual prototyping. Garcia. Gocke, and Johnson (1994) have assessed the feasibility of using virtual prototypes in the Department of Defense (DOD) acquisition process. They define virtual prototyping as:

> A computer based simulation of systems and subsystems, which exhibits both geometric and functional realism. This three-dimensional virtual mock-up may be used to evaluate prototypes or concepts, and provides a common platform from which all functional disciplines (design, test, manufacturing, logistics, training, and operations) can work. (Garcia, Gocke, & Johnson, 1994, p. I-8).

Lee (1995) describes virtual prototyping as visualizing and testing computer-aided design models on a computer before they are physically created.

Virtual prototypes can dramatically reduce the need for expensive, time consuming physical mockups (Gottschalk & Machlis, 1994). Burdea and Coiffet (1994) estimate that the time from concept to production could be shortened by approximately 50% by eliminating the hardware iterative test-build cycles required in the traditional prototyping process. Ellis (1997) observes that when General Motors uses digital prototypes, the needed design changes that would normally take 40 to 50 weeks before production begins are being discovered 100 weeks earlier. The investigator estimated that savings of $80 million dollars were realized after making a $5 million dollar investment in the virtual prototype. This approach is becoming an increasingly popular way to refine design assumptions and to improve new products (Lee, 1995). Today, the DOD is relying on the use of virtual prototypes to solve the problem of shrinking budgets, diverse requirements, and quick changes in operation (Ashley, 1995; Hamit, 1995; Garcia et al., 1994; Kitfield, 1994). In comparison, industry is facing similar challenges and many companies are investing in computational methods of improving the design process (Hedberg, 1994; Keebler, 1993).

The development of mental models through spatial visualization of new products through the use of physical prototypes, pictorial images, or virtual design replicas is evident in processes of design. By their nature, prototyping efforts are conducive to design review activities because they offer a platform and mechanism for evaluation of future design concepts. For this reason, product design review activities are explored.

Product Design Reviews

Product design reviews have been described in varying ways. Juran and Gryna (1993) define these reviews as a formal, documented, comprehensive, and systematic examination of a product design to: evaluate the design requirements and the capability of the design to meet these requirements, and to identify problems and propose solutions. Pugh (1990) describes the design review, which he also calls a design audit, as an essential part of modern industrial practice. These reviews provide a mechanism whereby the total design activity can be carried out in a balanced manner, leading to improved designs and products.

Fox (1993), Juran and Gryna (1993), and Pugh (1990) all suggest that design reviews be conducted at several phases of the progression of the design: minimally at the conceptual stage, detail design stage, prototyping stage, final design stage, and before production begins. At each review, comparisons and revisions should be made using up-to-date information on market shifts, reliability, maintainability, producibility, appearance, cost, and enhanced knowledge of product's design.

The formal review process helps to manage all aspects of the design process. Hales (1993) supports the claims that regular design reviews help monitor work in progress for any product development effort. Fox (1993) further iterates that information and understanding gained from the reviews are used to make decision on whether to foreword to the next phase of the development process or whether to revise the program strategy.

Another important objective of design reviews is to integrate knowledge from various functional areas into one common pool of knowledge through consensus development. To make this possible, people who contribute to the design review must represent several different, but relevant functional organizations. These functional members are best suited to identify the strengths and weaknesses of the product development effort because in some way the product and its design affect them. The combined source of information these representatives possess promotes the achievement of an optimal design by creating a unique place where information exchange, interaction, and conflict resolution can take place (Mitchell, 1994). In this way, all of the people who have a part to play in making the design and product successful are involved.

Team member interaction plays a major role in the product design review process. Teams have the capacity to plan, organize, make decisions, communicate, and negotiate the actions to achieve the teams' objectives (Floyd & Turner, 1989). In collaborative work environments, there is a need to communicate design decisions and to coordinate the creative process among diverse disciplines. Inter-team member communications is required to provide information sharing, resource allocation, problem solving, and negotiation.

Advantages of Team Product Design Review

Wilson (1993) discusses several advantages of team-based problem solving. Teams provide better solutions and these solutions are usually more cost effective. Team results and solutions become the ownership of all members. This collective problem solving helps to ensure that various functions within an organization buy into the product and the design approach, because representative participants have a stake in the outcome of the project. Teams generally require less management control, since critical decisions are placed in the hands of experts instead of traditional management. Teams also provide a synergy of expertise.

Some reasons for the usefulness of design reviews are as follows: they give the team official time to look at their progress from a fresh viewpoint, they provide documented status, and they can achieve their main goal to confirm that the program is on the right track or is being corrected (Fox, 1993).

Group problem solving increases understanding and commitment, participation increases the likelihood of good solutions and of their effective implementation (Fox, 1987). Participation helps us to know the *why* as well as the *what* that are involved, and gives individuals a stake in what happens. Other benefits of participation are enhanced team spirit, increased respect for the team leader, and increased self-respect.

People also want to participate because group members want a role in defining, analyzing, and solving problems that concern them in their community and workplace. On an average, several people will produce more and better solutions to a nonroutine problem than will a single person. Participation in goal setting and problem solving increases an individual's understanding of what is to be done and of how it will be done. Participation in group problem solving is one of the most effective means for gaining commitment. It is better to have created solutions to problems based on team consensus and team input. Multi-functional team interaction and sharing of information gives teams the capability to make more informed and better decisions.

Disadvantages of Team Product Design Review

Cross-functional project teams do not always guarantee effective product development (Clark & Fujimoto, 1991), and the use of groups in product design can cause problems. The disadvantages of group problem solving are concerned mainly with the requirement for effective communications. If communication channels are broken, then group synergy is destroyed. Multi-functional teamwork involves getting the right data to the right place at the right time and in the right format. Communication is all about how an organization distributes and disseminates critical information.

Today, a design team may be in one location or geographically dispersed (Hedberg, 1994), adding an extra burden to the design process because communication may become a major issue. Exchanging viewpoints and ideas while sharing product information is critical to making more informed decisions regarding a product's design in a complex environment that incorporates multiple person interactions. Frequent meetings are necessary to keep communications flowing.

Regular meetings can help the review process and provoke important decisions. However, for those in distant locations travel time and associated expenses are costly (Yager, 1993). These expenses and disruptions to normal work can inhibit the regularity of meetings and the spontaneity of team interactions, and act as a barrier to successful implementation of team interaction techniques (Maxfield, Fernando, & Dew, 1995).

What is necessary to overcome these problems is the development of better and more effective processes, which promote communications and sharing of information.

Better design team performance can be translated into improved processes, reduced cost, and increased product profit. The next section describes measures of design performance in terms of effectiveness and efficiency of the design process.

Measures of Design Performance

Hales (1993) describes how a design team is expected to be efficient (doing things right) and effective (doing the right things). Soukhanov (1984) defines efficiency as the degree to which quality is exercised or as the ratio of the useful output to the total input of the system. This researcher defines effectiveness as producing or designed to produce a desired effect.

Clark and Fujimoto (1991) believe that three outcomes of a product development process affect the ability to attract and satisfy customers. These are lead time, total product quality, and performance. Lead-time, or design cycle time, is defined as the time it takes a company to move from concept, to production, and finally to market. Lead-time affects the design and market acceptance of the design. Total product quality is defined as the extent to which the product satisfies customers' requirements. Both objective and subjective evaluations affect quality. Objective evaluations could be such things as fuel efficiency or other performance parameters. Subjective evaluations could include aesthetics and styling. Product development affects total product quality at two levels: the level of design, called design quality; and the firm's ability to produce the design, called conformance quality. The third dimension of development performance is productivity. This is the level of resources required to take the project from concept to commercial product. This includes hours worked, materials used, and any services used during product development. According to Clark and Fujimoto (1991), to analyze product development performance one must develop measures of these three performance dimensions.

Lead-time can be measured as the time elapsed between the beginning of concept development and market introduction. Development lead-time is a measure of how quickly a firm can perform the many different activities that must be accomplished to advance from concept to market introduction. Because some of these activities are conducted in parallel it is more difficult to measure development lead-time.

Total product quality is based on external evaluation of many attributes. Clark and Fujimoto (1991) used multiple indicators to measure total product quality. These include customer evaluation of product characteristics, customer satisfaction, and product reliability surveys. Total product quality includes conformance quality (how well products delivered to customers conform to specifications), and design quality (the degree to which product designs match customer expectations). Customer satisfaction surveys can be used as an indicator of quality.

Trends have shown that product design processes are becoming more focused on team activities through new management techniques that rely on multi-functional teaming. Within this type of environment it is necessary for individuals to share information and collaborate in the decision making process. The next section discusses the relationship between collaboration and the nature of product design.

Collaborative Nature of Product Design

The concept of group work is often referred to as collaborative work. The term collaboration refers to a goal-orientated process of two or more individuals. Collaborative work requires communication and problem solving (Dhar & Olson, 1989). Communication refers to the exchange of information for purposes such as notification and clarification. Problem solving refers to processing of information for monitoring, negotiating, and decision making. Projects are generally monitored and decisions made to modify or achieve goals as the project evolves. Planning, monitoring, negotiating, and decision making are all basic components of collaborative work.

The importance of collaboration or group activity in the design process is becoming more and more apparent in today's business environment. The industry norm is becoming reliant on the utilization of cross-functional teams. This trend is documented in both concurrent engineering and Computer Supported Cooperative Work (CSCW) literature.

Concurrent Engineering

There are several analogous terms in the literature referring to the strategy of applying downstream product development functions at an early concept level. These terms include: concurrent engineering, concurrent design, integrated product and process design, and simultaneous engineering (Nevins, 1992). Juran and Gryna (1993) describe concurrent engineering as a process of designing a product using all inputs and evaluations simultaneously and early in the design process to ensure that internal and external customers' needs are met. These investigators also believe that the purpose of concurrent engineering is to reduce design cycle time, prevent quality and reliability problems, and reduce costs. One of the basic ideas of concurrent engineering is to create and assemble a team that is focused on developing or redesigning a product. These teams are composed of people from various functional elements: product management, development, engineering, and manufacturing (Sansone & Singer, 1992). Juran and Gryna (1993) contend that concurrent engineering is not a set of techniques but a conceptual methodology that enables all who are impacted by the design to have early access to design information and to have the ability to influence the final design to identify and prevent future problems.

Clark and Fujimoto (1991) observed a trend in the early 1980's from purely functional forms of organizations to more integrated structures. These researchers found that the straightforward functional organizations of the 1960's, had all incorporated formal mechanisms for cross-functional coordination by the late 1980's. In this later period, the principal job of many engineers working in these new organizational structures was to link one department with one or more related departments -- called liaison engineering. Meetings were a necessary mechanism for information exchange and communication, and small teams were established around particular problems or products. Clark and Fujimoto (1991) also discuss a type of integration that never appears in formal organizational charts, yet is vital to product integrity -- informal face to face contact between working engineers and managers. As a result of the evaluation, the use of multifunctional teams is commonplace in today's business environment.

Communication is the key activity for group work. Floyd and Turner (1989) describe how group work differs from individual work that supports the need for communication. First, group work involves extensive, person-to-person communications. Second, group processes need to be supported by roles, protocols, and procedures. Third, a task management function is required to monitor individual contributions. Lastly, the relationship of the group to the organization must be considered. In this way, organizational culture, norms, power, authority, and values are integrated.

Stickleym, Evbuomwan, and Sivaloganathan (1994) expounded that human interaction has become more important at the individual and management levels. They believe that organizations are moving toward a cooperative organizational culture. Not all design work involves teams, but a team setting is required for brainstorming, discussion, consensus decision making, presentations, reporting results, giving recognition, and communication. Team members are also a needed source of help and support to each other.

Concurrent engineering requires a change and awareness between all people and functions within an organization. As an example of an innovative concurrent engineering management technique, AT&T's Consumer Products Group restructured their development cycle into three phases: definition, development, and production. During the definition phase functional team members are required to sign the initial specification as a gesture of their personal commitment (Sansone & Singer, 1992). This formal agreement brought functional groups together in the early stages of a product development effort. Many companies have found that they do not need to make large investments to begin the process; they only need to invest in appropriate training that teaches people how to communicate and cut across organizational barriers. Concurrent engineering methods have encouraged the exchange of information between functional groups to improve the quality of decisions made during product development.

Some research has been conducted on expanding the concurrent engineering philosophy into a truly shared world of information (Toye, Cutosky, Leifer, Tenebaum, & Glicksman, 1994; Maxfield, Fernando, & Dew, 1995). These ideas are based on the interconnection and share distributed information through standard PC workstations -- an idea called collaborative virtual concurrent engineering. Effective concurrent engineering practices require that functional teams have access to knowledge regarding product versions, customers, and design data. Special knowledge sources have to be shared and coordinated if successful product design is to be accomplished (Subrahmanian et al., 1993). Automated processes can assist in this coordination, sharing effort.

Toye et al. (1994) studied how to apply technologies to help design teams gather, organize, reassess, and communicate design information. These researchers define team design as a shared understanding of the domain, requirements, product, design, and design process. The shared understanding is developed as each team member develops an understanding of their responsibilities and need to provide information to other team members. The process involves communication and negotiation. The researchers' system called SHARE enables engineers to participate as a team using their tools and databases. SHARE contains six features: familiar displays, such as on-line requirement documents; collaborative services, such as desktop video conferencing; on-line ordering and fabrication services, such as shipping information; specialized services, such as simulation tools; a distributed data management system; and an integration infrastructure that allows heterogeneous design tools in the environment.

Maxfield, Fernando, and Dew (1995) developed a system called Distributed Virtual Engineering (DVE) which supports collaboration among members of geographically disperses teams engaged in concurrent engineering. DVE supports and environment which allows a team to interact and make decisions from multiple perspectives in a shared information space using accurate virtual prototypes of mechanical components. This system uses a library of shared objects that can be populated with new product information and uses a video conferencing system to support communication between members of the product development team.

Researchers in the field of CSCW have investigated the use of automation on group activities. Automated technologies include email, videoteleconferencing, and more recently the use of virtual environments in collaborative group efforts. The next section discusses CSCW and its contribution to product design.

Computer Supported Cooperative Work (CSCW)

CSCW emerged in 1984 from the growing interest of product developers in supporting networked groups and from a common interest among various researchers as to how people work. There are several analogous terms in the literature associated with the term CSCW. These are: technology for teams, computer-aided teamwork, groupware, and workgroup computing. CSCW is an interdisciplinary approach with two major fields strongly influencing its growth: human computer interaction and computer science. Applications evolved from ideas in office automation including desktop conferencing, videoconferencing, collaborative authorship, and email (Grudin, 1994; Wilson, 1994).

Wilson (1994) identifies a range of CSCW activities, including supporting varying sizes of groups from two people to large organizations, supporting both face to face and dispersed cooperation, and supporting real-time, asynchronous communications. The researcher further divides CSCW into two components: technology and human. The technology component is further broken into four categories: communications systems, shared workspaces, shared information, and group activity support. The human component is also divided into four categories: individual, organizational, group work design, and group dynamics. CSCW touches on a wide range of activities that involve groups of people working together with help from computer technology.

Scrivener and Clark (1994) identify a four-category classification strategy for describing CSCW systems. These investigators believe that CSCW systems vary in two principals: their mode of interaction, and the geographic distribution of users. Mode of interaction can be asynchronous, occurring at different times; or synchronous, occurring at the same time. Geographic distribution can be either local, meaning users are located in the same environment or remote, meaning that they are at different locations. Shneiderman (1993) supports this idea and refers to this distinction as the time-space matrix. Examples of this classification identified by the latter researcher are: class rooms and meeting places are considered same time and same place; shared editors are same time and different place; project scheduling tools are different time and same place; and lastly email, bulletin boards are different time and different place.

CSCW researchers have identified some problems with multi-users sharing the same workspace. Some of these problems, as described by Broll (1995), are the distribution of objects and information plus the delegation of rights and the representation of group structure. Also, according to Wexelblat (1993), CSCW programs must provide the capability to exchange objects, to vary views of information, and to coordinate group interactions.

Darnton (1995) has identified five categories to describe ways in which people work together. The first is a common task with people working in a group to produce some product. As an example, a group of different specialists may collaborate to design a car. Second, is sequence of tasks, where people collaborate in a chain of activities. Third, is problem solving, where multi-disciplinary teams and multi-skilled teams work together to solve various problems. Fourth, is the concept of command and control. for example in air traffic control. Fifth, is mutual aid or reliance of people for mutual benefit, as in a customer-supplier relationship. This description of *how* and *why* people work together can be directly associated with scenarios involved in the product design and development process and perhaps in a VE environment. As organizations continue to strive towards collaborative interaction with customers, suppliers, and other relevant participants in an organization, the field of CSCW will continue to evaluate ways in which people interact and cooperatively work (Darnton, 1995).

CSCW is based on conventional user interface devices (mouse, pointer, etc.), but according to Takemura (1992) cooperative work using virtual environments offers more flexibility and offers the user an enhanced sense of belonging and true sharing of resources. Prior to the emergence of VEs, however, most multi-user systems gave each user the illusion that he or she was the only one using the computer tool thus providing an indirect means of sharing information. Wexelblat (1993) believes that VEs provide a more natural, intuitive approach to sharing data where a user can go back and directly indicate objects through gestures and conversion, thus making interactions more smooth and efficient as they are in the real world.

The need for the development of collaborative design tools and collaborative concurrent engineering tools has risen from the changes occurring in the product design process towards multi-functional design team interactivity. In today's design environment, people are bombarded with an overabundance of information regarding the product, the customer, the system, the process, and its suppliers. A need exists for a holistic approach whose foundation is in automation of the process.

Computer Assistance in Product Design -- Emerging Technologies

This section discusses current computer aided design technologies, their effect on performance, and their relevance to collaborative team design. It then transitions into a new emerging technology that has the capability of enhancing product design -- virtual environments.

Computer Aided Design (CAD)

The automation of the design process through the development of computer aided design (CAD) tools began in the early 1950's and bloomed in the 1980's (Barfield et al., 1987). CAD remains a major tool in today's design world.

The term CAD describes any system that uses computers to assist in the creation and modification of a design. The goal for creating this tool was to augment the creativity and decision making ability of the designer. A typical CAD system consists of a graphics display terminal, a digitized tablet, a keyboard, a plotter and a local graphics processor. The system can be classified according to size and processing capability of the hardware: microcomputer, workstation, minicomputer, or mainframe computer. The tool has two distinct features: it allows a designer to create an object and to perform an engineering analysis directly and interactively on the object.

CAD has significantly reduced the design cycle time for many products because designers are provided with a set of tools that enhance their performance. CAD has been documented as saving up to 70% of a total manual design time (Barfield et al, 1987). CAD technology has made it possible for product designers to develop an assortment of options when designing new products. Switching to a computer-based process increased the amount of possible designs that could be considered and allowed designers to develop many design iterations in a reasonably short time. Chang, Joshi, and Hoberecht (1992) identify several advantages of CAD. They are: increased productivity of the design process, improved design quality and accuracy, reduced development and testing time, and better design documentation.

An example of the product development community's movement towards full usage of CAD can be found in the recent Boeing 777 jetliner project. This jetliner product development, described by Norris (1995), has its foundation in advances in electronics, CAD, manufacture, and simulation. It is the first commercial jetliner to be 100% designed on a computer and is Boeing's first truly digital-designed plane -- a development that moved directly from the computer screen to production.

Pratt (1994) provides a historical overview of CAD tool development. The tool was originally developed to automate the drafting process of a single designer. These first systems yielded 2-D engineering drawings and provided a means for the generation of traditional drawings. The next major change came with the introduction of 3-D wire frame models. Wire frame models provided a unified model of the object rather than the several partial models, as is the case of the traditional three orthogonal views in engineering drawing. One advantage of wire frame models is that the computer can automatically generate drawings from any point of view and in any projection chosen by the user. The next development was the solid modeler, which brought together the benefits of wire frame and surface models. These systems contain information concerning all faces of the object, including the surface they lie on and the edge curves that bind them. Also stored is topological information indicating how all these elements are connected.

Today, new development in CAD includes parametric modeling, constraint-based modeling, and feature-based modeling. Parametric modeling allows the design of a product in which certain dimensions are not fixed, but can be varied. This approach is based on bi-directional associativity of design elements (Engineering Automation Report, 1995). Constraint-based modeling builds constraints into the system. Once a constraint is defined they are required to hold even when any design modifications are made. Feature-based modeling, include features that are a local geometric configuration on the surface of a manufactured part that has some engineering significance. These approaches are the first step towards developing a design tool that could support multiple persons working on the same part or assembly -- collaborative CAD.

Product data management systems play a key role in achieving today's collaborative CAD capabilities. Gear (1996) describes these systems as being either a check-in or check-out types, i.e. data management system monitors the configuration of the design through a comparison and checking procedure. For example, two people can work on the same part or assembly. Each would open or create a file for the part they are designing. Each designer could edit, modify or create the design. This work would be completed independently, then stored in individual files with different names. The product data management system knows that two individual people have updated the part. The next step requires the integration of the work of the independent designers. When the part is called up, the user is informed that two part files exist. The data management program then shows all the changes made by the two designers. The system then progresses to ask the user to make decisions on each modification made, and which modifications should be kept and which should be eliminated. The integration process is not automatic, but requires a decision-maker to confirm which modifications or additions are appropriate.

The previous description of collaborative-CAD identifies some of the limitations associated with current CAD capabilities. As the design changes towards more dependence on collaboration, new design tools will emerge and new strategies for group interaction will be investigated--especially if companies are to remain competitive. Exploring new technologies that may contribute to shorter design times and lower design costs are continuously necessary. One such emerging technology is virtual environments.

The next section describes the value of virtual environments by providing the reader with a brief description of how VE systems work, differences between monoscopic and stereoscopic vision, human factor research on 3-D displays, and product design applications.

Virtual Environments (VEs)

General Description

There are several analogous terms in the literature referring to virtual environment (VE) technology. These include: virtual reality (VR), telepresence, enhanced reality, or synthetic environments (SE) (Burdea & Coiffet, 1994). These investigators also define VR as a high-end user interface that involves real-time simulation and interactions through multiple human sensorial channels or modalities -- visual, auditory, and tactile. In different but related definitions, others describe VEs as synthetic sensory experiences that communicate physical and abstract components to a human operator (Kalawsky, 1993), or an immersive, interactive experience based on real-time 3-D graphic images generated by the computer (Stuart, 1996). VE technology has the capability of providing real-time customer feedback and interaction necessary for successful product evaluation. This technology allows a person to experience phenomena that appear to be real but exist only in the computer. A user or designer can be immersed into the concept to get a realistic visualization of the final product.

VR allows the designer or user to go one step further and truly experience the design. For instance, an automotive designer could sit in an automobile and visualize the interior and layout. Then the designer could navigate in the virtual world around the car and look at exterior qualities of the vehicle (Kalawsky, 1993). This technology provides a new approach to exploring reality and extends our senses so we can animate products to study how they behave. One can fly inside it and watch the vehicle vibrate as it moves across a terrain (Pimentel & Teixeira, 1995). This type of tool can be useful and even invaluable for ergonomic layouts allowing a designer to make extensive changes in these virtual concepts to insure they meet their customer's needs.

The incorporation of a 3-D CAD data files into a virtual world allows for visual evaluations. There are problems associated with file translation from standard CAD formats to formats compatible in virtual environments. CAD data files are much more complex than required for virtual environment application, and may contain several million polygons that are a burden in a VE system because each polygon must be processed and rendered in real-time. Due to the lack of maturity of the technology, VEs are not being considered as the next generation CAD tool. Instead VEs are being used to aid in fleshing out initial concepts, analyzing stress, aerodynamics, checking ergonomics. designing for maintainability, and taking designs to virtual test grounds (Gottschalk & Machlis, 1994). These systems are not something from which detailed engineering information can be derived, but VEs provide the capability to rotate and look at objects in a 3-D perspective.

Utilizing VEs in the design phase of the development process can increase design flexibility by allowing the exploration of various alternatives. It provides a worthwhile, low-cost approach to evaluate products prior to physical prototype builds. Significant cost savings can be attributed to the fact that problems would be identified and corrected in the early stages of development before any commitment is made. This system also brings users into the design process much earlier, and creates a common platform and environment that is capable of multi-user participation by an entire design and evaluation product team.

In 1995, the National Research Council (NRC) created a Committee on Virtual Reality Research and Development and charged them with a goal to "recommend a national research and development agenda in the area of virtual reality" which would guide government research and development over the next generation. The committee concluded that four application domains show the most promise. They are: design, manufacturing, and marketing; medicine and health care; hazardous operations; and training. The committee recommended that the design function be one of the principal focus areas of VE development and testing. The committee also recommended that the federal government provide funding for a program aimed at developing networking capabilities and standards for large distributed VEs. Used by the committee was the rationale that VEs can help manufacturing throughout the entire product development cycle. For example, when developing design requirements VEs can serve as a medium in which a customer's mental image of a product can be fashioned. During detailed design VEs allow designers to reach inside, test accessibility, plan maintenance. Prior to producing a product VEs can create pilot manufacturing lines and predict product performance. In the marketing stage VEs can provide potential customers with the ability to visualize various uses of a product.

The following description of a VE system is presented to the reader as a basis for understanding the value, capability, and complexity of the technology.

The VE System

VE systems generate and display a virtual world, and process inputs and outputs of data. The system consists of two major components: hardware and software.

Hardware

The hardware system consists of a main processor and input/output devices. The user interacts with the virtual world through various input devices, and the virtual world in turn responds to the user's actions by using appropriate output devices. Dani, Fathallah. and Gadh (1994) diagrammed a typical VE system. A modified version is depicted in Figure 2.

Input Devices

An input device is a piece of hardware that is used to put data into a computer and allow the participant to interact with the virtual world. Dani et al. (1994) categorized input devices into five equipment types: position tracker, digitizer (3-D mouse), glove, biocontrollers, and voice input. These devices allow a person to pick up and move objects while navigating in a virtual world, or they allow a person to change position, viewpoint and field of view within the simulation (Eddings, 1994). They also sense a participant's physical position and orientation, translating them into corresponding images in the virtual world.

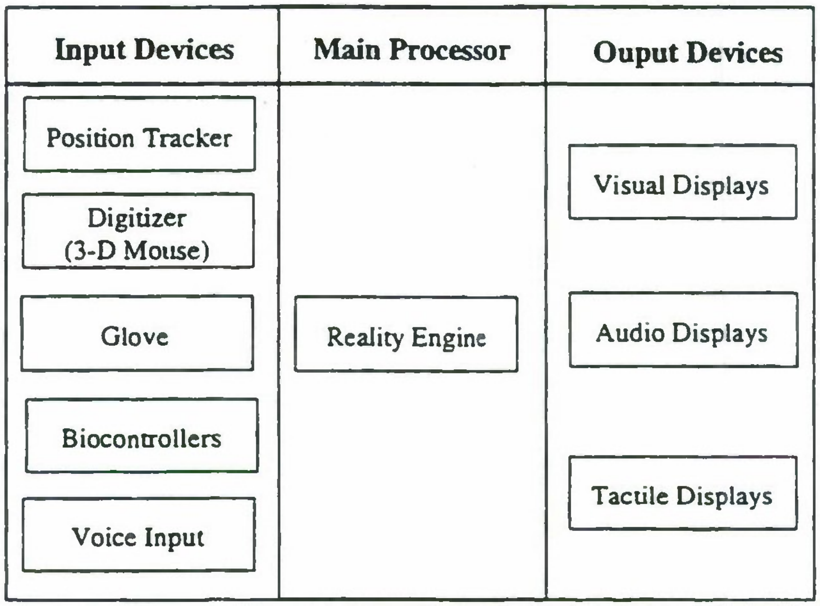

Figure 2. Typical VE system (Modified from Dani et al., 1994).

Position Tracker

Position trackers are used to track the position and orientation of the user. The state of the technology has been focused on tracking the position and orientation of the users head and/or hand. Currently, tracking systems are based on mechanical, magnetic, acoustic, optical, or inertial technologies (Dani et al., 1994; Stuart, 1996; Haas, 1998).

Mechanical tracking systems physically connect the user to the tracker with jointed linkages and consequently mechanically measure the user's position. Haas (1998) describes one of the first systems developed by Sutherland in 1968 as a shaft-like mechanical assembly that hung from the ceiling and attached to a head mounted display. The researcher indicates that the design resembled an automobile drive shaft and was often referred to as the "Sword of Damocles" because it hung precariously over the users head. Disadvantages of mechanical systems identified were that they were heavy and uncomfortable to use. While mechanical trackers are precise and responsive, their mechanical nature restricts motion and are more suited for telerobotic applications or use in cases where user mobility is not a problem (Haas, 1998).

Magnetic systems rely on processing the behavior of magnetic fields to calculate the position and orientation of the user. Currently two commercial types of magnetic trackers are available. One type, offered by Polhemus (1998), uses alternating current (ac) and the other, Ascension (1998), uses direct current (dc) (Haas, 1998). These tracker systems are composed of a magnetic emitter, a magnetic receiver, and a controller unit. For a detailed description of how these systems operate, the reader is referred to Haas (1998).

Acoustic tracking systems use ultrasonic frequencies to track user position. Frequencies above 20kHz are used so that emitter sounds are not heard by persons working in the environment (Haas, 1998). Haas describes two basic approaches to acoustic tracker design: time-of-flight (TOF) measurement and phase-coherent (PC) measurement. The TOF measurement approach calculates position and orientation by using multiple emitters and sensors and measuring the elapsed time of an acoustic wave. The PC measurement approach determines distance by comparing the phase of a reference signal to the phase of an emitted signal detected by sensors. This type of tracking system can generate high data rates because phase can be measured continuously, which leads to improved accuracy, responsiveness, range, and robustness. This type is more conducive for larger volume environments.

Optical tracking systems use light emitters and detectors to calculate user position. Currently there are three optical tracking systems that have been implemented in VEs. They are image processing, laser ranging, or beacon systems. Image processing types of systems are based on pattern recognition comparisons between known and sensed patterns. Haas (1998) identifies that image processing systems are inherently less accurate as the distance from the sensor to remote object increases. Laser-ranging systems measure position by transmitting laser light onto a remote object and sensing the reflected light. The reflected light is sensed using a camera that sees a diffraction pattern on the object. Measure of distance is made from pattern distortions on the objects. Beacon systems rely on a known distance between either emitters or sensors to determine position. This type is also referred to as fixed-transducer. These systems are the most common form of optical trackers. Regardless of type, optical trackers can suffer from ranging errors caused by spurious light, ambiguity of surface, and occlusion. In contrast, their positive attributes include high data rates and good responsiveness (Haas, 1998).

Inertial tracking systems use gyroscopes to sense the orientation of an object in space. These systems measure changes in pitch, yaw, and roll. Haas (1998) comments that these systems are more robust because they make direct measurements of angular change. Inertial trackers are immune to the interference experienced when using magnetic or acoustic tracker systems. The disadvantage of this type of tracker is that small inexpensive commercial solid-state gyros are less accurate (Haas, 1998).

Digitizer

A digitizer includes devices such as a six-degree freedom mouse, trackballs, and joysticks. Dani et al. (1994) observes that these devices have evolved from traditional mouse/trackball technology to a more advanced form of data input. They are used to allow a user to interactively select coordinate positions of an object (Hearn & Baker, 1997) and to navigate through a virtual world.

Glove

Instrumented gloves are often refereed to as datagloves, virtual hand controllers, or hand-gesture interface devices (Stuart, 1996). These devices can be used to grasp a virtual object or make gestures. They can be worn over the hand like a normal glove, but contain sensors that are used to measure the position of the hand (Hearn & Baker, 1997). These devices combine bend sensing and position tracking technologies to detect posture and position of the hand; and function to capture the movement of the fingers, thumb and wrist, to provide input signals to VE systems. Stuart (1996) discusses some approaches to sense bending and joint flexion capture. The DataGlove™ developed by VPL uses fiber-optic cables attached to lycra gloves. The amount of light passing through the cables is a measurement of joint flexion. When a joint is flexed less light is passing through the optic cable. Another less expensive type developed by Mattel is based on measuring the strain of flexion with flexible polyester strips covered by special ink.

Biocontrollers

Biocontrollers are devices that detect and process bioelectrical signals. These signals can be the result of muscle or brain activity (Stuart, 1996). Stuart (1996) defines the term myoelectric as muscle movement and their transmission of electrical signals. The researcher suggests that myoelectric biocontrollers are used for gaze control interfaces and that they are important for users with physical handicaps. Related is the term cerebroelectric which refers to electrical activity associated with brain signals.

Voice

Voice input systems interact with the VE through the use of voice or speech recognition technology. These systems allow the user to interact and navigate in the VE through voice command. Speech recognition systems can be categorized as speaker dependent or speaker independent. Speaker dependent systems require users to train the system prior to use. These systems have a good recognition rate because they only deal with a single voice. In contrast, speaker independent systems have lower recognition rates because they have to detect different individual voices. However, the advantage in this type of voice recognition system is that the system is trained only one time.

Main Processor

The main processor contains the processing power to run the simulated virtual world and produces a sense of reality. The main processor is sometimes referred to as the reality engine because it is an essential element in the VE sensory feedback loop. The reality engine's function is to create and manage the interactions in a virtual environment.

and perform real-time computations that produce correct system performance. Stuart (1996) defines real-time image generation as the generation of images at quick enough speeds to be displayed at a chosen frame-rate. In VE applications, fast processing speed is essential because it is necessary to have the physical movements of a user synchronized with movements in the virtual world. It is also important for users to accurately perceive the correct and appropriate movement responses in the virtual world otherwise they may feel nausea or suffer other negative effects. Main processors for VE application range from low-end PC based systems to high-end, high performance computing stations.

Output Devices

Human brains allow individuals to perceive the exterior, physical world through five primary senses: sight, sound, touch, smell, and taste (Sekuler & Blake, 1994). A VE system presents a simulated world to the human senses through VE output devices. These devices are the primary feedback users in VEs so they can perceive appropriate information for interacting in the VE and perform tasks. Currently, the state of VE technology output devices is limited to the sense of sight, sound, and to some degree touch.

Visual Display Devices

Human vision is considered the most powerful sensorial channel providing a sense of sight. Humans are capable of processing extremely large bandwidths of information at any single moment in time without conscious effort. Because human vision is critical in providing humans necessary information, there has been a multitude of visual display developments both in industry and academia. The most common visual display systems are helmet-mounted displays (HMDs), binocular omni orientation monitors (BOOMs), and stereoscopic glasses. Other visual display systems such as the CAVE Automatic Virtual Environment (CAVE) use large-screen projectors, while others use holographic optics to create virtual, visual experiences.

The breadth of this study is restricted to the application of commercial 3-D visual display systems on the CDR process, therefore the following information provides the reader with a general understanding of commercially available 3-D visual display systems. Before describing these systems a description of stereoscopic and monoscopic vision is provided to show the relationship between visual display systems and human depth perception -- a human's ability to see 3-D scenes. More specific technical requirements for visual display systems for VEs include spatial resolution, depth resolution, responsiveness, field of view (FOV), storage and refresh rate, and color (Stuart, 1996). Each 3-D visual display system offers different technical capabilities and thresholds. For a more in-depth understanding of these technical aspects, the reader is referred to McKenna and Zeltzer (1992) who provide a detailed description of underlying technology requirements and limitations for 3-D display systems and performance comparisons with the human visual system.

Monoscopic versus Stereoscopic Vision

Visual display systems are often categorized by how the observer uses his or her eyes to create the visual image. Monoscopic systems display the same 2-D image to both eyes. When using these systems, depth is only perceived based on cues inherent in the image created. These cues are: shadows, occlusions, texture, and object detail (Burdea & Coiffet, 1994). Other cues identified by Wickens (1990) are highlighting, proximity-luminance covariance. linear perspective, occlusion, and height in the visual field. In contrast, stereoscopic systems present different images to the each eye, creating the effect of depth (Wickens, 1990; Sekuler & Blake, 1994; Kalawsky, 1993; Burdea & Coiffet, 1994; Diner & Fender, 1993). Sekuler and Blake (1994) provide a description of stereoscopic vision. In their description it is pointed out that the anatomy of the human eyes plays a major role in providing humans with the ability to see depth. Because the eyes are located in the front of the head and are laterally separated, they view objects from slightly different. These differences or disparities between the view seen by each eye give humans the ability to discriminate extremely small differences in relative depth. Ma, Hollerback, and Hunter (1993) list the advantages of stereoscopic vision as producing superior ability to resolve spatial detail, visual detection, and form recognition. HMD, BOOM, and stereoscopic glass visual display systems discussed next are considered stereoscopic visual display devices.

Helmet Mounted Display (HMD)

Larijani (1994) defines a Helmet Mounted Display (HMD) as a headpiece or head-held brace with viewing or optical devices located or suspended in front of the user's eyes. The design itself places screens very close to the eye, because of the limited distance special optics are required to allow the eyes to focus at such a short distance.

Special optics are also used to magnify the screen image in order to fill the eye's FOV (Burdea & Coiffet, 1994). The physical design of an HMD takes into account the head geometry of the user (Stuart, 1996). Today most HMDs are based on either cathode ray tube (CRT) technology or liquid crystal display (LCD) technology (Burdea & Coiffet. 1994). HMDs based on small LCDs are relatively cheap but have low-resolution capability. In terms of volume of sales, most HMDs are CRT based (Kalawsky, 1993). CRTs have the advantage of higher resolution than their LCD competitors, but CRT based HMDs carry the added burden of weight. Adam (1994) comments that the CRT display device increases the weight and volume of the HMD. There are ongoing research activities aiming at the elimination of CRTs by placing the display directly on a microchip. This technology researched by Texas Instruments is referred to as a Digital Micromirror Device (DMD) (Burdea & Coiffet, 1994). It has the capability of improving resolution and decreasing problems associated with high weight.

The importance of HMD devices are that they have the capability of generating 3-D images and providing the user with the effect of being fully immersed in a virtual world, but the technology is limiting. Singh, Feiner, and Thalmann (1996) comment that low-resolution display, small field of views, and poor ergonomics hinder current generation HMDs. Because of these limitations, these researchers believe that current HMD technology is not suited for precision work or efforts that require extended use. In addition, these researchers point out that insufficient computing power, lack of good interaction techniques, and high development costs are a probable cause for the lack of adaptation as useful tools. Deering (1996) supports these statements claiming that low resolution and extremely distorted optics of most HMD displays make them unsuitable for fine manipulation of 3-D objects. The researcher further believes that HMD technology is limited to simple positioning tasks where objects are already created outside the VE. Holmgren and Robinett (1993) claim that VR applications require a display device that are lightweight, small, and provide high resolution. The weight requirement is needed for reasons of comfort for long use. These researchers suggest that an ideal HMD should resemble a pair of sunglasses. Pimental and Teixeira (1995) provide a resource guide of current HMD developers and suppliers.

Binocular Omni-Orientation Monitor (BOOM)

A BOOM developed by Fakespace Laboratories was first introduced in1988 (Fakespace, 1998; Kalawsky, 1993; Stuart, 1996). It is a display device that is based on mounting a viewer on a stand and permitting the user to navigate or move through the virtual world. Users bring the viewer to their face and holding it there, use it to view the virtual environment. The device is a mechanical arm that supports either a CRT or LCD based imaging system at one end. Boom displays have a six-degree of freedom motion (x, y, z, roll, pitch, and yaw) support structure (Fakespace, 1998). The system uses optical encoders at each of six joints on the support structure to provide high-speed, high precision information regarding position and orientation of the display as the viewpoint changes. The arm of the system is counterbalanced so that the display has zero weight. By using this design, problems with optics and display weight, and display size are eliminated (Pimentel & Teixeira, 1995). BOOM systems can use higher resolution CRT-based displays because they can offset their additional weight. However, the improved resolution and performance has higher associated costs.

The design of a BOOM system provides users with ease of access. Users can easily switch between the VE and their work environment without having to get in and out of a HMD (Stuart, 1996). The BOOM device has been applied to a variety of research projects (Fakespace, 1998). NASA Ames Research Center has used the technology for scientific visualization of windtunnel characteristics (Bryson, 1993). This device has been used for CAD and concurrent engineering work at Ford Motor Company, Boeing Computer Services, and the U.S Army TACOM. Academia has explored the technology; one example is the University of Central Florida's Institute of Simulation and Training, where the BOOM is used for training military hostage rescue teams.

Stereoscopic Glasses

Stereoscopic glasses used in conjunction with a display monitor are an alternative approach to 3-D visualization that permits very high resolution at the expense of immersion. Stereoscopic glasses are also referred to as shutter glasses. They are synchronized to the alternating display of two separate images on a monitor. When the right side image is shown, the shutter over the left eye is closed, and the one over the right eye is opened (Stuart, 1996). When the second image is shown, the left eyes shutter opens, and the one over the right eye closes. Dani et al. (1994) describes this system where two images of a virtual scene are shown alternately at a very high rate on a CRT monitor. The rate of at least 60 times per second per eye is required for the brain to interpret the resulting image as a single stereoscopic view (Eddings, 1994). When combined with tracking technologies one can determine the position of the user and use it to display viewpoint dependent images on the display monitor

There are several ways to shutter the glasses including manually closing and opening the shutters, but the most widely used technology are liquid crystal shutters. By using an infrared transmitter one can coordinate the display rate to the frequency with which each of the glasses is blacked out providing the user with the perceived 3-D image. Stereoscopic glasses are a lightweight, wireless, and hands free viewing device (Stereographics, 1998). Stereoscopic glasses provide low cost alternatives therefore are more prevalent in the entertainment industry.

The stereoscopic glasses device has been applied to a variety of research projects (Stereographics, 1998). Researchers at Parke-Davis Pharmaceuticals are using stereoscopic glasses system to visualize complex molecules in order to design new drugs. Designers at Ford Motor Company, General Motors, and Chrysler Corporation are using the technology to assist in the design and evaluation of new car concepts. Military researchers at the U.S Army TACOM are using the technology to bring the user in the design process by allowing them to evaluate new concept designs.

Other Visual Display Systems

The Cave Automatic Virtual Environment (CAVE) system was originally developed at the University of Illinois-Chicago's Electronic Visualization Laboratory in

1992. Today this product is commercially available through Pyramid Systems, Incorporated. The CAVE is a projection-based VE system that surrounds the user with four screens. The screens are arranged in a cube 10 x 10 x 10 feet made up of three rear projection screens for walls and a down projection screen suspended from the ceiling for the floor (Eddings, 1994). The down projector overhead points to a mirror, which reflects the images onto the floor. Graphics are projected onto the screens. A viewer wears stereoscopic glasses and a headtracking device. As the user movers inside the CAVE, the correct stereoscopic perspective projections are calculated for each wall. The image moves with and surrounds the user. An SGI Onyx computer with three Reality Engine graphic pipes controls the projected images. Each reality engine is attached to a CAVE wall. The CAVE was originally designed to be a useful tool for scientific visualization and for multiple person viewing. Six to ten people can view the projection, while one person with a headset and joystick computer controls the simulation's perspective. In the CAVE a user sees his/her own body.

Like the CAVE, other systems based on projector and stereoscopic glasses have emerged in the commercial market. These include the ImmersaDesk™ developed by Pyramid Systems, Inc., Immersive Workbench™ by Fakespace, Inc, Visionarium by SGI, and various powerwall concepts. The first two systems offer a stereoscopic imaging system designed to resemble traditional designer drafting boards. The Visionarium uses a 180 degree curved screen providing users with the sense of surrounding themselves in the

VE. The powerwall system uses a 20 x 8 feet rear projected screen to create life-like sized virtual images.

Typical projector-based head tracked stereo systems have only been able to produce a single head-tracked image. Recently, Fakespace, Inc has introduced an additional feature to their Immersive Workbench called the Duo system. This system allows two simultaneously and individually head-tracked stereo pairs to be displayed. This system allows for collaborative activities, where two people can be immersed in a shared workspace (McDowell & Bolas, 1997; Agrawala et al., 1997). It is postulated that this type of VE system is appropriate when the sense of an objects presence is needed and when one wants a virtual model that appears to sit on the surface of a workbench (Bolas, Bryson, & McDowell, 1998). Some case studies using the Immersive Workbench technology have been explored. These include jet simulations, molecular docking, molecular dynamic simulation, and visualizing unsteady flow above a destroyer vessel.

Other research has explored the use of holographic imaging to develop 3-D virtual objects. U.S. Army researchers at the U.S. Army TACOM have developed a prototype Holographic Imaging system that combines holographic laser technology with real-time computer simulation to develop the capability to view objects in 3-D (Bochenek & Buck, 1997). The current prototype system uses a high performance graphics computer, projectors, a holographic optical element, and custom software to create the 3-D imagery. These 3-D objects appear to float just in front of the holographic optical element in 3-D space (Keebler, 1995). The system can be configured in either a high or low-resolution version. The low-resolution prototype relies on using LCD projectors and the high-resolution prototype uses high definition projectors. The high definition projectors provide greater resolution at the expense of losing viewing mobility. The prototype system requires the viewer to be in a stationary location. Research plans are to increase the performance of the prototype system while maintaining high resolution.

Audio Devices

The sense of sound is the second most important sensorial channel for virtual experiences. The sensation of sound compliments the visual modality because a human can process both visual and audio information in parallel (Sekuler & Blake, 1994). Gilkey and Weisenberger (1995) have argued that sound is just as important in virtual environment systems because sound is critical in achieving maximum sense of presence. Auditory information is used to provide the user feedback about his/her interactions in the virtual world. When sound is added, the overall user interactivity and immersion are increased (Burdea & Coiffet, 1994). Three-dimensional sound, which appears to come from different directions, can provide a more realistic virtual experience. In VEs the sound position changes dynamically in real-time. Few vendors develop devices that can produce realistic 3-D sound in real time. Crystal River Engineering has been in the forefront of developing commercial 3-D audio systems. One product, the Acoustron II provides a full spectrum of 3-D sound to include Doppler shifts, spatialization, and acoustic raytracing of environments. Inputs to the system include sound source position and orientation, listener position and orientation, acoustic environment characteristics, and wall reflection and transmission attributes. For information regarding other vendor sources, model availability, technology basis, and related cost the reader is referred to Pimental and Teixeira (1995) or Stuart (1996). Each provides product resource guides for current sound developers and suppliers.

Tactile Devices

Tactile or haptic feedback provides a user with a sense of touching objects in the virtual world. There are a variety of technologies that have been used to create the sense of touch. Stuart (1996) provides a comparative evaluation of tactile display technologies. In summary, there exist five technologies. Vibro-tactile displays give the sense of touch via vibration on the fingertip. Pneumatic displays create the impression of touch by creating pressure with air ring, jets, or pockets that touch the user. Electrocutaneous displays create the sense of touch by sending tiny pulses of electricity through electrodes touching the users skin. Shape memory alloys change shape and create the sense of touch through their pressure on the skin. Functional neuromuscular stimulation creates the impression of touch through direct stimulation to the neuromuscular system

Current tactile devices according to Burdea (1996) are limiting and do not give users the sense of weight, surface smoothness, compliance, or temperature. Burdea (1996) feels that the usefulness and realism of current generation VR systems are hampered by the lack of force and tactile feedback to the user. Kontarinis and Howe (1995) offer some insight into the usefulness of vibration tactile devices. These researchers suggest that tactile information may be useful for inspection tasks where one is detecting the looseness in an assembly of parts or smoothness of a surface. These devices can also be used to indicate that contact between an object has occurred, and for simple positioning and enhanced sense of presence. Burdea (1996) details tactile feedback interfaces, haptic sensing and controls, human factor issues, and haptic feedback applications. Much research needs to be conducted to develop new concepts and products, which will give the human the sensation of touch in virtual space thereby, a more realistic experience in the VE.

Software

VE software packages are used to build virtual worlds. This software is used to design the landscape and objects participant encounters in a virtual world. Bricken and Coco (1994) classify VE software development systems into two categories: VR Toolkits, or integrated software systems.

VE toolkits contain libraries of program functions and objects that let a world builder create an application. These libraries include functions for importing geometric objects from computer aided design programs that generate a virtual world. They also allow the designer to assign behaviors to objects in the virtual world. In these systems C or C++ programming language is often used. This type of tool offers tremendous flexibility but requires programming experience to use it. The toolkits have built in device drivers for interfacing with commercial input and output devices (Wang, Green, & Shaw, 1995) and built in rendering functions such as coloring, texturing, and shadowing. Some of the available software products are MR toolkit, created by the University of

Alberta; VLib, created by University of North Carolina; World Toolkit, created by Sense 8; Performer, created by SGI; and Cyberspace Developer's kit for linkage with AutoCAD.

Integrated systems are intended for use by nonprogrammers. These systems hide the low-level computational details by providing an intuitive visual and default options for constructing events. These systems also provide standard software facilities required for virtual world development and support for input and output devices. This type of system allows users to create a virtual world database giving objects physical and behavioral properties. These include object geometry, color, texture, motion, collision, auditory, and haptic. Some of these systems are RB2 developed by VPL Research and dVS from Division Ltd. (Bricken & Coco, 1994).

Immersion and the Sense of Presence

The term's immersion and sense of presence are often intermingled in discussions about VEs. For this reason a description of this phenomena is provided to the reader. VEs convey a level of presence to the user within the synthetic environment. A greater sense of presence is considered a desirable outcome for VE participants. Kalawsky (1993) describes that many people who have tried VE systems have claimed that they felt as though they were "immersed' or "present" in the VE. Slater and Usoh (1993) define the sense of presence as the belief that people using VE technologies believe they are in a world other than where there real bodies are located. Gilkey and Weisenberger (1995) list some design goals that have been suggested to provide a maximum sense of presence.

These goals are:

1. Users should receive high bandwidth and high fidelity sensory information that is consistent across modalities.
2. The visual display should provide users a wide field of view.
3. Users should be able to see their own virtual bodies through the visual displays.
4. Users should be able to move sensors and control viewpoint with the environment.
5. Users should be able to change the environment.
6. The virtual environment generation system should be responsive, with minimal internal delays.
7. The behavior of the environment would be orderly, in that it appears to obey some set of user predicable laws.
8. Other beings or objects in the environment should respond to the presence of the observer.
9. Users should be isolated from the real world. (pp. 357-358)

Currently, there is no standard metrics that defines the level or degree of immersion or presence conveyed in a VE. Sheriden (1992) notes "that presence is a subjective sensation--a mental manifestation that is not so amenable to objective physiological definition and measurement." Travis, Watson, and Atyeo (1994) define this lack of standards regarding immersion as the great immersion debate. They indicate that the debate is about what the systems requirements are for true immersion. These researchers believe that vendors of HMDs use immersion as a defining feature of VR while vendors of desktop systems are more liberal in their definition. Several other researchers indicate that great emphasis has been placed on creating methods for measuring the level of immersion or presence within a VE. Slater and Usoh (1993) defined the sense of presence as having both external and internal properties. Internal properties are a person's subjective sense of presence and external properties are how the subject interacted with the VE. These researchers also have explored application of neurolinguistic programming to quantify the sense of presence. Hendrix and Barfield (1995) measured the level of presence within visual and auditory VEs. They found that head tracking, larger field of view, and stereoscopic cues provided significantly higher sense of presence. Further investigation by Barfield, Hendrix, and Bystrom (1997) support ··evious findings that head tracking improved the sense of presence.

Most of the work in measuring the sense of presence has focused on the visual aspects of the systems. However, Gilkey and Weisenberger (1995) provide arguments that the auditory channel is just as important and may be crucial in attaining maximum sense of presence. These researchers provide a corollary to deafen adults, suggesting that like experiences of the deaf, the sense of sound is crucial to making one feel that they are in the environment. These researchers also feel that more money should be dedicated to the creation of auditory systems for VEs. Hendrix and Barfield (1996) also found that spacialized sound increased the sense of presence, but not the sense of realism in the VE. They suggest that perceived realism is more influenced by changes that occur in the visual display rather than in the auditory sense. More research needs to be accomplished to develop standard metrics for measuring the sense of presence in a VE and the sense of presence per task.

Human Factors Research and 3-D Displays

Human factor researchers have been interested in how to design systems for human use and how humans perform when using these systems (Sanders & McCormick, 1993). Wickens (1992) believes that 3-D displays should be used to represent 3-D worlds, such as a product design on a computer-aided design workstation. The investigator stresses that a 3-D display is more compatible with the operator's mental model of a 3-D world than is a traditional 2-D display. While 2-D representations provide the user with the necessary information to reconstruct a 3-D picture, 2-D renderings require mental gymnastics to integrate and reconstruct the picture. In an earlier work, Wickens (1990) discussed two basic arguments for implementation of 3-D displays: the visual scene of a 3-D world is more intuitive and natural representation than 2-D displays, and a single integrated object reduces the need for a mental integration of two or three representations.

Sanders and McCormick (1993) discuss 3-D displays in an aircraft environment. They contend that an aircraft occupies a position in 3-D space and that pilots must assimilate and integrate information from 2-D displays into a coherent 3-D image or mental model of the environment. In experiments comparing pilots' initiation of evasive maneuvers to avoid collision, findings show that pilot decision time with 3-D displays was 3 to 6 seconds faster than with 2-D displays.

Wichansky (1991) investigated user benefits of visualization with 3-D stereoscopic displays. Data analysis from controlled human factor experiments showed that user performance with stereoscopic displays exceeded performance of those using 2-D displays for various tasks (visual search, cursor positioning, tracking) and applications (teleoperation, military simulation, and CAD). This researcher also conducted a study of a stereoscopic display system for computer workstations with 20 users and third party software developers, to determine whether a 3-D stereo display was perceived as better than flat, 2-D displays. Results indicated that users perceived more benefits of 3-D stereo in applications such as molecular modeling and cell biology, which involved viewing of complex, abstract, amorphous objects. In these experiments, users typically mentioned clearer visualization and better understanding of data, easier recognition of form and pattern, and more fun and excitement at work as the chief benefits of stereoscopic displays. Stereoscopic displays have also been judged superior for visual search and interactive cursor positioning tasks, for spatial judgment tasks, and for communication of design information (McWhorter, Hodges, & Rodriguez, 1991). These researchers conducted two experiments to rank different types of display formats common to CAD applications for geometric information conveyed and perceived realism of objects. Display types tested were: wireframe, wireframe with hidden lines removed, shaded solid, orthogonal multi-view, stereoscopic wireframe, stereoscopic with hidden lines removed, and stereoscopic shaded solid. The results of the geometric information experiment indicated that the orthogonal multi-view display was judged inferior to both the non-stereo and stereo pictorial displays and that the stereo displays were judged superior to the non-stereo displays in providing geometric information to the subject.

Human factor research related to 3-D displays show that 3-D images are better suited for displaying complex data where relationships are important (Wichansky, 1991;

McWhorter, Hodges, & Rodriguez, 1991). Complexity similar to those seen in CAD models.

Virtual Environment Applications in Design

Applications of VEs can be found in the airline industry, the automotive industry, and in government organizations.

Airline Industry

In 1989, Boeing conducted a company-wide evaluation of the causes of there past design problems as experienced in the traditional design process. One year later. based on that evaluation, a corporate decision was made that by 1992 all design work would be done digitally (Mathes, 1993). Boeing began their research in VEs by focusing on two major projects.

The first involved importing aircraft CAD data into a VR environment with the goal of integrating it into the design test, and mock-up process. Dr. Mizell, Director of Boeing Computer Services Research and Technology Organization, discussed Boeing's purpose for using virtual prototypes indicating that electronic mockups provided company designers with the opportunity to check interference and provided an environment for multiple participants' involvement in the design process. One of the problems articulated by Dr. Mitzell was the problem of converting CAD data into VE data. Airplane virtual mock-ups are 5-10 billion polygons in size. The enormous number of polygons makes it computationally difficult to get the information into memory and difficult to display. These are current limitations of the technologies. CAD part geometry is orders of magnitude more complex than the objects represented in virtual worlds, and it is a tremendous computational challenge to render the images fast enough for useful immersion interaction with the data. To circumvent the problem Boeing developed proprietary algorithms to reduce the number of polygons and improve rendering speed (Norris, 1995).

The second project involved application of augmented reality. It provides the ability to superimpose diagrams or text such as templates or instructions onto the surface or workpiece (Mitzell, 1994). Boeing plans to use this technology to provide appropriate superimposed information to a factory worker for each step in a manufacturing or assembly operation (Mizell, 1994). The goal is to improve the productivity of workers by getting them the information they need when they need it (Pimentel & Teixeira, 1995).

Automotive Industry

VE application has not yet become an integral part of new car product developments, but several engineering departments in the automotive industry are looking at future products through stereoscopic display devices (Sedgwick, 1993). The automotive industry is investigating VE technology to identify its possible benefits and areas of promising application. Mahoney (1995) indicated that the automotive industry is pinning their hopes on the creation of virtual prototype vehicles that can be manipulated in real time. The investigator explains that the real time aspect of vehicle prototype evaluation provides tremendous opportunity to develop the product right the first time.

Since, VE technology is still in its infancy, the benefits of VR applications in automotive design have been restricted to assessments of safety issues, evaluation of maintenance procedures, and vehicle aerodynamics and ergonomics. An excellent example of how VE can be used for product design evaluation is demonstrated when an engineer looks under the hood of an automobile to examine a 3-D-engine compartment. Using a glove the designer could then determine whether a mechanic could reach the spark plugs or change the oil filter. This demonstrates the prevention of future maintenance issues.

The Federal government has encouraged the industrial use of VR technology. A consortium of US Auto leaders and automotive suppliers was formed to establish cooperative efforts to speed research in new technologies that could improve product development and manufacturing (Sedgwick, 1993). This consortium, USCAR, has the power to influence the electronics industry into developing products that will be faster and provide increased computational power necessary for product rendering in VEs.

A proof-of-concept project was developed by the British Aerospace Brough Laboratory to demonstrate the use of VR for product design. Researchers created the interior of a Rover 400 automobile using CAD and a graphical programming language. The system consisted of a high resolution Eyephone™, a Dataglove™, a 3-D sound module, and SGI computers for rendering. Increased realism was obtained by including a real car seat for the user to sit on. Designers were able to study the ergonomics of the car interior accurately and change the position of virtual parts when needed. Using this method it was possible to redesign the whole vehicle while immersed in the simulation. Designers could for example, grab and move the steering wheel assembly from the UK's right handed drive position to the American left handed position (Burdea & Coiffet, 1994; Kalawsky, 1993).

Each automotive manufacturer has taken a different research approach to VEs and product design. However, the fundamental reasons for their research in this area are the same, they all are committed to replacing expensive hardware prototypes with virtual or electronic ones. Ford Motor Company's Vice President for Design, Jack Telnack, is quoted as saying, "It is my vision to link seven worldwide design studios together with computers. VR would allow Ford designers and engineers in England or Japan to work on projects together in real-time" (Keebler, 1993). Strong visions from automotive leaders will play an important role in developing VE technology as a viable tool for product design. Today, General Motors (GM) Corporation is using the CAVE approach combined with GM proprietary software, VisualEyes™. Ellis (1997) explains that GM felt that the CAVE system was a natural way to wrap a car around a human using the system for design team evaluations of ergonomic and vehicle operations. Ford Motor Company and Chrysler Corporation are using traditional head mounted displays and other stereo display devices (Mahoney, 1995). Automotive manufactures are beginning to integrate the powerwall technology for large-scale design evaluations.

Government Organizations

The majority of the work on simulation and VE technology is found in the Department of Defense (DOD) and National Aeronautics and Space Administration (NASA). A summary of their work is provided.

Department of Defense

In the DOD, post-cold war budget cuts have forced military leaders to rethink and restructure the way they train and maintain their forces. U. S. Army leaders are making fundamental changes by placing a greater reliance on computer technology. Simulation is becoming key in all aspects of operations, including research and development, acquisition, testing, evaluation, and training. In 1994 the then, Chief of Staff of the Army, General Gordon Sullivan was quoted as saying "simulation helps us identify and reduce risk" (Kitfield, 1994). The inherent capabilities of simulation offer a tremendous potential to save time and money. In the military, the current trend is for increased technological complexity, maintaining the cutting of edge of state-of-the-art technology, and shorter military hardware lifespans. This requires investments in technologies that are flexible, upgradeable and networkable. The networking capability allows remote simulation without having to transport trainees to the simulator site. This is important because it is another source of cost savings. VR provides this flexibility and networking capability that ideally matches the needs of the military (Burdea & Coiffet, 1994).

A demonstration of DOD's commitment is seen in their current contracting approach. As an example, General Dynamics Electric Boat Division under contract with the U. S. Navy designed a nuclear attack submarine using supercomputers, advanced simulation software, and a centralized database. In addition, they projected stereoscopic images on a special wall size screen, which provides users with the feeling of 3-D immersion. They also placed a multi-disciplinary team of designers, shipyard operators, Navy representatives, and suppliers in a darkened meeting room where they could simultaneously discuss and evaluate the detailed design of submarine components (Ashley, 1995). The researcher further identified the Navy's goal of reducing the design period from nine to five years, thus reducing costs significantly.

NASA

Space is a conducive environment for exploiting VE technology because building a physical prototype for iterative evaluation and training is not practically financially feasible. The Lockheed Group, the prime contractor for NASA Hubble effort, was able to examine a virtual prototype of the Hubble telescope from all angles and rehearse its deployment. Using VE technology during the development and training phases they discovered two important flaws in the original engineering design (Hancock, 1993). These flaws were discovered early enough for the actual flight hardware to be fixed. The investigator postulates that if the virtual prototype had not been available those flaws would have likely remained undetected until much later, after the physical build. This could have increased the risk of the project and might have impacted the success of the mission.

Original VE systems were developed to allow single user immersion. Networking technology offers the capability to link multiple people in an interactive virtual environment. The next section provides information regarding multi-user VE research.

Multi-user Virtual Environments

Wang (1995) defines networked VE as an environment where multiple users are connected by a network and can share information with each other. This networked architecture controls the interaction support, communication handling, and VE knowledge among multiple users. Much of the fundamental research on multi-user virtual environments is found in the computer science literature where computer scientists are developing architectures and operating systems that allow multi-user interaction in a VE. This research focuses on the underlying software and hardware technology issues that are essential to making multi-user VEs a reality. For instance, researchers are working on improvements to networking, operating systems, database management, and communication protocols. Two representative systems are discussed to demonstrate the type of research being conducted in this area: Virtual Environment Operating System (VEOS) and Distributed Interactive Virtual Environment (DIVE). Other network systems include Bricknet, which is based on sharing object geometry and behavior (Singh, Serra, Pag, Wong, & Hg, 1995); and NPSNET, which is based on a Defense Internet Simulation protocols developed at Naval Post Graduate School for military simulation application (Broll, 1995).

Virtual Environment Operating System (VEOS) developed by Human Interface Technology Laboratory at the University of Washington is an infrastructure for VE research based on a distributed UNIX environment (Bricken & Coco, 1994). VEOS was intended for distribution and noncommercial usage. When multiple participants exist in a virtual world, different participants see different views. Each participant can occupy a unique personalized world, sharing the public database partition and not sharing private database partitions. Using the VEOS system demonstration of multi-participant interactivity was conducted within two projects called "Block World" and "Catch." Block World allowed four participants to independently navigate and manipulate moveable objects. Catch demonstrated interparticipant spatial voice communication. Catch allowed individual participants to customize their personal view of the shared world in terms of color, shape, scale, and texture.

Carlsson and Hagsand (1993) developed DIVE. Their research is focused on distribution, collaboration, interaction and multi-user aspects of VE. The system is based on UNIX, Internet protocols, and multicast protocols. Graphical objects called "body icons" represent users. Body icons facilitate awareness of ongoing activities since it defines the position from which the user sees the world. Users can select and grasp objects using interaction devices and these selected objects are attached to the body icon for movement in the VE. DIVE also distributes messages to all members of the world and these messages are interpreted by the application so those objects react autonomously according to their pre-assigned behavior.

The combination of collaborative product design with VE technology may play a key role in next generation CAD tools and design process strategies. The next section describes research in the area of collaborative design using virtual environments. The research conducted to date has focused on the initial developments of collaborative computer aided design tools and studies to evaluate how multiple people will interact in a common design. The goal of these studies is to develop criteria for future collaborative virtual design environments.

Collaborative Virtual Design Environments

Today, most CAD systems are limited in their ability to allow designers to create designs intuitively. Before a design can be created, the designer must have complete knowledge of all the features they are attempting to create (Lansdown, 1994). Designs themselves are 3-D in nature but current CAD input devices, keyboard and mouse, are 2-D. Theses 2-D input mechanisms often restrict the designer because objects must be created using points and lines. Even free form must be defined in terms of control points that bound it. This can prove to be a limitation, especially during the concept design stage of the product when the dimensions are not precisely known (Gadh, 1994). Recent research has focused on applying VE technologies to the product design process. Creating design methods based on 3-D tools in a 3-D environment. This system would contain actual design information with an added feature of product creation, visualization and object manipulation. Deering (1996) developed a VR sketching system called the Holosketch that allows the construction and manipulation of 3-D objects using 3-D tools.

The Holosketch system is based on a desktop VR system with head tracking stereoscopic glasses and a 3-D mouse and wand. The software extends the 2-D sketch-draw paradigm to the third dimension. The system is controlled through the use of a 3-D multi-level fade-up pie menu. Deering (1996) found that significant productivity gains are possible over conventional 2-D interface technologies.

Dani et al. (1994) developed a conceptual virtual design system (COVIRDS) that creates an interactive 3-D environment in which the designer can use a combination of hand gestures, voice input, and a keyboard to create and view an object. COVIRDS uses VR hardware and software technology to provide a designer with a user interface that no longer restricts the user to a 2-D screen. This development is specifically geared toward the early concept phase of development where product dimensions are not precisely known. It allows a more intuitive means for designer creativity. Future features will include a mechanism to translate the conceptual design to a format acceptable by CAD packages. The current system was developed for single user application.

Gisi and Sacchi (1994) developed a system called Co-CAD. A designer can construct complex 3-D objects from primitive 3-D objects such as cones, or blocks. This system functions as a single unit or linked to form a collaborative design environment. When operating in a multi-user capacity each site runs a copy of Co-CAD that shares the semantic data of the design to the other systems. The researchers describe some features that facilitate collaborative interactions: customizable local views, shared pointer, view synchronization, object ownership and access permissions, joining a design session already in progress, and participant termination and failure robustness. These researchers found through interviews with design engineers that this type of tool would not be useful throughout the design phase instead they felt the tool was more beneficial for intermittent consultations or design review uses.

Teledesign (Shu & Flowers, 1994), developed at the Massachusetts Institute of Technology Computer Aided Design Laboratory, is a groupware system that allows people to modify a common design. The system was implemented to study user interface issues. Teledesign supports real time, physically dispersed or face to face meetings of several people using a replicated architecture. This experimental architecture requires each linked site to run individual software applications. It allows sequential access where only one designer can enter edits at a time and simultaneous access where all the designers can edit at the same time. Two experiments were conducted using five groups of two subjects each. In the first experiment, the primary goal was to determine the effects of different modes of edit access or floor passing schemes on the performance of different types of collaborative design tasks. Two modes were investigated: simultaneous editing and sequential editing. It was revealed that a simultaneous mode of edit access was preferred over a forced turn-taking mode. The second experiment was designed to evaluate performance of a software system expert-novice team, where the expert demonstrated the available functions and system features. It was found that the use of a telepointer was critical during the teaching/instructional phases. It was also found that allowing designers to have independent point of views optimized parallel activity when independent tasks were performed. Also, the need for a 3-D pointer and knowledge of the other designer's point of view was established.

The Institute of Simulation and Training at the University of Central Florida developed a prototype system called Polyshop which utilized a unique two handed interface and an immersive stereoscopic display system that allowed a modeler the ability to manipulate data in a true 3-D perspective. The two-handed direct manipulation interface described by Mapes and Moshell (1995) is based on real world object manipulation. As in the real world, it allows the user to use head rotation to easily view the object and allowed the user to grasp objects for manipulation. The prototype system featured simple operations of object rotation, translation, scaling, alignment, and gluing more than one object together. The system was developed as a rapid construction model for urban combat mission training (Blau, Mapes, & Moshell, 1993). This prototype further developed and commercialized by Multigen, Inc., a product called SmartScene™ (Multigen, 1998). This product allows for real-time 3-D-scene assembly. Users are immersed in a 3-D visual workspace, and within this virtual workspace using a two-handed interface and Smart Model Time Behaviors can create 3-D world objects. The two-handed interface incorporates natural hand gestures to grab and manipulate models with two hands. The Model Time Behavior allows users to quickly snap objects together, position them, and scale them. This system is targeting the visual simulation, urban planning, entertainment, and mechanical assembly tasks and markets.

The literature clearly demonstrates that new emerging VE technologies have the potential to enhance the design process by offering a more natural mechanism for design teams to assemble and evaluate future product concepts.

Summary

The product development literature clearly identifies a need for organizations to strive towards decreasing time to market, to improving product quality and to creating customer interfaces as integral parts of the design process. These basic requirements are necessary for organizations to remain competitive.

The literature surrounding the concept design process indicates that design is a creative process, where visualization promotes identification of design problems by providing humans with feedback to analyze concepts and this potentially can help to achieve improved product design efficiency and effectiveness. Visualization can be achieved through pictorial representations, physical mockups or virtual replicas of a real object.

Product design reviews are critical milestones in product development efforts. Individuals are assembled to evaluate the progress of a design. Team design reviews have been beneficial for improving product designs because control and decisions are placed in the hands of functional experts, participants take stake in the outcome, and teams generate a synergy of expertise that assists in problem solving.

Product design relies on the activity of teams of individuals with varying backgrounds and experience. Concurrent engineering methodologies have been successful in improving product design cycle time and product quality by allowing multi-functional teams to interact and share information giving these teams the capability to make more informed, better decisions. Collaboration or group work has also been investigated within the field of computer supported cooperative work where researchers are interested in developing a greater understanding for automation of group activities and tool interaction. The literature in this area demonstrates the initial kindling of researchers interested in developing collaborative product design tools.

Product design is in a state of evolution, depending heavily on improvements in computer technology. Transitions occurred from traditional 2-D hand drawings to 3-D solid model CAD that has automated the performance of individual designers, cutting design times dramatically. This reduction of time and cost is directly attributed to the fact that the designer is provided with a set of tools that enhance product design activity.

A new emerging technology, VEs hold promise for product design improvement. VE offers a potential to cut product design time and to improve product quality because VE has the capability to provide a sense of reality to a product design and to allow multiple people to interact in the same virtual design environment without ever building a physical prototype.

This review of relevant literature demonstrates that the concepts and theories which compromise and mold the intriguing problem of integrating the requirements of VE visualization tools and automation into a multi-functional collaborative product design environment is still in an eariy stage of research. Researchers have only begun to understand the complexity of how to use commercial visual display devices, how to develop better design tools, and how to use them in a more efficient and effective manner.

CHAPTER 3

METHODS AND PROCEDURE

This study was conducted at the U. S. Army Tank-automotive and Armaments Command (TACOM) in Warren, Michigan. Research data were collected over a four-day period to empirically examine the effects of 3-D stereoscopic visual display technologies on the CDR process. Test subjects representing several functional areas were grouped into three person design teams. These teams conducted a design review task using each of the four visual display systems being investigated. This chapter details the research design, data collection procedures, and data analysis methodology.

Research Design

The purpose of this study was to evaluate, through comparative empirical testing and data analysis, how several commercially-available virtual 3-D visual display systems contribute to cross-functional team collaboration in a product design review environment. These computer visual display technologies, often referred to as output devices for VE systems, allow users to perceive 3-D objects in virtual space. This study focused on an evaluation of several visual display technologies that are currently being used and evaluated in various public and private sector product development organizations. Display systems tested were a Helmet Mounted Display (HMD), Binocular Omni-Orientation Monitor (BOOM), Stereoscopic glasses and monitor (with

IR emitter and sensor), and for comparison a traditional monoscopic CRT monitor. Figure 3 illustrates the visual display technologies used in this study.

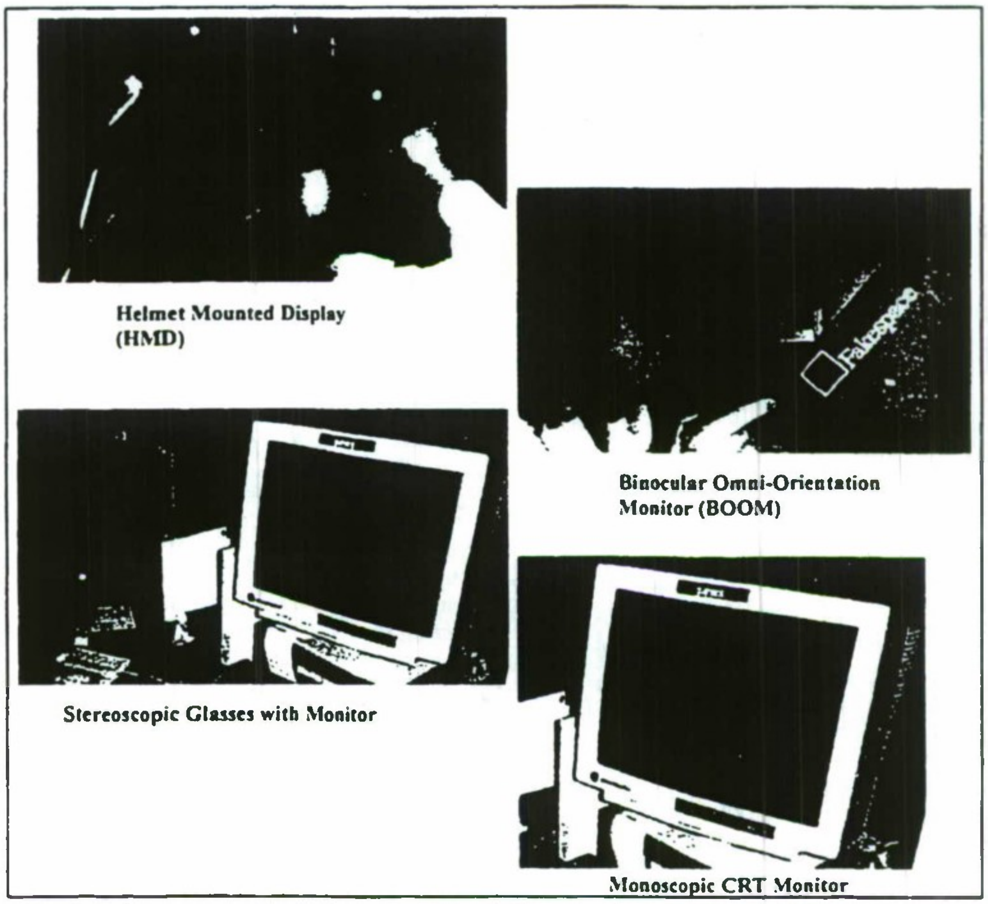

Figure 3. Commercial Visual Display Systems

Visual display systems are often categorized by how the observer uses his or her eyes to create a visual image. Monoscopic systems display the same 2-D image to both eyes. In contrast, stereoscopic systems present a different image to each eye, creating the effect of depth. Table 1 associates the visual display systems used in this study with the type of display system. As shown, three of the test visual display systems were stereoscopic devices and for comparison one monoscopic system was used.

Table 1.

Visual Display System Categorization

Helmet Mounted Display System (HMD)	**Stereoscopic**
Binocular Omni-Orientation Monitor (BOOM)	**Stereoscopic**
Stereoscopic Glasses and Monitor (IR Emitter/Sensor)	**Stereoscopic**
Traditional CRT Monitor	**Monoscopic**

It was hypothesized for this study that the use of VE technologies and their capability would allow users to visualize and interact in virtual concept designs and conduct CDRs more effectively and efficiently, and their use would improve the design process and the inherent qualities of end products. These improvements can be associated with the capabilities that visualization technologies offer. It was also hypothesized that these technologies may have the potential to provide product design teams with a common platform to evaluate early conceptual designs and may assist in the resolution of design problems. However, no existing empirical data supports these hypotheses. Only broad claims demonstrating the value of the technologies have been made (Ellis, 1997). The research design method used in this study served to provide insight into these broad claims. Five questions were developed to address the impact of 3-D visual display technologies on the CDR process. They are:

1. Do design teams detect and identify more design problems and design errors when using 3-D visualization tools?
2. Do design teams detect and identify design problems and errors more quickly when using 3-D visualization tools?
3. Do design teams resolve design problems more quickly when using 3-D visualization tools?
4. What is the perceived impact on the design process, the quality of the design process, and the physiological state of the design team members after using 3-D visualization tools?
5. When comparing the four visual display technologies, what are preferences of their usefulness, difficulty, practicality, stimulation for team interactivity, and development of team consensus?

Subjects

CDRs are periodically conducted throughout the conceptual design and product development process. Design teams are formed using volunteer representatives from several functional areas within an organization. These teams consist of members with differing educational backgrounds and functional responsibilities.

Participants for the study were personnel from the TACOM center in Warren. Michigan. TACOM is a Department of the Army organization with 4,800 employees whose responsibilities encompass the design, development, and procurement of military ground vehicle systems. The sample population consisted of 12 male volunteers from the following operational organizations: new equipment training, human factors, logistics and maintenance, configuration management, quality assurance, and design.

Participants were tested for color deficiency and visual acuity prior to the experimentation using a standard Ishihara Color Deficiency test (Ishihara, 1996) and a Snelling Chart Examination. Participants that tested positive for color deficiency were eliminated from the subject pool. Design teams were purposefully created with similar backgrounds and characteristics based on an aggregation of their work experience, computer usage, education, and design review experience. Table 2 indicates the demographics of the test population. The table summarizes test participant background data and design team composition. As shown, each design team consisted of one designer and two non-designers.

Experimental Design

The experimental design used in this study is a 4x4 Graeco-Latin Square as described by Box, Hunter, and Hunter (1978). This experimental design permits the study of four treatments (technologies) simultaneously with three different blocking factors (teams, TFTS subassemblies, and experiment order). A matrix showing the relationships between visual display technologies (A-D), teams (T), TFTS subassemblies (1-4), and experiment order (E) is depicted in Figure 4.

Table 2.

Summary VE Participant Background Data

	Test Participants and Their Backgrounds											
Subject	1	2	3	4	5	6	7	8	9	10	11	12
Team	T_1			T_2			T_3			T_4		
Type	D	N	N	D	N	N	D	N	N	D	N	N
Organization	D	NT	CM	D	M	NT	D	HF	CM	D	QA	L
Education	3	2	2	3	4	2	3	3	3	4	3	1
Work Experience in Field	5	6	6	5	4	5	3	6	4	4	6	5
Number of Computer Systems Experienced	6	3	6	6	5	1	3	1	5	3	2	4
Number of 3-D Visualization Tools Experienced	4	3	1	3	1	0	4	0	0	4	0	1
Number of Design Reviews	6	0	0	6	0	0	2	6	0	2	0	3

Notes:

Type: D = Designer; N = Non-designer

Organization: D = Design; NT = New Equipment Training; CM = Configuration Management; HF = Human Factors; QA = Quality Assurance; L = Logistics

Education: 1 = High School; 2 = Associates Degree; 3 = Bachelors Degree; 4 = Masters Degree and Post Graduate

Work Experience: 1 = less than one year; 2 = 1 up to 3 years; 3 = 3 up to 5 years; 4 = 5 up to 10 years; 6 = 10 up to 15 years

Teams

Experiment	T_1	T_2	T_3	T_4
E_1	A1	B2	C3	D4
E_2	B3	A4	D1	C2
E_3	C4	D3	A2	B1
E_4	D2	C1	B4	A3

Visual Display Technologies

A =Helmet Mounted Display System (HMD)
B = Binocular Omni-Orientation Monitor (BOOM)
C = Stereoscopic Glasses and Monitor
D = 3-D Monoscopic CRT Monitor

TFTS Subassemblies

1 = Fuel Transfer
2 = Fuel Container
3 = Towing
4 = Suspension

Figure 4. Experimental Design: A 4x4 Graeco-Latin Square

The Graeco-Latin Square was selected for its appropriateness to the research hypotheses proposed in this study. The treatments that are to be compared are four visual display technologies. These technologies are referenced as A, B, C, and D and are defined as a HMD, BOOM, stereoscopic glasses and monitor, and traditional monoscopic CRT monitor, respectively. The three blocking factors were the four design teams (T_1, T_2, T_3, T_4), the four different TFTS subassemblies (1, 2, 3, 4), and the four experimental orders (E_1, E_2, E_3, E_4).

The Graeco-Latin Square Model protects against the possible confounding effects that jeopardize the internal validity of an experiment. Campbell and Stanley (1966) defined seven threats to the internal validity of an experiment as follows:

1. History: Any events occurring between the first and second measurement of the experiment, in addition to the experimental variable.
2. Maturation: Processes of the subjects operating as a function of the passage of time, such as growing older, growing hungrier, and growing more tired.
3. Testing: The effects of taking a test upon scores of a second test.
4. Instrumentation: When changes in the calibration of an evaluation instrument or changes in the observers and administrators of a test may produce changes in the obtained measurements and scores.
5. Statistical Regression: A circumstance occurring where groups have been selected on the basis of their extreme scores.
6. Biases resulting in differential selection of respondents for the comparison groups.
7. Experimental Mortality: The loss of subjects from the comparison groups, which are potential threats to the internal validity of an experiment. (p. 5)

In this study, the duration of the experiment was one week, with each design team completing their experimentation in one day. The short time in between each treatment precludes possible effects of history and maturation. In addition, because purposeful assignment of design team members and randomization of factor assignment controlled initial differences between design teams, threats such as testing and statistical regression, if they occurred at all, affected design teams equally. A single independent test observer collected data for the experiment and subjective data was collected on printed questionnaires. These controlled for changes in instrumentation. The treatment period of the study was extremely short, a one hour duration. The short time span eliminated any effect of differential mortality between treatments. In summary, seven threats to internal validity of the study were controlled.

External validity refers to the generalization of results of an experiment to other populations and/or settings. The study involved the task of concept design review and evaluation. Caution is suggested when generalizing findings from this research to other tasks or settings. Details of the TFTS concept used for this study and operational requirements were provided to form a basis for estimating the degree to which research findings were likely to apply to other tasks. In addition, the use of U. S. Army personnel assembled into teams suggested caution in generalizing findings from this research to individual performances or to other team composition. Information regarding team composition, such as organization, education, work experience, computer usage, and design review experience of the research sample was provided to form a basis for estimating the degree to which research findings were likely to apply to other populations.

Tracked Fuel Trailer System (TFTS) Model Development

The TFTS was an exploratory idea being investigated by the U. S. Army TACOM. The TFTS was based on novel operational requirements for a trailer system that could carry a 600-gallon fuel pod and that would continuously provide fuel to an

Abrams M1 Main Battle Tank while in tow. Appendix B provides the operational requirements for the system. Based on the operational requirements one concept of the TFTS was designed, modeled, and translated into a virtual software environment. Figure 5 pictures the conceptual model of the Abrams M1 Main Battle Tank and TFTS used for this study.

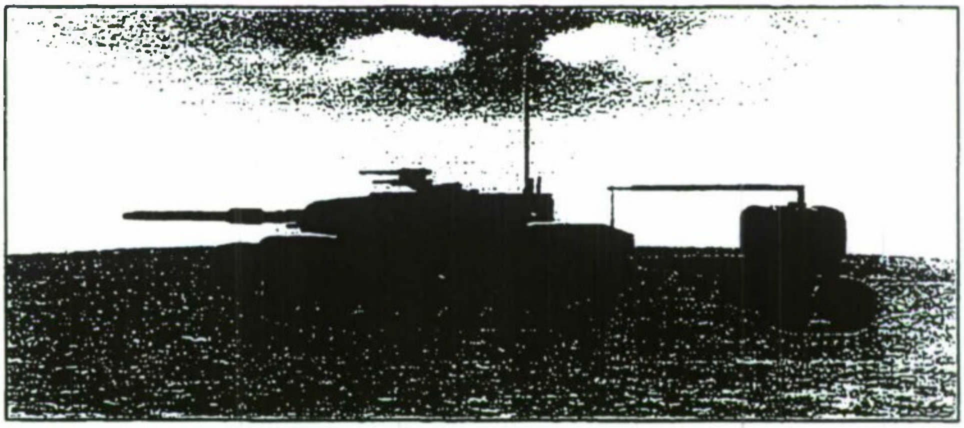

Figure 5. Abrams M1 Main Battle Tank and TFTS

The TFTS design was separated into four major subassemblies. These are the fuel transfer, fuel container, suspension, and towing subsystems. Figure 6 identifies the four subassemblies used in this study.

The four subassemblies of the TFTS contained design problems and design issues with similar levels of complexity based on an evaluation by a senior-level designer. These problems and issues are related to mechanical, ergonomic, maintenance, and operational functions.

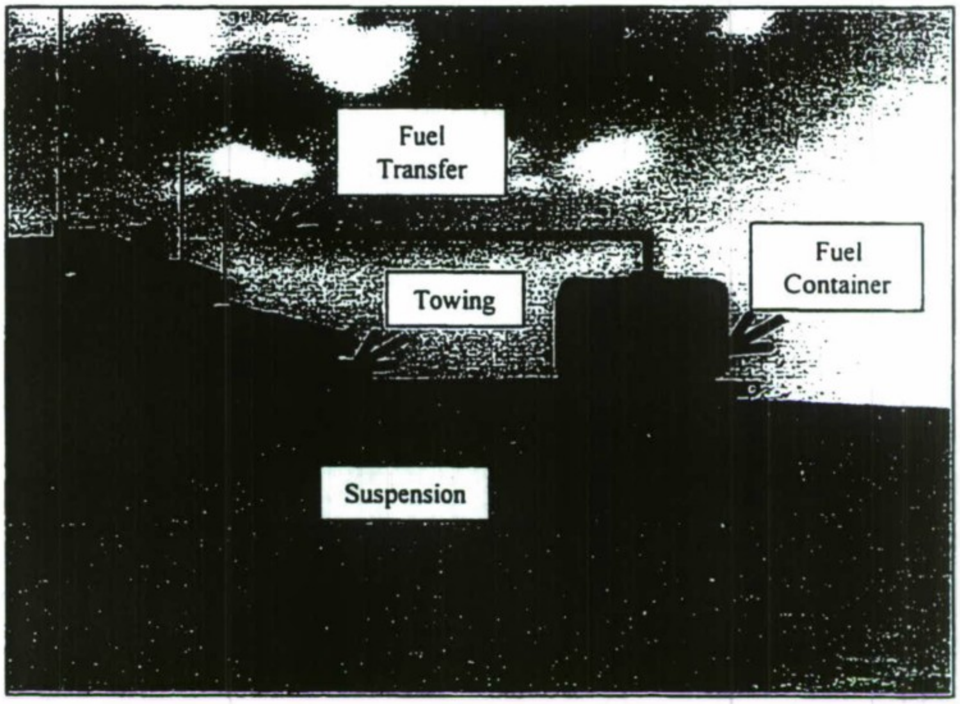

Figure 6. TFTS Subassemblies

The model of the TFTS was designed using commercial Intergraph CAD software. The TFTS CAD file was then translated using commercial DIVISION, Inc. VE software. This software uses dVS as its virtual reality operating system. The dVS operating environment is a flexible environment for the development of immersive and desktop VR applications. In addition, DIVISION uses dVISE as a VR interactive authoring tool. This tool allows for the creation and experiencing of complex virtual environments. The software is capable of interfacing with the four visual display configurations being investigated in this study.

Treatment Conditions

To provide four treatment visualization technologies necessary for this study, four different hardware visual display configurations were set-up:

1. HMD
2. BOOM
3. Stereoscopic Glasses and Monitor
4. Monoscopic CRT Monitor

Helmet Mounted Display (HMD)

The HMD hardware visual peripheral device used for this study was a Virtual Research Systems, Inc. VR4™ Helmet Mounted Display system. The set-up also included: Silicon Graphics Onyx RE2 computer system, 21-inch CRT monitor, Virtual Research Systems controller box, and a Division, Inc. 3-D pointer device. Figure 7 provides a schematic of the HMD configuration used in the experiment. As illustrated, the test participants used a single HMD with electromagnetic head tracking, a 3-D Mouse Pointer for navigation, and a monitor system for team viewing.

During testing participants individually shared the HMD resource. While the test operator used the stereoscopic HMD device, the remaining team members viewed the operators perspective on a computer monitor. Test participants took turns using the HMD and watching the monitor.

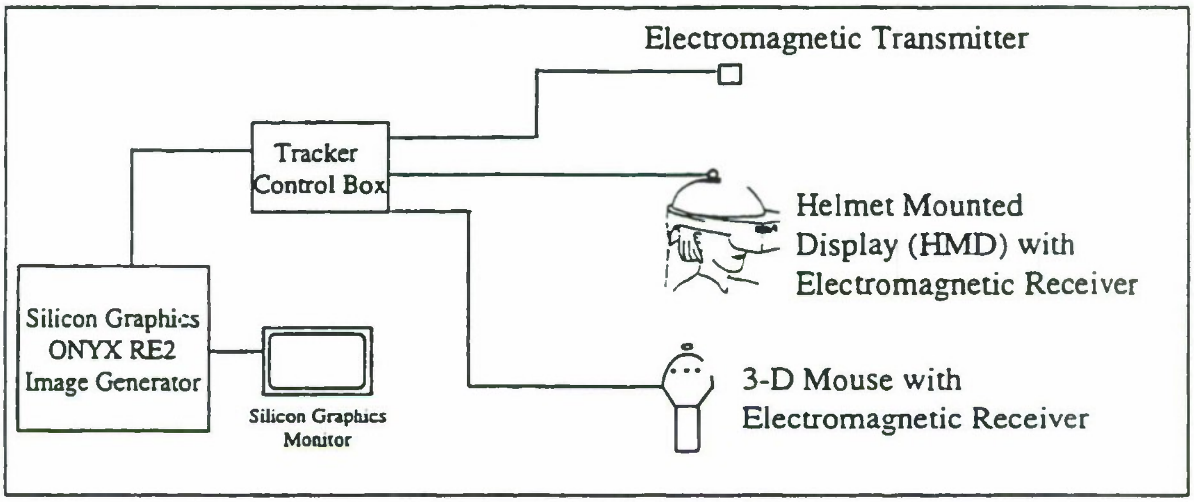

Figure 7. HMD Hardware Configuration

3-D Pointer Navigation for HMD

Figure 8 diagrams the 3-D pointer device that was used to navigate in the virtual world. As shown in the top view, the left button is used to move forward, the right button is used to move backward, and if depressed the center button brings up an interactive tool bar menu that allows immersed users the capability to alter the virtual model. The center button was deactivated and not used for this experiment. The side view shows the handle grip of the 3-D pointer device. The top button can be depress using the index finger, and has the function of selecting. The bottom button is only used in combination with the forward or reverse button, in order to set the viewers height in the virtual world. For instance, if the viewer wants to see the virtual model from the top perspective, system users would have to physically look up with their HMD on, depress both the forward and set height buttons. This would move the viewer's perspective to the top of the model.

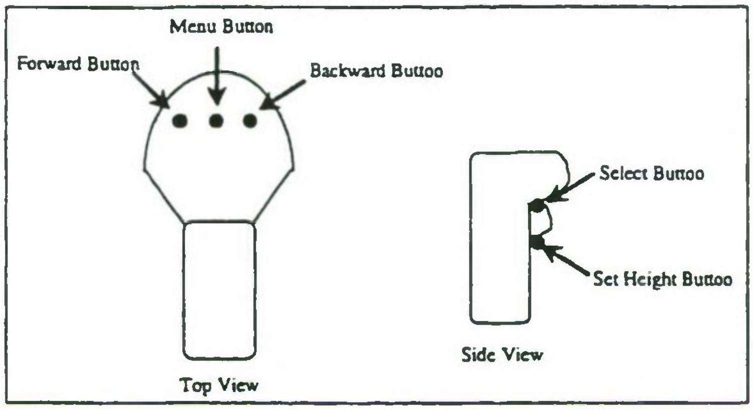

Figure 8. 3-D Pointer Functionality

Binocular Omni-Orientation Monitor (BOOM)

The BOOM hardware visual peripheral device used for this study was a Fakespace, Inc. BOOM3C™ model. Figure 9 illustrates the BOOM configuration for the experiment. As shown, the system consists of a single BOOM device linked to a system 21-inch monitor for concurrent viewing. The set-up also included: Silicon Graphics Onyx RE2 computer system and a Fakespace interface box. Inherent in the BOOM design are six encoders that track the user position in the virtual world.

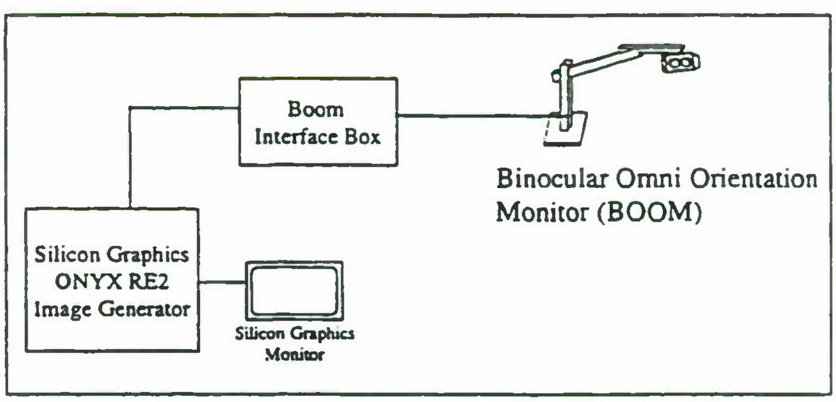

Figure 9. BOOM Hardware Configuration

Test participants individually operated the stereoscopic BOOM resource. While the test operator used the BOOM device, the remaining team members viewed the operators perspective on the system monitor. Test participant took turns using the BOOM.

Navigation for BOOM

Figure 10 illustrates the BOOM navigational device that is used to move in the virtual world. As illustrated, the functionality of the right button is acceleration, the left button is used for de-acceleration, and simultaneously depressing both buttons stops any movement.

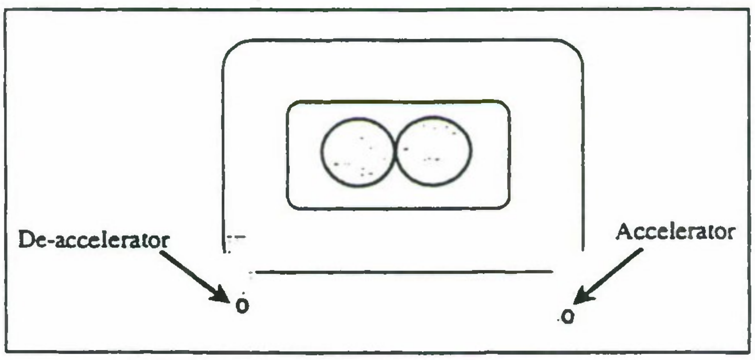

Figure 10. BOOM Operation

Stereoscopic Glasses and Monitor

The stereoscopic glasses visual peripheral device used for this study was a StereoGraphics, Inc., CrystalEyes™ product. CrystalEyes hardware includes eyeware and an infrared (IR) emitter. Figure 11 provides a schematic of the stereoscopic glasses configuration for the experimentation. As illustrated, the experimentation used a Silicon Graphics Onyx RE2 computer system, 21-inch computer monitor, stereoscopic glasses, electromagnetic emitter, and mouse.

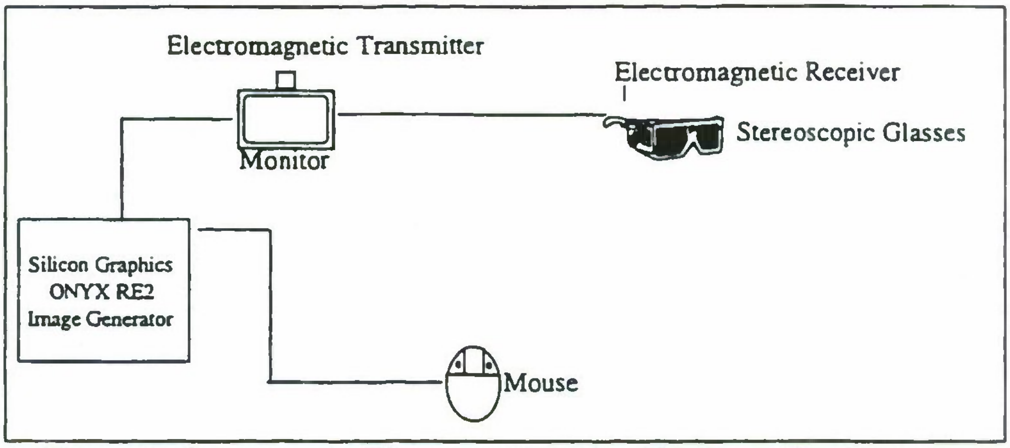

Figure 11. Stereoscopic Glasses and Monitor Hardware Configuration

The stereoscopic glasses configuration allowed all test participants to view the virtual world simultaneously. Each participant wore a pair of stereoscopic glasses that created the 3-D stereoscopic visual perception. However, the mouse device allowed only one person to navigate the computer-based model at a time. Test participants shared the mouse resource. While one person navigated using the mouse device, the other team participants viewed the operator's perspective through a computer monitor and stereoscopic glasses.

Mouse Navigation for Stereoscopic Glasses and Monitor

Figure 12 illustrates the mouse device that is used to navigate in the virtual world. As shown in the top view, the center button is used to move right, left, up, or down. Depressing both the center and right buttons creates a panning effect that allows the user to freely move in any direction. The left button is used for selecting objects. For this experiment, no object selection was required.

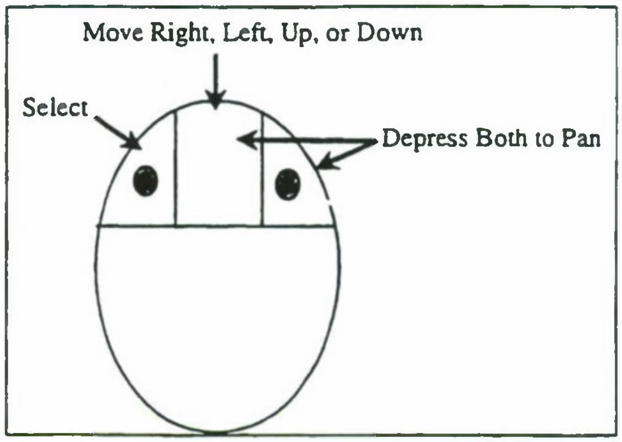

Figure 12. Mouse functionality

Monoscopic CRT Monitor

Figure 13 provides a schematic of the monoscopic configuration for the experiment. As illustrated, the experiment used a Silicon Graphics Onyx RE2 computer system, 21-inch computer monitor and a mouse. By definition the monoscopic configuration does not provide the users with any depth perception, analogous to traditional desktop PC computer systems.

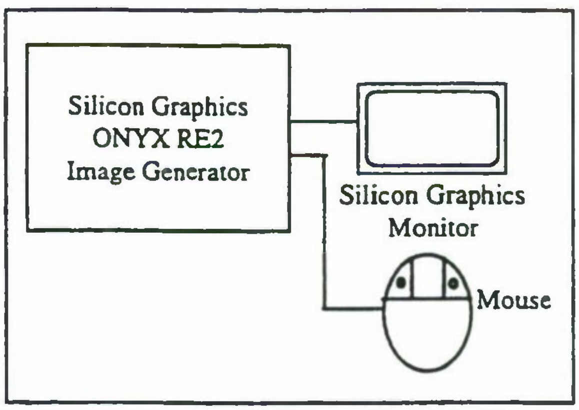

Figure 13. Monoscopic CRT Monitor Hardware Configuration

Similar to the Stereoscopic glasses and monitor configuration, the monoscopic configuration allowed all test participants to share the computer monitor and simultaneously view the virtual model. However, the mouse device only allowed one person at a time to navigate the computer-based model at a time. Test participants shared the mouse resource. While one person, navigated and used the mouse device, the other team members viewed the operator's perspective by looking at the computer monitor.

Mouse Navigation for Monoscopic CRT Monitor Configuration

Operation and navigation in the monoscopic setup is identical to the stereoscopic glasses and monitor configuration. For more detail refer to Figure 12 and the description paragraph associated with navigation for stereoscopic glasses configuration.

A summarized listing of some of technical and general specifications of the four visual display systems tested in this study is provided in Table 3. FOV is defined as the part of space you can see immediately, without moving your head or your eyes. In terms of a visual display, the FOV is the visual angle subtended by the display (Stuart, 1996). In each configuration, a separate 21-inch CRT monitor was used for team participant viewing. As shown, the cost of the visual displays range from $800 per individual Crystal Eye glasses to over $100,000 for a BOOM system. The systems were implemented using a SGI Onyx Reality Engine 2 computer with graphics capability costing approximately $350,000. The cost of this system may be reduced as newer, SGI Infinite Reality machines are introduced into the marketplace.

Data Collection

Experimental tasks, data collection procedures, and instrumentation were required for investigation of four visual display technologies on their contribution to the CDR process. This study employed several evaluation approaches documented in human-computer interface and usability literature. These approaches were: empirical evaluation of the task, Likert-like questionnaires, human interface comparisons, and open-ended questions (Stuart, 1996; Nielsen, 1993; Bardsley & Sexton, 1997). The later two methods were designed to gather supplemental data regarding the use of the four visual display technologies. This researcher developed a test plan summary that outlines the research design and methodology for completion of this study. A copy of the test plan summary is contained in Appendix C.

Table 3.

Test Visual Display Systems Specifications

Company	Model	FOV (degrees)	Type of Optics	Resolution	Weight (Ounces)	Cost 1998 ($)
Virtual Research Systems, Inc.	VR4	60	Dual LCD	640x480	33	6,900
Fakespace, Inc.	BOOM 3C	45	CRT	640x480	**0	110,700
Stereographics Inc.	Crystal Eyes	*70H 140V	Liquid Crystal Shutter	1280x1024	3.3	Glasses 795 Emitter 200
Silicon Graphics, Inc.	CRT Monitor	Full Monitor	None	1280x1024	0	0

Notes: * CrystalEyes FOV is the infrared angle of view of the emitter. H=horizontal and V=vertical

** BOOM weight is interpreted as the weight a user would sustain when using the system.

Each test system configuration included a 21-inch SGI CRT monitor which costs $3,000 and a SGI Onyx RE2 which costs approximately $350,000. These costs reflect government pricing.

Experimental Tasks

Traditionally, design reviews are conducted periodically during the product development and design process. The intent of these reviews is to identify problems, formulate solutions, and develop a consensus among design review participants. Emulating this environment, the experimental task consisted of having multi-functional design teams identify and solve design problems with the assistance of four visual display systems.

Procedures

Illustrated in Figure 14 is the methodology used in conducting this study. The procedures are separated into seven sections: VE Assessment Survey One, pre-test orientation, test protocol, technology familiarization, experiment and data collection, VE Assessment Survey Two, and VE Assessment Survey Three.

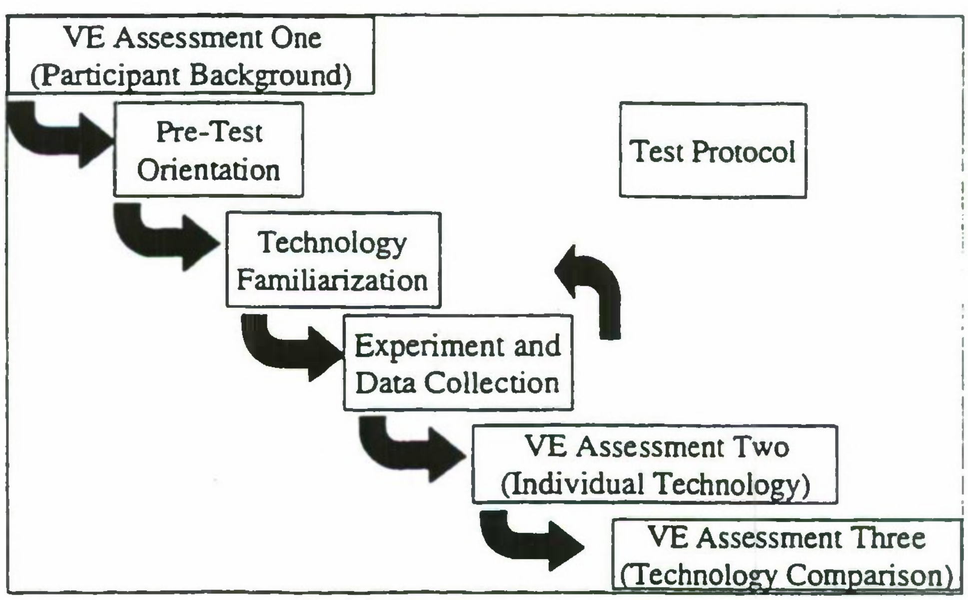

Figure 14. Design Methodology and Procedures

Prior to formal experimentation at the U. S. Army TACOM, a pilot test served to validate the experiment and experimental procedures used. One team consisting of three members volunteered to participate in the pilot test. Using the same experiment procedures, hardware configurations, TFTS model, and experiment location as the final experimentation pilot subjects conducted CDRs using the four test visual display systems. The pilot design team used each of the four visual display technologies to evaluate each of the four TFTS subassemblies. Result from the pilot study identified potential experimental set-up deficiencies, enabling improved experimental organization. Difficulty in taking time measurements for team performance was identified and corrected. A change in the design protocol was made requiring teams to conduct their CDRs in a sequential manner by identifying and resolving one design problem at a time before moving to the next. This eliminated the data collection problem with regard to the sequencing and timing events. The pilot test also provided confirmation of the structure of the questionnaires and identified areas for improvement on the data collection forms.

VE Assessment Survey One: Participant Background

A VE Assessment Survey One questionnaire was designed by the researcher to obtain test participant background information. A copy of this survey is contained in Appendix D. The questionnaire-included sections on educational background, professional work experience, level of computer usage, and design review experience. Questions regarding participant's computer experience were based on a Questionnaire for

User Interface Satisfaction (QUIS) created at the Human-Computer Interaction Laboratory at the University of Maryland (Chin, Diehl, & Norman, 1988). Participants completed VE Assessment Survey One prior to the start of experimentation. Questionnaire data were used to assign participants to four design teams to achieve team balance with regard to their work experience, computer experience, education, and design review experience. A total of three test participants composed each design team. Each design team consisted of one designer and two non-designer functional members.

Pre-test Orientation

A pre-test orientation was given to each team in a TACOM conference room on the day of their experiment. The researcher presented an experiment overview of the following: general experiment purpose and objectives, a description of the TFTS, system requirements, a schedule of events, and a description of test conduct and protocol. A copy of this presentation is contained in Appendix E.

Test Protocol

Participants were asked to strictly adhere to the test protocol to facilitate data collection. A summarized list of the protocol is contained in the test plan summary located in Appendix C. The test was conducted in the Design Laboratory at U. S. Army TACOM. Each day, a experiment design team moved sequentially between technology stations and were given a one-hour time limit to conduct their observations and design reviews. Design teams were asked to focus on one TFTS subassembly at a time. Order was defined following the design sequence of the Graeco-Latin Square. In addition, groups were told that there were at *least* three problems in each TFTS subassembly. Participants were then asked to identify a design problem sequentially, and to resolve the problem before moving on to the next problem. The purpose of the design review task was to reach group consensus on problem identification and possible resolution. If a design team could not solve a problem it was required that team members must agree that the resolution is not solvable at this time. The teams were then allowed to move to the next problem. The design representative in each experiment team was designated as the team leader and discussion facilitator. It was suggested that the teams use the technology in anyway they felt was appropriate for the problem identification and resolution.

For consistency, an outside single independent test observer served as a data collector for each day and moved between technology stations with the experiment design teams. This observer, a senior-level project engineer, was given brief instructions on subject testing methodologies and data collection procedures.

The study researcher served three roles during the experimentation: technology administrator, technology trainer, and secondary observer. As the technology administrator, this researcher was responsible for setting up each experiment configuration and starting up each system prior to each technology experiment. As the technology trainer, the researcher taught the test participants basic operating procedures for each technology. As the secondary observer, the researcher moved between technology stations with the experiment design teams and conducted outside evaluations of each experimental session. Appendix F contains a summary of the comments made during these observation.

Technology Familiarization

The researcher conducted a standard 15-minute system familiarization using an alternate model at each technology station prior to testing. All experimental team participants received technology familiarization that provided them with the basic skills necessary to operate each of the technologies.

Empirical Evaluation of the Task

The independent outside test observer documented the performance of design teams by taking continuous time measurements of the start and completion times of each problem identified and resolved by the team. In addition, the test observer documented how the design teams used the technologies and made comments on anything unusual that occurred that may have impacted the data during the experimentation. The data was documented on a quantitative data collection sheet designed by the researcher and is included as Appendix G.

VE Assessment Survey Two: Individual Technology

A VE Assessment Survey Two questionnaire was designed by the researcher to measure the strengths and weaknesses of the visual display technologies to support the design review process. Refer to Appendix H for details. This questionnaire is based on a fundamental usability assessment method and used Likert-like questions. Stuart (1996) defines this type of assessment as rating scales with which users retrospectively express their subjective satisfaction with specified aspects of the human-computer interface. Participants were asked to make their assessment on a 1 to 5 scale, where the value of one was related to a negative feeling and a value of 5 was related to a positive feeling. The questionnaire contained 29 questions divided into four sections: training, CDR process, quality, and physiological effects.

Training questions were designed to assess whether users felt they had an adequate level of technology familiarization to conduct the design review task. Questions in the quality section were based a Questionnaire for User Interface Satisfaction (QUIS) created at the Human-Computer Interaction Laboratory at the University of Maryland (Chin, Diehl, & Norman, 1988). The physiological section of the questionnaire focuses on the mental and physical state of the participant's experience in the VE after exposure to the four treatment technologies. A scoring procedure developed by Kennedy, Lane, Lilienthal, Berbaum, and Hettingger (1992) was the source of the 16 symptoms identified in the questionnaire. One question regarding measures of perceived mental workload was included to assess how mentally demanding the technology was to the test participants. This question was based on a modified Cooper-Harper (1969) scale.

To gain insight into the value of the technologies and possible design improvements, additional user feedback questions were developed. Participants were asked how many hours a day they would be willing to use the technology, if they felt the technology was more beneficial for individual use, and if there was any aspect of the visualization tool that could be improved to enhance CDR tasks.

A second usability assessment approach was incorporated in VE Assessment Survey Two. This assessment used open-ended questions, which allowed users to record observations and subjective comments that could not be captured with a Likert-like questionnaire (Stuart, 1996; Nielsen, 1993). Space was provided at the end of each section in the questionnaire for participants to make any comments regarding: the training they received prior to the test phase, the effect of the visualization tool to perform CDR tasks, the quality of the technology as it applies to product design, and their physical and emotional state after using each technology. The questionnaire was administered to each test participant in the TACOM Design Lab immediately following completion of each treatment condition. There was no maximum time limit for VE Assessment Survey Two completion.

At the completion of each technology experiment and survey, the design team moved to the next experimental technology according to their assigned test sequence. This staging was repeated four times, until each design team completed experimentation with all four-visual display technologies.

VE Assessment Survey Three: Technology Comparison

At the end of the entire experiment, and after each team had completed experimentation using all four visual display technologies, individual participants were asked to complete VE Assessment Survey Three which consisted of five questions. Participants were individually asked to compare the technologies by ranking them from one to four. Where a value of one was considered the most useful, most difficult, most practical, most helpful in stimulating team interactivity, or most beneficial for developing team consensus. The value of four was equated to the least performance for each technology.

Space was also provided at the end of this questionnaire for participants, in retrospect after experiencing all four visualization technologies, to make any changes to their previous responses on VE Assessment Survey Two. Appendix I contains VE Assessment Survey Three -- the technology comparison. This survey was administered in the U.S. Army TACOM Design Lab immediately following completion of all four-treatment conditions. There was no maximum time limit for the survey.

Upon completion participants were asked to refrain from discussing any of the visualization technologies with any other colleagues to eliminate the possibility of biasing any future testing or experimentation.

Instrumentation

Data Measurement

An independent outside test observer using a digital stop watch took continuous time measurements of the start and completion times of each problem identified and resolved by the team. Time measures were taken and recorded to the second. Using a single independent test observer maintained consistency and reliability of the data collected.

VE Assessment Surveys One, Two, and Three

The instruments VE Assessment Surveys One, Two, and Three were constructed on the basis of the review of related literature and recommendations from dissertation committee members. However, because of the nature of the instrument, no attempt was made to establish reliability or validity.

Data Analysis Methodology

Several methodologies were planned for quantitative and qualitative data analyses. The quantitative analyses employed four-way analysis of variance. Dependent measures were the number of design errors detected, the average time to detect a design error, and the average time to resolve a detected design problem. Significant mean differences were analyzed via separate post hoc analysis utilizing Bonfererroni pairwise comparison methodologies. Descriptive findings and Kruskal-Wallis analysis on the cumulated data were reported for qualitative data collected in VE Assessment Survey Two -- Individual Technology. Data collected in VE Assessment Survey Three -- Technology Comparisons, were analyzed using non-parametric Freidman analyses. Significant mean differences were analyzed via separate post hoc analysis utilizing a follow-on pairwise comparison test to the Freidman statistic method.

Summary

The methods and procedure for the experiment followed standard laboratory research testing practices. The subjects were 12 personnel from the U. S. Army TACOM who served as subjects to test the hypotheses of the effect of VE visual display technologies on the CDR process. This experimental design focused on the use of data to show the differences between the four visual display technologies. The objective of the study was to evaluate the use and value of four different commercial visual display systems during the multi-functional group CDR process and to measure how this process is impacted by the use of these tools. The next chapter presents analysis of the data collected from the experimentation.

CHAPTER 4

DATA ANALYSIS

This chapter reports the results of the analyses performed on collected experimental data. This study employed several human-computer interface evaluation methods to assess the impact of the four tested visual display technologies on the CDR process. This chapter is organized into sections based on the sequence of data collection methodologies used. These are: empirical task evaluation, perception (VE Assessment Survey Two), and preference (VE Assessment Survey Three). The latter two methods, described in Chapter 3, used questionnaires designed to gather supplemental subjective data.

Data analyses are based on the performance of 12 test participants following a 4x4 Graeco-Latin square experimental design. The four independent factors were: visual display technologies (A, B, C, D), design teams (T_1, T_2, T_3, T_4), Tracked Fuel Trailer System (TFTS) subassemblies (1, 2, 3, 4), and experiment order (E_1, E_2, E_3, E_4).

<u>Empirical evaluation of the task.</u> The three dependent measures evaluated were: (1) the number of design errors detected, (2) the average time to detect a design error, and (3) the average time to resolve a detected design error.

<u>Perception (VE Assessment Survey Two).</u> The five measures for test participant perceptions included: (1) technology training, (2) the CDR process, (3) quality of the

CDR process, (4) physiological state of the design team members after using the 3-D visual display devices, and (5) some additional questions including how many hours each user would be willing to use the technologies and if they thought the technologies were more beneficial for individual use.

Preferences (VE Assessment Survey Three). The five measures of test participant preferences include: (1) usefulness, (2) difficulty, (3) practicality, (4) team interaction, and (5) development of team consensus when comparing the four visual display technologies.

Results from the empirical evaluations of the task were derived from four-way ANOVA and Bonferroni pairwise comparison testing. These results are summarized in Table 4. Empirical data collected during the experiment are contained in Appendix J. The p values shown are the smallest level of α where the null hypothesis can still be rejected. The pairwise comparison portion of Table 4, shown as horizontal bars, are a pictorial representation of the similarities between the four visual display technologies. The technologies are ranked from left to right corresponding to best to worst performances.

1. Error Detection. Design teams detected more errors when using either the stereoscopic glasses or the monoscopic CRT monitor systems and the least when using the HMD and BOOM system.
2. Time to Detect. Design teams detected design problems fastest using the HMD and slowest when using the stereoscopic glasses and BOOM systems.

Table 4.

Four-Way ANOVA Data Summary

Dependent Variable	Hypothesis	p value	Pairwise Comparison Best ⟷ Worst C D A B
The number of deign errors detected	Technology: $A = B = C = D$	.019	
	Team: $T_1 = T_2 = T_3 = T_4$	.046	
	Subassembly: $1 = 2 = 3 = 4$	.733	
	Experiment Order: $E_1 = E_2 = E_3 = E_4$	.960	
			A D C B
The average time to detect a design error	Technology: $A = B = C = D$	.008	
	Team: $T_1 = T_2 = T_3 = T_4$	.003	
	Subassembly: $1 = 2 = 3 = 4$	.008	
	Experiment Order: $E_1 = E_2 = E_3 = E_4$	.003	
			A B C D
The average time to resolve a detected design problem	Technology: $A = B = C = D$	.777	Not Statistically Significant
	Team: $T_1 = T_2 = T_3 = T_4$	.340	
	Subassembly: $1 = 2 = 3 = 4$	.551	
	Experiment Order: $E_1 = E_2 = E_3 = E_4$	.748	

<u>Note:</u> A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.

3. Time to Resolve. No statistically significant differences among or between the four treatment visual display technologies were detected for the dependent variable -- average resolution time.

Results from VE Assessment Survey Two, participants' perception of the technologies were derived from nonparametric Kruskal-Wallis analyses, follow-on pairwise comparison tests, and percentage score reporting. The results from Kruskal-Wallis testing are summarized in Table 5. The p values shown are the smallest level of α where the null hypothesis can still be rejected. The pairwise comparison portion of Table 5, shown as horizontal bars, are a pictorial representation of the similarities between the four visual display technologies. The technologies are ranked from left to right corresponding to the best to the worst performances.

4. Perception: VE Assessment Survey Two -- the individual technology.

   a. Training. Based on the frequency of participant responses in the training section of the questionnaire, participants received an adequate level of training prior to the experiment.

   b. CDR Process. Participants perceived that the HMD and BOOM added the most value to the CDR process and stereoscopic glasses with monitor system the least.

   c. Quality. Participants believed the quality of the CDR process was best when using the HMD and monoscopic CRT monitor systems and worst when using the stereoscopic glasses with monitor system.

Table 5.

Kruskal-Wallis Data Summary

Dependent Variable	Hypothesis	p value	Pairwise Comparison Best ←→ Worst
			A B D C
Effect on the design **process**	A = B = C = D	.000	
			A D B C
Effect on the **quality** of the design process	A = B = C = D	.000	
			D A B C
Number of **hours** willing to use the technologies	A = B = C = D	.029	
Are the technologies more **beneficial** for individual use?	A = B = C = D	.826	Not Statistically Significant

Note: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.

d. Physiological. A valid statistical assessment of the mental and physical state of the participants could not be made because sharing hardware resources minimized the exposure time for individuals. However, eye fatigue was experienced when participants used the stereoscopic glasses.

e. Additional Questions. Test participants indicated they would be willing to use monoscopic CRT monitor and HMD systems for longer periods of time. Their responses reveal that they would be willing to use a traditional monoscopic monitor 34% longer than a HMD, and 55% longer than either the BOOM or stereoscopic glasses. A second question asked users whether they thought the technologies were better suited for individual rather than team use. Kruskal-Wallis analysis revealed that there was not sufficient evidence to detect differences between the four visual display systems for this study.

Results from VE Assessment Survey Three, participant preferences of the technologies, were derived from nonparametric Friedman tests and follow-on pairwise comparison testing described by Daniel (1978). These results are summarized in Table 6. The p values shown are the smallest level of α where the null hypothesis can still be rejected. The pairwise comparison portion of Table 6, shown as horizontal bars, are a pictorial representation of the similarities between the visual display technologies. The technologies are ranked from left to right corresponding to best to worst performances.

5. Preferences: VE Assessment Survey Three -- technology comparisons.

   a. Usefulness. Test participants ranked the HMD and monoscopic CRT as the most useful technologies and BOOM and stereoscopic glasses as the least.

   b. Difficulty. Results for the difficulty in using the technology dependent variable revealed that no statistically significant differences exist between the four visual display technologies.

c. Practicality. Test participants indicate that the monoscopic CRT monitor system was the most practical technology and that it differed significantly from the other visual display systems.

Table 6.

Freidman Analysis Data Summary

Dependent Variable	Hypothesis	p value	Pairwise Comparison Best ↔ Worst A D B C
Usefulness on the CDR process	A = B = C = D	.042	
Difficulty using the technology for CDR	A = B = C = D	.220	Not Statistically Significant
			D A C B
Practicality of using the technology for CDR	A =B = C = D	.001	
			D A C B
Stimulation of **team interactivity** using the technology for CDR	A = B = C = D	.021	
			D A C B
Usefulness for developing **team consensus** using the technology for CDR	A = B = C = D	.006	

Note: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.

d. Team Interactivity. When ranking usefulness for team interactivity, participants felt that the monoscopic CRT monitor and HMD systems were the most useful for team interaction and differed significantly from both the BOOM and stereoscopic glasses systems.

e. Team Consensus. Test participants thought that the monoscopic CRT monitor system was the most beneficial for helping design teams formulate consensus. Results also reveal that the HMD differed significantly and performed better than the BOOM and stereoscopic glasses systems.

The next sections provide more detailed evaluations and discussions of the data collected in this study.

Number of Design Errors Detected

Hypothesis #1: There will be no significant difference among the four visual display technologies (A, B, C, D), among the four design teams (T_1, T_2, T_3, T_4), among the four TFTS subassemblies (1, 2, 3, 4), and among the four experiment orders (E_1, E_2, E_3, E_4) in the *number of design errors detected* during a CDR task.

The first hypothesis was tested using a four-way ANOVA. The criterion variable used to assess the number of design errors detected was the numerical count of design errors identified by the design teams when conducting a CDR of the TFTS. Results of the four-way ANOVA concluded rejection of the null hypothesis indicating significant differences ($p < .05$) exist between the four visual display technologies and the four design teams. The results also showed that there is not sufficient evidence that differences exist between the four subassemblies and experimental order.

A post hoc Bonferroni pairwise comparison test was used to determine the differences found between four visual display technologies. This analysis revealed that design teams detected more design errors when using either the stereoscopic glasses or monoscopic CRT monitor systems and the least when using HMD or the BOOM technologies. Appendix K contains means and standard deviations of the number of design errors detected for each treatment.

The average number of design errors detected for each experiment variable are listed in Table 7. On average, design teams were able to detect more design errors when using either stereoscopic glasses or monoscopic CRT monitor systems. This table also shows that on average design team one (T_1) detected the least number of errors. This finding could be explained because this team had the longest error detection time and did not fully identify all the design errors before completing their evaluation. Table 7 also shows the average number of errors detected for each TFTS subassemblies and each experiment order. These support ANOVA findings that no significant differences exist between the TFTS subassemblies and experiment order.

Graphs of the least square means for experiment variables vs. the dependent measure (number of design errors detected) are shown in Figure 15. The greater number of errors detected is defined as the best team performance. The graphs pictorially support findings of the four-way ANOVA and Bonferroni tests, indicating that design teams detect the greatest amount of design errors when using stereoscopic glasses and the least amount when using the BOOM.

Table 7.

Average Number of Design Errors Detected for Each Experiment Variable

Variable	**Average Number of Design Errors**
Visual Display Technology	
A	5.25
B	5.00
C	9.25
D	8.00
Design Team	
T_1	4.75
T_2	7.50
T_3	7.00
T_4	8.25
TFTS Subassembly	
1	6.75
2	6.75
3	7.00
4	7.00
Experiment Order	
E_1	6.75
E_2	7.25
E_3	7.00
E_4	6.50

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.
Larger number of errors = Better Performance.

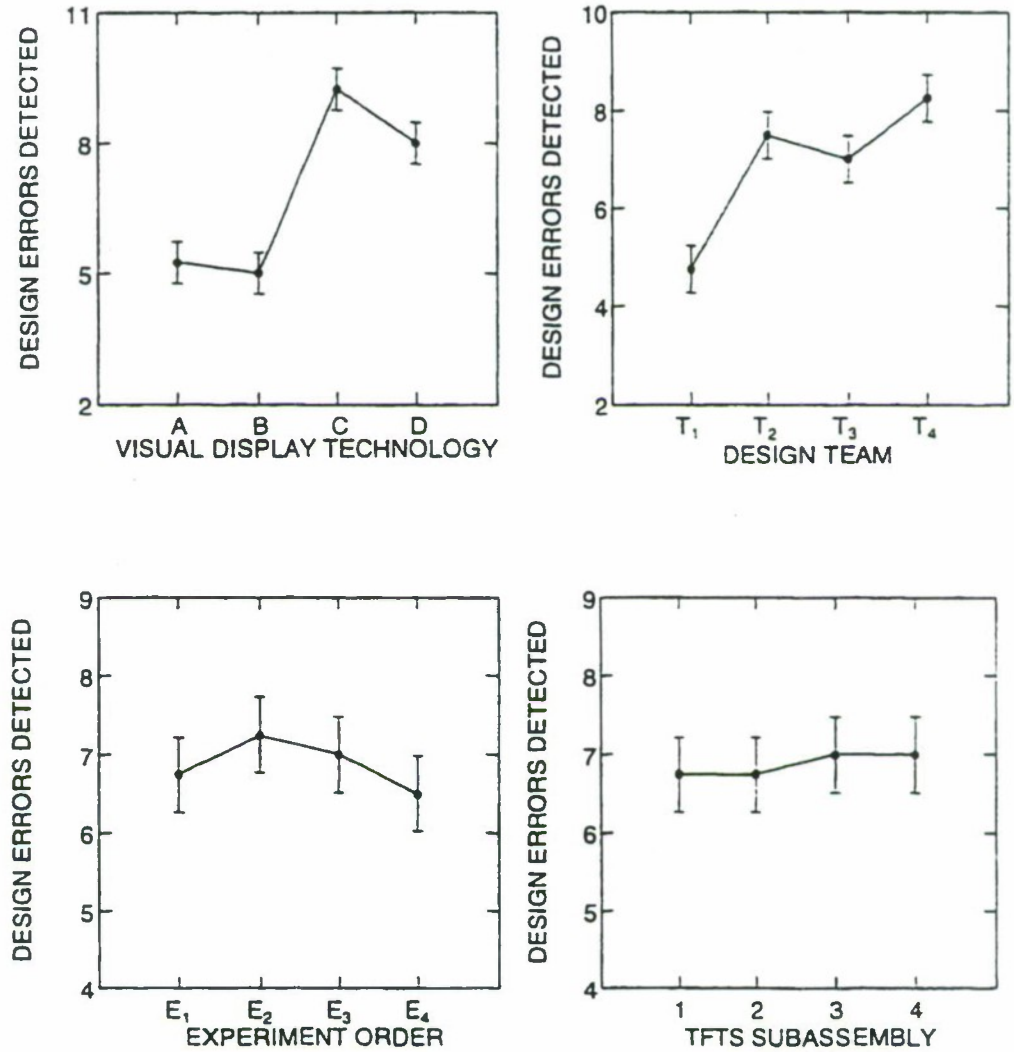

Figure 15. Graphs Of the Least Square Means for the Number of Design Errors Detected.

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.
Large number of errors detected = best performance.

Time to Detect

Hypothesis #2: There will be no significant difference among the four visual display technologies (A, B, C, D), among the four design teams (T_1, T_2, T_3, T_4), among the four TFTS subassemblies (1, 2, 3, 4), and among the four experiment orders (E_1, E_2, E_3, E_4) in the *average time it takes to detect a design error* during a CDR task.

The second hypothesis was tested using a four-way ANOVA. The criterion variable used to assess the time to detect a design error was the average number of seconds each group required to detect TFTS subassembly design errors when conducting the CDR. An independent data collector made continuous time measurements of both the start and completion times of each design error identified and resolved by the teams. The time to detect a design error was calculated as the difference between the time of resolving a problem and the time of detecting a new design problem. To facilitate data collection, design teams were asked to follow a testing protocol that required them to sequentially identify design problems, flaws, and issues. They were asked not to move on to another design problem until they developed a team consensus on the current problem.

The results of the four-way ANOVA indicate a significant difference ($p< .01$) between the four visual display technologies, four design teams, four TFTS subassemblies, and four experiment orders in the average time to detect a design error. Appendix L contains means, and standard deviations of the average time to detect a design error for each treatment.

A post hoc Bonferroni pairwise comparison test was used to determine the differences found between the four visual display technologies. This analysis revealed that the average time to detect a design problem using the HMD were significantly different and better than average detection times when design teams used any of the other visual display technologies. The post hoc analysis also revealed that the monoscopic CRT monitor differed significantly and better than the BOOM and stereoscopic glasses configurations which, were found to be similar and performed the worst.

Table 8 contains the mean detection times for each experiment variable. By definition, the smallest detection time is associated with best performance On average design teams were able to detect design errors faster using either the HMD or monoscopic CRT monitor systems.

Graphs of the least square means for experiment independent variables vs. the dependent measure (average time to detect a design error) are shown in Figure 16. These graphs pictorially show the differences between the four visual display systems. This supports conclusions drawn from post hoc testing. The graph indicates that design teams detect design errors fastest when using the HMD and the slowest when using the BOOM and stereoscopic glasses systems.

Note that the results for the number of errors detected appears to be inconsistent with the results obtained for the average detection time. The stereoscopic glasses yielded the best performance when measuring the design errors detected and in contrast yielded worse performance when measuring for the dependent variable average detection time. Similarly, the HMD yielded the best performance for average detection time and a worse performance for the design errors detected. On the surface the results of the data appear to be inconsistent, but they were based on the collected data. These findings indicate that in a team setting, the technology that promotes natural dialogue yields the most number of errors detected, but the technology that provides the users with the best sense of presence in the VE yields the fastest error detection times.

Table 8.

Mean Detection Time (Seconds) for Each Variable

Variable	Average Detection Time (sec)
Visual Display Technology	
A	51.945
B	66.477
C	64.468
D	57.777
Design Team	
T_1	69.453
T_2	63.788
T_3	48.750
T_4	58.678
TFTS Subassembly	
1	51.915
2	59.402
3	61.615
4	67.735
Experiment Order	
E_1	51.458
E_2	57.053
E_3	73.930
E_4	58.228

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor. Lower detection time = greater performance.

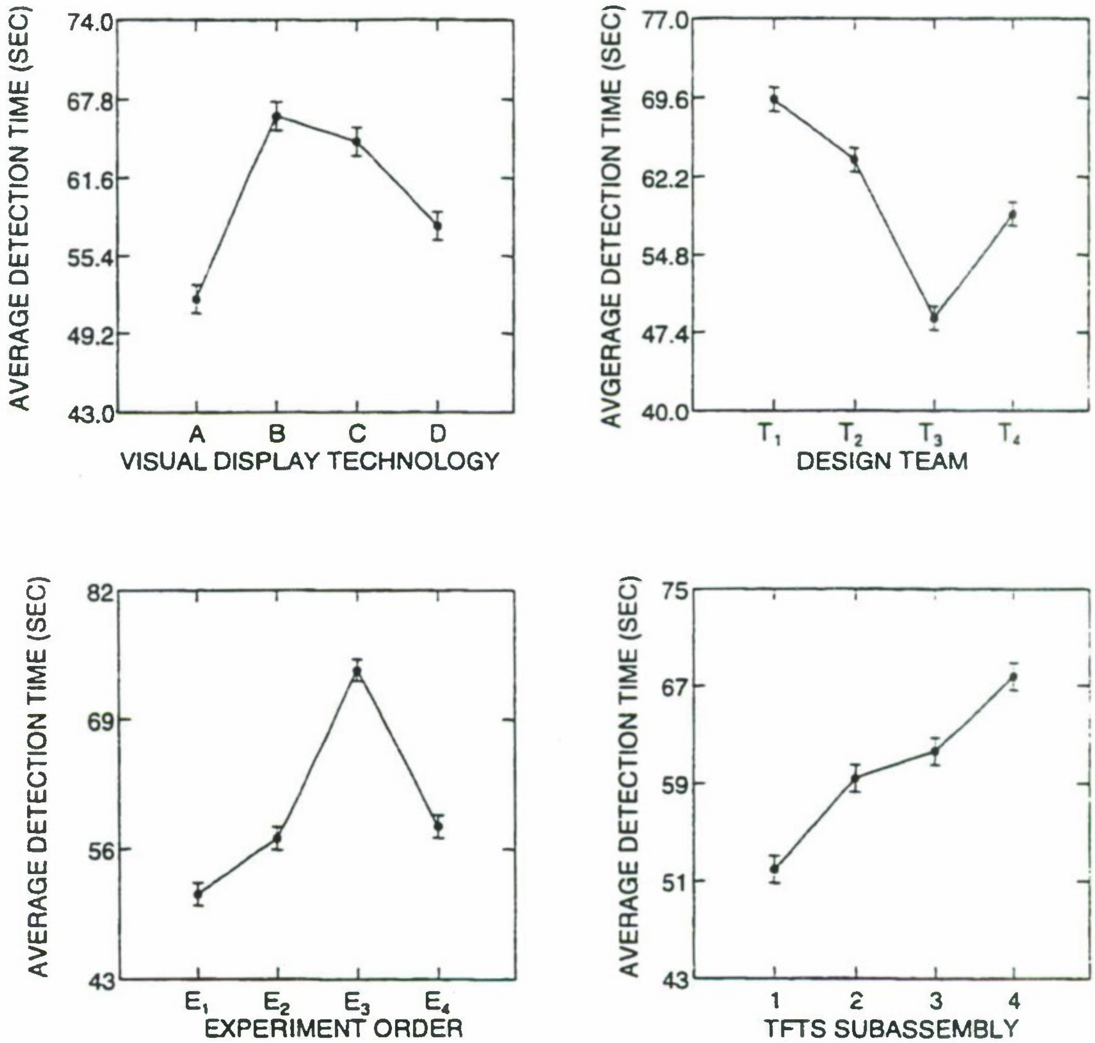

Figure 16. Graphs of the Least Square Means for the Average Time to Detect a Design Error

<u>Notes:</u> A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor. Lower detection time = better performance.

<u>Time to Resolve</u>

Hypothesis #3: There will be no significant difference among the four visual display technologies (A, B, C, D), among the four design teams (T_1, T_2, T_3, T_4), among the four subassemblies (1, 2, 3, 4), and among the four experiment orders (E_1, E_2, E_3, E_4) in the *average time to resolve* an identified design error.

The third hypothesis was tested using a four-way ANOVA. The criterion variable used to assess the time to resolve a design error was the average number of seconds each group required to resolve an identified design error or flaw, achieving group consensus when conducting a CDR of the TFTS model. An independent data collector made continuous time measurements of both the start and completion time of each design error identified and resolved by the groups. The design error resolution time was calculated as the difference between the time of identifying a design problem and the time of reaching a design team consensus on the problem's resolution. The testing protocol required that design teams sequentially identify design problems. To facilitate data collection design teams were asked not to move on to a new design problem until they developed a consensus on the current problem identified.

The results of the four-way ANOVA indicated no significant differences ($p>.7$) between the four visual display technologies, the four design teams, the four TFTS subassemblies, and the four experiment orders for the average time to resolve a design problem. Appendix M contains means, and standard deviations of the average detection time for each experiment treatment.

This study failed to find differences between the four visual display technologies for the problem resolution time dependent variable. Investigation into probable causes revealed widely disparate standard deviation values. The ANOVA F test used to test the null hypothesis of equality of means was based on the assumption that the populations are normally distributed with a common variance (Mendenhall & Sincich, 1988). The disparate variances could have caused the insignificant results obtained from the four-way ANOVA, therefore, a nonparametric Kruskal-Wallis test was conducted to eliminate the potential variance problem. This test is similar to the ANOVA F test except that the population is not assumed to have a normal distribution with a common variance. Mendenhall & Sincich (1988) state that the primary advantage of this test is that no assumptions are made about the nature of the sampled population.

The Kruskal-Wallis test was conducted to test the null hypothesis that the four visual display technologies possess the same probability distribution against the alternative hypothesis that the distributions differ in location. The results of the Kruskal-Wallis test revealed that there is insufficient evidence to indicate a difference in location among the distributions of design error resolution time for the four visual display technologies ($p > .95$). No significant differences between the four visual display technologies were found, indicating that this study failed to detect any differences for the dependent variable -- problem resolution time. Table 9 contains the mean resolution times for each independent variable.

Table 9.

Mean Resolution Time (Seconds) for Each Variable

Variable	Average Resolution Time (seconds)
Visual Display Technology	
A	59.403
B	85.503
C	77.320
D	59.595
Design Team	
T_1	110.925
T_2	49.268
T_3	63.320
T_4	58.307
TFTS Subassembly	
1	57.235
2	56.128
3	98.368
4	70.090
Experiment Order	
E_1	85.648
E_2	69.125
E_3	74.750
E_4	52.298

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.
Lower average resolution time = greater performance.

Perception: VE Assessment Survey Two -- The Individual Technology

A 29-item questionnaire, VE Assessment Survey Two: Individual Technology, was provided to each participant at the end of each experiment treatment and is included as Appendix H. The questionnaire was designed to analyze test participants' perceptions of the four visual display technologies on the CDR process. The assessment was divided into four sections: training, CDR process, quality, and physiological. Participants were asked to make their assessment on a 1 to 5 Likert scale, because of the small sample size in this study the data was condensed into two values. The scale values of 1, 2, and 3 were combined to a value of 1 and scale values 4 and 5 were combined to a value of 5. These values were then equated to No and Yes, respectively. Sparse data restricted the ability to conduct Chi-square analyses. Instead questions in each section of the questionnaire were combined into one and were evaluated using Kruskal-Wallis analysis. Percentage score reporting also was used to support the analysis. In addition, supplemental data were collected by providing space at the end of each section and at the end of the questionnaire for participants to make comments. A compilation of user comments is provided in Appendix N.

Technology Training

Hypothesis #4: There will be no practical difference in the perception of *technology training and familiarization* among the four visual display technologies.

The purpose of the technology training section of VE Assessment Survey Two -- Individual Technology was to verify technology familiarization and to assess if test participants felt they were adequately prepared to conduct the CDR task using the four visual display technologies. Table 10 includes participant response frequency by technology for each question in the training section of the survey.

Few negative responses were obtained in this section of the assessment, therefore, valid statistical methods could not be conducted. For that reason, the data was analyzed using percentage scores. Based on higher percentage of yes responses in the training section of the questionnaire, it was concluded that test participants received an adequate level of training and had the competency to use and operate the technologies prior to the experimentation. For example, 87.5% (42/48) "found the training to be sufficient"(Q1), 85.4% (41/48) "thought that they fully understood the correct operating procedures for the technologies" (Q2), and only 20.8% (10/48) "thought they were not prepared" (Q3). Ninety-one percent (11/12) of the test participants felt that BOOM was easy to operate compared to 83.3% (10/12) for the HMD. Only 50% (6/12) of the participants responded that the stereoscopic glasses configuration were easy to operate (Q4).

Table 10.

Frequency of Training Responses

		VISUAL DISPLAY TECHNOLOGY							
	Effects of Training	**A**		**B**		**C**		**D**	
		Y	N	Y	N	Y	N	Y	N
Q1	Was the training **sufficient**?	11	1	11	1	9	3	11	1
Q2	Did you fully **understand** the correct operating procedures?	12	0	11	1	9	3	9	3
Q3	Were you **prepared**?	11	1	11	1	8	4	8	4
Q4	**Learning** to operate the system was easy?	10	2	11	1	6	6	8	4

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.
Y= Yes, N=No.

As can be seen from Table 10, more negative responses were associated with the stereoscopic glasses and monoscopic CRT monitor configurations. This could be attributed to the navigation method employed in these two configurations -- a mouse. Movement in the environment when using a mouse may have required additional technology familiarization.

Concept Design Review Process

Hypothesis #5: There will be no practical difference in the perception of the *value* of the four visual display technologies *on the CDR process*.

The CDR process section of VE Assessment Survey Two was designed to assess the impact the four visual display technologies had on the CDR process. Table 11 includes the frequency per technology for each item included on the process section of the questionnaire.

Cumulative participant responses for the questions in the design process section were used to obtain an overall design process comparison. A Kruskal-Wallis analysis was then conducted on the independent variable, technology. Results of the Kruskal-Wallis test reveal significant differences ($p < .01$) between the four visual display technologies for the dependent variable -- effect on the design process. A follow-on pairwise comparison procedure as described by Conover (1980) was conducted to determine the differences found in the Kruskal-Wallis analysis. Pairwise comparison results indicate that the HMD, BOOM, and monoscopic CRT monitor differed significantly ($\alpha=0.05$) from the stereoscopic glasses. Participants perceived that the HMD and BOOM added the most value to the CDR process and stereoscopic glasses with monitor system the least.

Table 11.

Frequency of Concept Design Review Process Responses

		VISUAL DISPLAY TECHNOLOGY							
	Effects on the Design Review Process	A		B		C		D	
		Y	N	Y	N	Y	N	Y	N
Q5	Did the technology **assist** you in conducting a team concept review?	11	1	10	2	2	10	10	2
Q6	Did the technology assist in **detecting design problems** or issues?	10	2	10	2	5	7	7	5
Q7	Was the technology helpful in **describing issues** to team members?	10	2	8	3	7	5	8	4
Q8	Did the technology **stimulate creativity & problem solving**?	10	2	10	2	6	6	7	5
Q9	Did the technology **assist team interaction** & discussion?	10	2	10	2	8	4	10	2
Q10	Did the technology help develop a **team consensus**?	9	2	9	3	5	7	8	4
Q11	Did the technology assist in providing a **better understanding** of the concept (configuration)?	10	2	10	2	3	9	9	3
Q12	Did the technology provide easy **recognition of form & pattern**?	10	2	10	2	5	7	8	4
Q13	If this technology was a standard for concept reviews would the product **development time decrease**?	9	3	7	5	4	8	8	4
Q14	If this technology was a standard for concept reviews would the overall product **quality improve**?	10	2	7	5	5	7	7	5

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor. Y=Yes, N=No.

A bar chart showing the dependent measure, the average value on the CDR process, for each visual display technology is provided in Figure 17. This graph supports findings found in the Kruskal-Wallis test, i.e., users felt the stereoscopic glasses had a negative effect on design team processes. In contrast, the use of the other three technologies had a more positive effect or value on design review process.

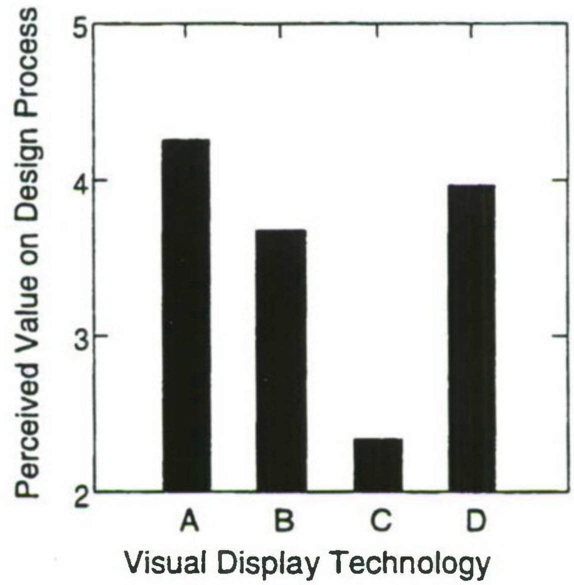

Figure 17. Bar Chart of Perceived Value on Design Process

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.
Scale larger value = better performance.

Five of the questions in the CDR process section of VE Assessment Survey Two addressed whether the technologies assisted in team activity (Q5), team discussion (Q7), team problem solving (Q8), team interaction (Q9), and team consensus (Q10). Participants' subjective responses indicate that the use of the visual display technologies did have an effect on the CDR process. Overall, the participants felt that stereoscopic glasses were the least helpful. Only 16% (2/12) felt that they "assisted the design process" (Q5), only 58% (7/12) thought they "helped describe problems to other team members" (Q7), and only 41% (5/12) felt they "assisted in developing team consensus"

(Q10). In contrast, users felt that the HMD, BOOM, and monoscopic CRT monitor were more helpful and useful to the CDR process. Ninety-one percent (11/12) of the participants believed the "the HMD assisted in the process, and 83.3% (10/12) thought that the HMD, BOOM, and monoscopic CRT monitor assisted in team interaction and discussion.

Three questions focused on how the technologies effected the detection of design problems (Q6), whether the technologies provided an improved understanding of the design (Q11), and if the technologies helped in recognition of forms and patterns (Q12). Test participants' subjective responses indicate that the use of the visual display technologies did have an effect on the design process. Eighty-three percent (10/12) responded that either the HMD or BOOM helped them identify and detect design problems (Q6). In contrast, only 41.67% (5/12) felt that stereoscopic glasses and 58.33% (7/12) thought using the monoscopic CRT monitor aided in problem detection.

Users were asked whether they felt that the four visual display technologies would help decrease product development times (Q13). Seventy-five percent (9/12) felt that the HMD could help reduce development time and only 33.33% (4/12) felt that the stereoscopic glasses could decrease development times. Users were also asked whether they felt that the four visual display technologies would help improve overall product quality (Q14). Responses indicate that 83.33% (10/12) felt that the quality would be improved when using the HMD, 58.33% (7/12) thought that the BOOM and monoscopic

CRT monitor would make improvements to quality, and 41.67% (5/12) felt that stereoscopic glasses could impact quality.

Quality

Hypothesis #6: There will be no practical difference in the perception of the *effect* on the *quality* of the design process among the four visual display technologies.

The quality section of VE Assessment Survey Two was used to examine how the quality of the CDR process was effected by the four visual display systems. Cumulative participant responses for questions in the quality section of VE Assessment Survey Two were used to evaluate the effect of the display systems on the factor of "quality." A Kruskal-Wallis analysis was then conducted on the independent variable -- technology. Results of the Kruskal-Wallis test revealed significant differences ($p<.01$) between the four visual display technologies for the dependent variable -- overall quality. A post hoc pairwise comparison test (Conover, 1980) was conducted to determine the differences found in the Kruskal-Wallis test. Results indicate that the overall quality of the stereoscopic glasses differed significantly and were perceived worst than the other technologies. Participants believed the quality of the CDR process was best when using the HMD and monoscopic CRT monitor systems.

Table 12 includes the frequency per technology for each item included on the quality section of the questionnaire. In some cases, test participants did not respond to the question, therefore not all questions have a total of 12 responses.

Table 12.

Frequency of Quality Responses

		VISUAL DISPLAY TECHNOLOGY							
	Effects on the Quality of the Design Review Process	**A**		**B**		**C**		**D**	
		Y	N	Y	N	Y	N	Y	N
Q15	The technology is **helpful** as a platform for team discussion	10	2	9	3	5	7	9	3
Q16	The technology is totally **useful** to the product design review process	10	2	8	4	3	9	10	2
Q17	**Time** was **well spent** using the technology	10	2	9	3	5	7	8	4
Q18	**Adequate time** was given to use the technology	9	3	9	3	7	5	9	3
Q19	**No time** was **wasted** using the technology	10	2	7	5	6	6	8	4
Q20	The technology had a **positive effect** on the **quality** of the design review process	9	3	8	4	4	8	8	4
Q21	Overall, the technology was **wonderful**	10	2	6	6	2	10	9	3
Q22	Overall, the technology was **satisfying**	8	3	6	4	2	10	9	3
Q23	Overall, the technology was **stimulating**	10	1	8	3	3	9	12	0
Q24	Operating the system was **easy to use**	10	2	7	3	3	9	7	5

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor. Y=Yes, N=No.

A bar chart graph of the dependent measure, quality of the design review process for each visual display technology is provided in Figure 18. This graph supports the findings from the Kruskal-Wallis test. Users felt that the stereoscopic glasses had the least effect or value on quality of CDR processes. In contrast, they felt that the other three technologies had a more positive effect on overall quality.

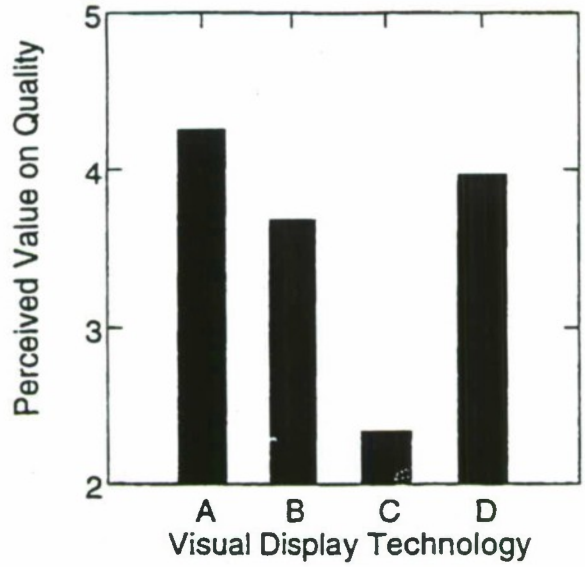

Figure 18. Bar Chart of Perceived Value on Quality

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor. Scale higher value = better performance.

Participants felt that the stereoscopic glasses were the least helpful for group discussion (Q15), the least useful to the design review process (Q16), and had little positive effect on the design review process (Q20). With regard to Q20, only 33.3% (4/12) of the participants felt that stereoscopic glasses impacted the quality of the design process in a positive way, while 81.8% (9/12) thought the HMD and 66.67% (8/12) thought BOOM and monoscopic CRT monitor positively enhanced the quality of the process.

Three time-related questions addressed how well the time was spent (Q17), if enough time was given to conduct the exercise (Q18), and if any time was wasted using the technology (Q19). Eighty-three percent (10/12) of the users felt that the time using the HMD was well spent, and only 41.67% (5/12) thought the time spent using stereoscopic glasses system was worthwhile. Seventy-five percent (9/12) of the design team participants felt that adequate time was given for the HMD, BOOM, and monoscopic CRT monitor systems. Users felt that some time was wasted using the stereoscopic glasses and monoscopic CRT monitor systems. Again these descriptive statistical findings may be attributable to the navigation systems used in these two configurations.

Four of the questions in the quality section of VE Assessment Survey Two are related to participant perceptions of the technologies. Participants felt that stereoscopic glasses were the least wonderful to use (Q21) the least satisfying to use (Q22), the least stimulating to use (Q23), and the most difficult to operate (Q24). Only 16.67% (2/12) thought that using stereoscopic glasses were wonderful and satisfying and only 25% (3/12) thought it was stimulating and easy to operate. In contrast, 83.3% (10/12) participants felt that the HMD was satisfying and 90.91% (10/11) felt it was stimulating.

Physiological Effects

Hypothesis #7: There is no practical difference in the physiological effect experienced by the test participants among the four visual display technologies.

The physiological section of VE Assessment Survey Two addressed the mental and physical state of the design team participants after exposure to four visual display technologies. A valid statistical assessment of the physiological effects could not be made because design teams had too short of an exposure time when using the HMD and

BOOM system. This was due to the need to share the hardware resource inherent to these technologies. Instead an analysis of descriptive statistics was conducted.

One question regarding measures of perceived mental workload assessed how mentally demanding the technology was to test participants. Table 13 includes the frequency per technology for those responses. Overall, 82.6% (38/46) of the participants' felt that the technologies were not mentally demanding, however, they did feel that the most mentally demanding of the technologies was the monoscopic CRT monitor.

Table 13.

Frequency of Mental Workload Responses

		VISUAL DISPLAY TECHNOLOGY							
	Physiological Effect	**A**		**B**		**C**		**D**	
		Y	N	Y	N	Y	N	Y	N
Q25	Is the system mentally demanding?	2	8	1	11	0	12	5	7

Note: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.

Design participants were also asked to identify how many of 16 simulator sickness symptoms they experienced after exposure to the four visual display technologies. These symptoms are based on a scoring procedure developed by Kennedy et al. (1992), and are listed the VE Assessment Survey Two questionnaire contained in Appendix H. Table 14 provides the number of symptoms experienced and the number of test participants who reported these findings.

Table 14.

Frequency of Physiological Symptoms

		VISUAL DISPLAY TECHNOLOGY			
	Physiological Effect	A	B	C	D
Q26	The number of **physiological symptoms** experienced	1	4	9	0
	The **number of persons** experiencing physiological symptoms	1	2	4	0

Note: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.

The majority of the participants did not experience any significant physiological symptoms associated with exposure to the test technologies. However, 33.3% (4/12) of the participants experienced some symptoms such as eyestrain, difficulty focusing, and blurred vision when using the stereoscopic glasses. Only 8.33% (1/12) of the participants experienced any problem when using the HMD and only 16.67% (2/12) when using the BOOM. No one experienced any symptoms when using the monoscopic CRT monitor configuration.

Additional Questions

Hypothesis #8: There is difference in the how many *hours* test participants are *willing to use* the four visual display technologies.

Participants were asked how many hours they would be willing to use each of the four visual display technologies (Q27). A Kruskal-Wallis analysis was conducted on the average time calculated from design participant responses. The hypothesis was that there would be no difference in the average number of hours that participants would be willing to use the four visual display technologies. The Kruskal-Wallis analysis conclude that there is significant evidence to reject the null hypothesis ($p<.03$), indicating differences between the four visual display technologies for the amount of time design participants would be willing to use the technologies. Pairwise comparison analysis revealed that monoscopic CRT monitor and HMD systems differed significantly from the other technologies and users are willing to use these technology systems for longer periods of time.

The means and standard deviations for each of the visual display technologies are provided in Table 15 as a source of insight into the similarities and differences between the four visual display technologies. Users are willing to use the traditional monoscopic CRT monitor for longer periods of time compared to the other three visual display technologies. On average, they are willing to use monoscopic CRT monitor for 5.08 hours, HMDs for 3.33 hours, and both the BOOM and stereoscopic glasses for 2.25 hours.

Table 15.

Average Time (Hours) Subjects Are Willing To Use The Technology

Technology	M	SD	N
A	3.33	2.42	12
B	2.25	2.30	12
C	2.25	2.18	12
D	5.08	3.20	12

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor. M = mean, S = standard deviation, N = number.

A graph of the least square means of the visual display technology vs. the time willing to use the technology dependent measure is provided in Figure 19. This graph supports previous ANOVA findings. Users are willing to use the traditional monoscopic CRT monitor for longer periods of time and are willing to use the BOOM and stereoscopic glasses for the least amount of time.

Design participants were also asked whether they thought the four visual display systems were more *beneficial for individual* use rather than team use (Q28). Design participant responses are shown in Table 16. A Kruskal-Wallis analysis was conducted on the data. The hypothesis was that there would be no differences in whether the participants felt the technologies were more beneficial for individual rather than team use. Results reveal that there is not significant evidence to reject the null hypothesis (p=. 83), indicating that no differences exist between the four visual display technologies for whether they are more beneficial for individual use.

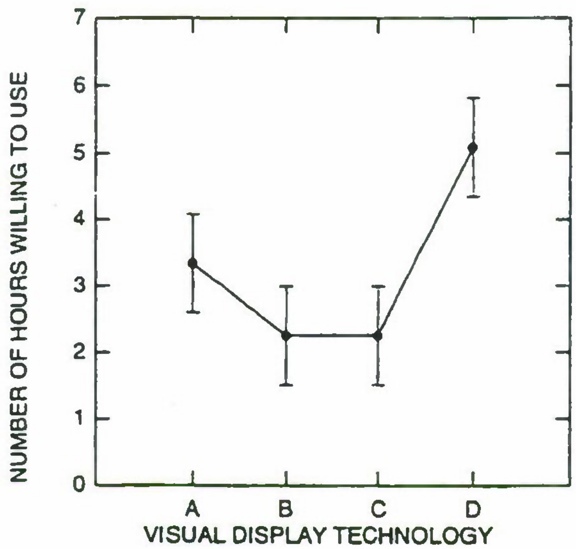

Figure 19. Least Square Mean Graph for Average Time (Hours) Subjects Are Willing To Use The Technology

Note: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.

Table 16.

Frequency of Responses for Beneficial for Individual Use

		VISUAL DISPLAY TECHNOLOGY							
		A		B		C		D	
		Y	N	Y	N	Y	N	Y	N
Q28	Is the technology more **beneficial** for **individual** use?	4	8	9	3	6	6	6	6

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.
Y=Yes, N=No.

Additionally, the survey asked participants if there was any aspect of the visualization tools that could be improved to enhance the CDR activity (Q29). Listings of their responses are included in Appendix N, participant comments. In general, participants wanted improved resolution of displays, better ability to navigate in the model, and the capability to dynamically change objects in the virtual model.

Preferences: VE Assessment Survey Three -- Technology Comparisons

Technology comparisons were conducted to assess differences between the technologies in terms of their usefulness, difficulty, practicality, stimulation of team interactivity, and development of team consensus to the CDR process. Nonparametric Friedman tests and follow-on multiple comparison procedures as described by Daniel (1978) were used to analyze the subjective comparison data. This test is often used for analyzing ranks of three or more objects by multiple judges. Individual participants were asked to rank the technologies on a scale of one to four corresponding to a ranking from best to worst. Where the value of one was considered the most useful, most difficult, most practical, most helpful in stimulating team interactivity or most beneficial for developing team consensus. Table 17 provides the frequency of ranked data per technology. The mean and standard deviation for each ranking of the dependent variable per visual display technology is provided in Table 18.

Usefulness

Hypothesis #9: There will be no significant differences among test participants in their ratings of four visual display technologies *usefulness* during CDR task.

The criterion used to assess the usefulness of the technologies was the subjective ranking of the four visual display technologies. The results of the Freidman tests, as measured by individual rankings, indicated that usefulness of the technologies on the CDR process did differ significantly (p<. 05) between the individual participants.

A multiple comparison procedure was used to determine the differences found in the Freidman test. Results of this test indicated that the usefulness of the HMD and the monoscopic CRT monitor were significantly different and ranked more useful than the BOOM and stereoscopic glasses.

Figure 20 contains a bar chart, which illustrate these findings. Design team participants felt that the most useful technologies were the HMD and monoscopic CRT monitor, while the BOOM, and stereoscopic glasses systems were least useful.

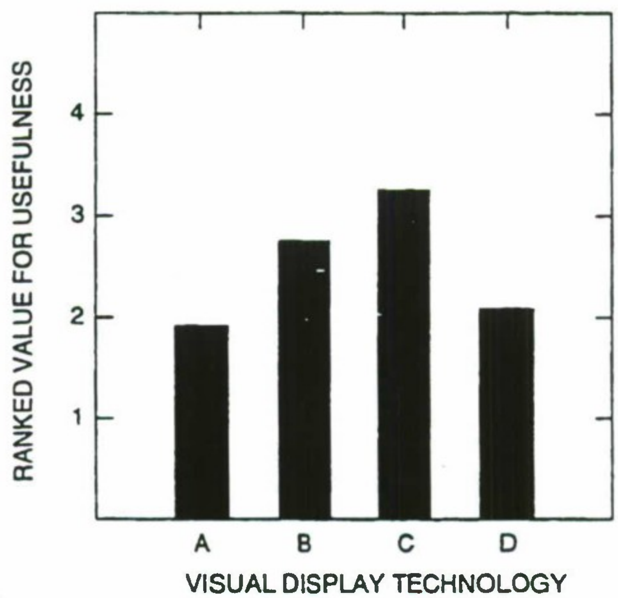

Figure 20. Bar Chart of Ranked Data for Usefulness

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.
Scale 1=most useful and 4 = least useful.

Table 17.

Frequency of Ranked Data Responses

Visual Display Technology	Rank	Usefulness	Difficulty	Practicality	Team Interactivity	Team Consensus
A	1	6	4	4	4	3
	2	1	3	3	3	3
	3	5	3	4	4	5
	4	0	1	1	1	1
B	1	1	4	0	0	0
	2	5	3	2	2	3
	3	2	3	5	5	4
	4	4	1	5	5	5
C	1	0	2	0	1	0
	2	3	2	4	5	5
	3	3	2	2	1	2
	4	6	5	6	5	5
D	1	5	1	8	7	9
	2	3	3	3	2	1
	3	2	3	1	2	1
	4	2	4	0	1	1

Note: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.

Table 18.

Mean and Standard Deviation for Ranked Data Responses

Dependent Variable	Visual Display Technology	M	SD	N
Usefulness	A	1.917	.996	12
	B	2.750	1.055	12
	C	3.250	0.866	12
	D	2.083	1.165	12
Difficulty	A	2.091	1.044	11
	B	2.091	1.044	11
	C	2.909	1.221	11
	D	2.909	1.044	11
Practicality	A	2.167	1.030	12
	B	3.250	0.754	12
	C	3.167	0.937	12
	D	1.417	0.669	12
Design Team Interactivity	A	2.167	1.030	12
	B	3.250	0.754	12
	C	2.833	1.115	12
	D	1.750	1.055	12
Design Team Consensus	A	2.333	0.985	12
	B	3.167	0.835	12
	C	3.000	0.953	12
	D	1.500	1.000	12

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor.
M = mean, S = standard deviation, N = number.

Difficulty

Hypothesis #10: There will be no significant differences among test participants in their ratings of four visual display technologies *difficulty* of use during a CDR task.

The criterion used to assess difficulty of using the technologies for a CDR was the subjective ranking of the four test systems. The results of the Freidman tests, as measured by individual rankings, indicated that the difficulty of using the visual display technologies during a CDR did not significantly differ ($p > .20$).

Practicality

Hypothesis #11: There will be no significant differences between test participants in their ratings of four visual display technologies for *practicality* of use during CDR task.

The criterion used to assess the practicality of using the technologies for a CDR was the subjective ranking of the four visual display technologies. The results of the Freidman tests as measured by individual rankings indicated that the practicality of using the four technologies during a CDR did differ significantly ($p < .005$) between the individual participants.

A multiple comparison procedure was used to determine the differences found in the Freidman test. Results of the pairwise comparison analysis indicate that the practicality of using the monoscopic CRT monitor and HMD for CDR differed significantly from the other two visual display technologies. Test participants felt these systems were the most practical and BOOM and stereoscopic glasses were the least.

Figure 21 contains a bar chart, which illustrates these findings. Design team participants felt that the most practical technology was the monoscopic CRT monitor, followed by the HMD, while the least practical were the stereoscopic glasses, and BOOM systems.

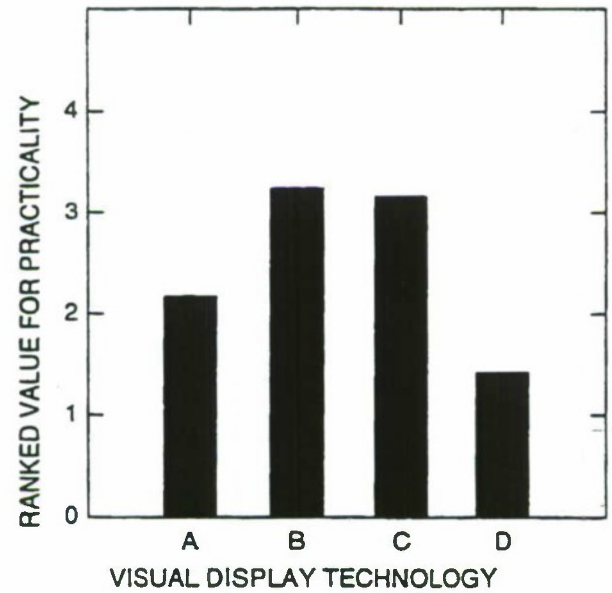

Figure 21. Bar Chart of Ranked Data for Practicality

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor. Scale 1=most practical and 4 = least practical.

Team Interactivity

Hypothesis #12: There will be no significant differences between test participants in their ratings of four visual display technologies for *design team interactivity* during CDR task.

The criterion used to assess the stimulation of design team interactivity when using the technologies for a CDR was the subjective ranking of the four visual display technologies, where 1 was considered the most stimulating for team interaction and 4 was the least stimulating for team interaction. The results of the Freidman tests, as measured by individual rankings, indicated that the four technologies did differ significantly ($p<.025$) when evaluating their effect on the stimulation of team activity.

Pairwise comparison analysis was used to determine the differences found in the Freidman test. Results of pairwise comparison testing revealed that the monoscopic CRT monitor and HMD systems were the most useful for team interaction and these systems differed significantly from both the BOOM and the stereoscopic glasses systems. Figure 21 contains a bar chart, which illustrate these findings. Design team participants felt that the technologies that assisted in design team interaction were the monoscopic CRT monitor and HMD systems, while the stereoscopic glasses, and BOOM systems were the least useful for design team interaction.

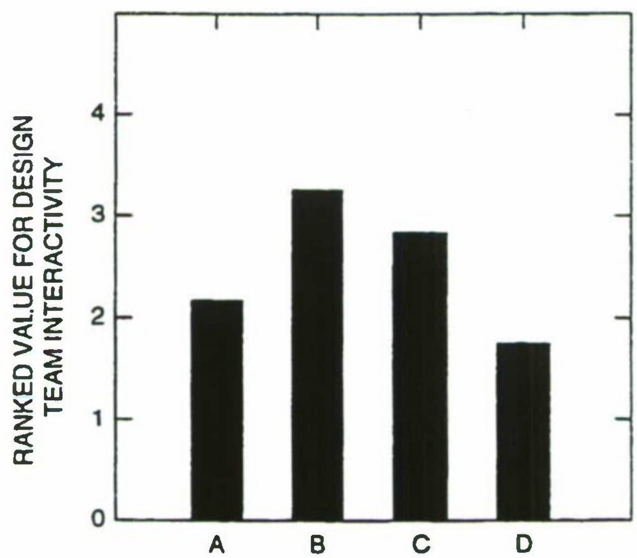

Figure 22. Bar Chart of Ranked Data for Design Team Interactivity

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor. Scale 1=most useful for team interactivity and 4 = least useful.

Team Consensus

Hypothesis #13: There will be no significant differences between test participants in their ratings of four visual display technologies for usefulness for *developing design team consensus* during CDR task.

The criterion used to assess the usefulness for developing design team consensus when using the technologies in a CDR was the subjective ranking of the four visual display technologies, where 1 was considered the most useful for developing group consensus and 4 was the least useful for developing group consensus. The results of the Freidman tests, as measured by individual rankings, indicated that the four visual display technologies differ significantly ($p < .01$) when evaluating their effect on the usefulness of the technology for developing team consensus.

A multiple comparison procedure was used to determine the differences found in the Freidman test. Results of the pairwise comparison procedure indicated that use of the monoscopic CRT monitor differed significantly from the other technologies and was ranked the best technology for usefulness in developing team consensus. Results also revealed that the HMD system differed significantly from the BOOM and stereoscopic glasses which, were ranked the worst. Figure 23 contains a bar chart, which illustrates these findings. Design team participants felt that the technology that best assisted in design team consensus was the monoscopic CRT monitor followed by the HMD, and jointly by stereoscopic glasses, and BOOM systems.

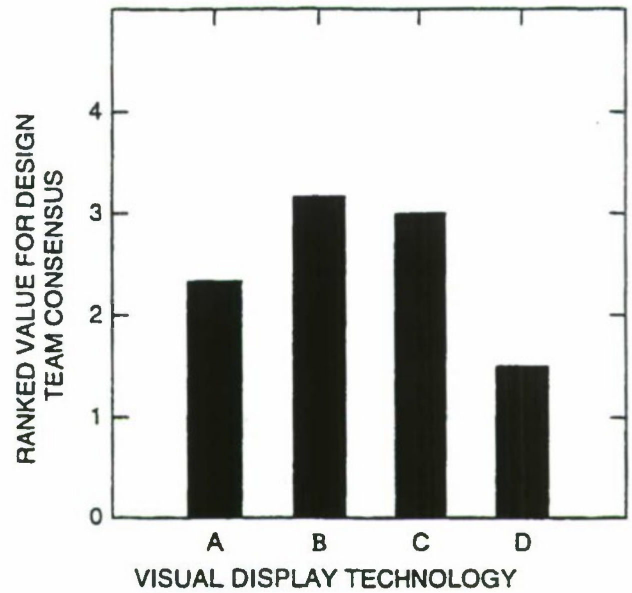

Figure 23. Bar Chart of Ranked Data for Design Team Consensus

Notes: A=HMD, B=BOOM, C=Stereoscopic Glasses, D= Monoscopic CRT Monitor. Scale 1=most useful for team consensus and 4 = least useful.

Summary

The results of the experiment reveal that VE technology had an important role in the CDR process. The findings encourage further research and development of VE tools for product design and evaluation. This experimental procedure identified differences and similarities between the four visual display systems.

Empirical evaluation of the CDR task measured the number of design errors detected, the average time to detect a design error, and the average time to resolve a design error. The most number of design errors detected were when design teams used either the stereoscopic glasses or the monoscopic CRT monitor. Evaluation of the average time to detect a design error concluded that design teams were able to detect design errors faster when using the HMD. There were no significant differences between the four visual display systems on average resolution time.

Test participants perceptions of each technology investigated in this study were assessed using data collected in VE Assessment Survey Two. The assessment was divided into four main sections with some additional questions. The first section addressed whether the design team participants felt they received adequate training prior to the experiment. It was determined that the 15-minute training period was sufficient. However, some users had difficulty understanding the functionality of the three-button mouse device in the stereoscopic glasses and monoscopic CRT configurations. The second section focused on the value of the technologies on the overall CDR process. Results showed that the test participants believed that the stereoscopic glasses had the least impact on the CDR process. In the third section, test participant's assessed the quality of the CDR process when using the test technologies. Design team participants perceived the stereoscopic glasses with monitor system to have the worst impact on quality of the CDR process. The fourth section investigated the physiological effects experienced by the users after exposure to the technologies. The exposure time for each participant was too short to assess these effects. However, some users experienced some eye fatigue and discomfort when using the stereoscopic glasses.

Additional questions of the study, determined that users were willing to use the monoscopic CRT monitor or HMD for longer periods of time when compared to the other visual display systems. On average, they were willing to use the monoscopic CRT monitor for 5.08 hours, the HMD for 3.33 hours, and both the stereoscopic glasses and BOOM for 2.25 hours. Users were also asked if they thought that the visual display technologies were more beneficial for individual use. Kruskal-Wallis test results conclude that there is no significant evidence to reject the null hypothesis, indicating no differences exist between the four visual display technologies for whether they are more beneficial for individual use.

Design participant preferences were evaluated from ranked-data captured in VE Assessment Survey Three. Design team members felt that the HMD and monoscopic CRT monitor were the most useful technologies to use for CDRs and the most helpful for team interaction. They felt that the monoscopic CRT monitor was the most practical and most useful for team consensus forming. Test participants also thought that all the test technologies were equally as difficult to use for CDR activities.

The next chapter will conclude the study and provide guidelines and recommendations for VE applications to CDR process and user interface design derived from this research.

CHAPTER 5

DISSCUSSION AND RECOMMENDATIONS

The purpose of this study was to evaluate, through comparative empirical testing and data analysis, how several commercially-available virtual 3-D visual display systems contribute to cross-functional team collaboration in a product design review environment. These display systems are 3-D HMD, BOOM, Stereoscopic glasses and monitor systems, and for comparison a traditional 2-D monoscopic CRT monitor. Investigation revealed significant differences in the number of design errors detected, and the time to detect a design error for team performance during a concept design evaluation using the 3-D and 2-D visualization technologies. Empirical data also yielded statistically significant differences when comparing individual perception of the value of the technologies and preferences for their use.

After summarizing research questions and findings, this chapter provides a discussion of each topic area. Guidelines for applying virtual visual display technologies to the CDR environment and applications to human interface design, and usability engineering are discussed based on the research results.

The Problem. The application of VEs, an emerging technology, to the CDR process has intrigued many researchers and practitioners in industry, government, and academia. This technology creates a unique capability with the potential to reduce cost, shrink time to market, and improve overall product quality by allowing multifunctional teams to make critical decisions early in the design process. However, a proliferation of visual display tools used to generate 3-D stereoscopic visual information, has forced organizations to make decisions about which tools to integrate to improve their design process. Today, most organizations do not have the resources to conduct a comparative study of these 3-D visual display devices to make appropriate trade-off decisions. As a result, often their decisions are arbitrary. Answers to the following questions were sought in this study:

1. Number of Errors Detected. Do design teams detect and identify more design errors when using 3-D visualization tools?
2. Time to Detect. Do design teams detect and identify design errors more quickly when using 3-D visualization tools?
3. Time to Resolve. Do design teams resolve design problems more quickly when using 3-D visualization tools?
4. Perception: VE Assessment Survey Two -- the individual technology.
    a. Training. Was device training prior to the experiment adequate?
    b. Design Review Process. What is the perceived value of the design process?
    c. Quality. Do design team participants perceive improved quality of the design process when using the 3-D display devices?
    d. Physiological. What is the physiological state of the design team members after using 3-D visualization tools?

e. Additional Questions. How many hours are they willing to use the technologies, and were the technologies more beneficial for individual use rather than team use?

5. Preferences: VE Assessment Survey Three – technology comparisons.

   a. Usefulness. What are preferences for usefulness when comparing the four display technologies?

   b. Difficulty. What are preferences for difficulty when comparing the four display technologies?

   c. Practicality. What are preferences for practicality when comparing the four display technologies?

   d. Team Interactivity. What are preferences for stimulation for team interactivity when comparing the four display technologies?

   e. Team Consensus. What are preferences for development of team consensus when comparing the four display technologies?

The Findings. Results from the investigation of study questions are summarized in Table 19. They are as follows:

1. Number of Errors Detected. The null hypothesis was rejected, indicating a significant difference in the number of design errors detected across the four technology treatments. Pairwise comparison testing revealed that design teams were able to detect more errors when using either the stereoscopic glasses or the monoscopic CRT monitor and the least when using the HMD or BOOM systems.

Table 19.

Summary of Test Results

	Research Question	Best	Worst
1	Errors detected	Stereoscopic Glasses & Monoscopic CRT Monitor	HMD & BOOM
2	Time to detect	HMD	Stereoscopic Glasses & BOOM
3	Time to resolve	Not Statistically Significant	
4	Perception		
a.	Technology Training	Not Statistically Significant	
b.	Design Review Process	HMD & BOOM	Stereoscopic Glasses
c.	Quality	HMD & Monoscopic CRT Monitor	Stereoscopic Glasses
d.	Physiological	Not Statistically Significant	
e.	Additional Questions		
	Number of Hours Willing to Use the Technology	Monoscopic CRT Monitor & HMD	Stereoscopic Glasses
	Beneficial for Individual Use	Not Statistically Significant	
5	Preferences		
a.	Usefulness	HMD & Monoscopic CRT Monitor	Stereoscopic Glasses & BOOM
b.	Difficulty	Not Statistically Significant	
c.	Practicality	Monoscopic CRT Monitor	Stereoscopic Glasses & BOOM
d.	Team Interactivity	Monoscopic CRT Monitor & HMD	Stereoscopic Glasses & BOOM
e.	Team Consensus	Monoscopic CRT Monitor	Stereoscopic Glasses & BOOM

2. Time to Detect. The null hypothesis was rejected, indicating a significant difference in the average time to detect a design error across the four treatment technologies. Post hoc comparison analysis concluded that design teams were able to detect errors faster when using the HMD system.

3. Time to Resolve. The null hypothesis was retained indicating that there were no significant differences among the four treatment visual display technologies in the average time to resolve a detected design problem. Outside observation revealed that this was due mainly to the fact that design team members elected not to use any technologies during this phase of the CDR activity. Team members chose to resolve design problems using natural, face-to-face communication.

4. Perception: VE Assessment Survey Two -- the individual technology.

a. Training. Based on descriptive analyses of participant perceptions of the 15-minute training period, it appeared that they received an adequate amount of training prior to conducting the experiment.

b. Design Review Process. Kruskal-Wallis analysis reveal significant differences between the four visual display systems for the value on the CDR process dependent variable. Pairwise comparison testing concluded that the HMD, BOOM, and monoscopic CRT monitor systems differed significantly from the stereoscopic glasses. Participants felt these systems had positive effect on the design review process.

c. Quality. Kruskal-Wallis analysis reveal significant differences between the four visual display systems for the value on the quality dependent variable. Pairwise comparison testing indicate that the HMD, BOOM, and monoscopic CRT monitor systems were significantly different and provided better quality to the CDR process than stereoscopic glasses.

d. Physiological. The physiological state of the design team members after using the 3-D visualization tools could not be sufficiently assessed because the exposure time was too short. However, users experienced some discomfort after exposure to the stereoscopic glasses.

e. Additional Questions. Kruskal-Wallis analyses on the average time users were willing to use the visual display systems revealed significant differences between the four visual display devices. Pairwise comparison testing indicated that the stereoscopic glasses differed significantly and performed the worst when comparing how many hours test participants were willing to use the technologies. Descriptive statistical analysis revealed that design team participants are willing to use a traditional monoscopic monitor 34% longer than a HMD and 55% longer than either the BOOM or stereoscopic glasses.

Additionally, Kruskal-Wallis analysis was also conducted on the data from the question whether users felt that the technologies were better suited for individual rather than team use. This test revealed that there was not sufficient evidence to detect differences between the four visual display systems.

5. Preferences: VE Assessment Survey Three -- technology comparisons.

a. Usefulness. Results of Freidman analysis concluded that the null hypothesis was rejected, indicating differences in design participant's preference for usefulness.

Pairwise comparison testing indicate that the HMD and monoscopic CRT monitor were significantly different and more useful than the BOOM and stereoscopic glasses systems.

b. Difficulty. The null hypothesis for individual preference for difficulty was retained indicating no significant differences in the design participant's perception of the difficulty of using the four visual display systems.

c. Practicality. Results of Freidman analysis concluded that the null hypothesis was rejected, indicating differences in design participant's preference for practicality. Post-hoc pairwise comparison testing revealed that the monoscopic CRT monitor differed significantly and was considered the most practical technology. Users felt that both the stereoscopic glasses and BOOM were the least practical.

d. Team Interactivity. Results of Freidman analysis concluded that the null hypothesis was rejected, indicating differences in design participant's preference for design team interactivity dependent variable. Pairwise comparison testing indicated that the monoscopic CRT monitor and HMD systems were the most helpful technology to stimulate team interaction and differed significantly from both the BOOM and stereoscopic glasses systems.

e. Team Consensus. Freidman analysis concluded rejection of the null hypothesis, indicating differences in design participant's preference for helping develop team consensus. Follow-on pairwise testing revealed that design participants felt that the

f. monoscopic CRT monitor best helped team consensus formulating followed by the HMD, and jointly by the stereoscopic glasses and BOOM systems.

Discussion

The discussion addresses the findings with regard to number of errors detected, time to detect, time to resolve, perception, and preferences.

Number of Design Errors Detected

Results indicated that significant differences exist between the four visual display technologies in the number of errors detected during a CDR. This can be interpreted to mean that the number of errors detected when conducting a CDR and evaluation task are dependent on which visual display technology is used. The results clearly show that a greater number of design errors were detected when design teams used the stereoscopic glasses or the monoscopic CRT monitor systems. Post hoc analysis indicated that these systems performed similarly and differed significantly from the HMD and BOOM systems, which preformed the worst.

This implies that team interaction is critical in this type of task. This finding supports the basic underlying premise of concurrent engineering. As discussed by Clark and Fujimoto (1991), informal face-to-face relationships between functional organizations is an important necessity in any organization. This also supports the fact that person-to-person communication is a key activity in-group work (Floyd & Turner, 1989). The need for multi-functional design teams to discuss and interact when conducting a design review is fundamental for the success of the design review. Both the stereoscopic glasses and monoscopic CRT monitor configurations allowed design teams to simultaneously interact with the virtual model. In these two configurations, all participants were able to see the same model view, concurrently. This created a more natural, intuitive communication mechanism between team members. Outside observation indicated that when using a common model view, participants appeared to be comfortable as if they were in a more familiar environment. There was no need for team members to switch devices or places to view the model -- activities that can distract team activity. It also implies that in team settings it is critical that persons see the same virtual model simultaneously. When all participants were able to see the 3-D stereoscopic model they were able to discuss problems through team interaction and this promoted the identification of new design errors. This implies that for team activity tasks such as CDRs, VE tools need to maintain the feeling of team cohesiveness.

In contrast, inherent properties of the HMD and BOOM configurations prevented the entire design team to simultaneously interact and view the TFTS model. Allowing only one person to control the model view restricted team dialogue and interaction and yielded lower performances in the number of errors detected. Supporting this claim, one participant commented "the guy in the HMD is like in the closet," and another said "the BOOM user is the odd man out and this is a problem with this technology."

In addition, results from this study reflect similar findings to those concluded by McWhorter, Hodges, and Rodriguez (1991). Their work focused on ranking different types of display formats common to CAD applications for geometric information conveyed and perceived realism of objects. They found that stereo displays were judged superior to non-stereo displays in providing users with geometric information about an object. It is apparent that the effect of stereoscopic vision is important in better understanding the data and for easier recognition of form and pattern.

An interesting point that can be made which is based on user perceptions and this researcher's observations is that users did not prefer to use the stereoscopic glasses, yet design teams performed better when using this technology. Most of the comments and observations about the stereoscopic glasses were negative. One user said "glasses are hindersome at times" and another user commented, "developed a bit of an eyestrain trying to focus." From an interface usability standpoint it can be inferred that 3-D stereoscopic visual perception of objects and common viewing of objects are important in helping design teams find and detect design errors.

The four-way ANOVA also detected differences between the design teams. The obvious explanation is that even though design teams were created with similar characteristics in terms of professional experience, academic backgrounds, computer skills there still was one major factor that could not be controlled. That is human individualism and varying approaches to problem solving. It was evident that during the experiment there were different types of people with different logic approaches to problem solving. Researcher observation reflected that the approach a team took to problem solving was based on the individual personality types of the team members. These variation in personalities and people ranged from strong and boisterous to nonaggressive and shy. These results support the beliefs of Shneiderman (1993) that personality type plays an important role in designing systems. He stressed that a clear understanding of personality and cognitive styles for specific communities of users is critical when designing interactive systems.

Time to Detect

The results concluded that differences between the four visual display technologies exists in the average time to detect a design error during a CDR. The results reveal that the average time to detect a design problem or to identify a design flaw when using the HMD were significantly different from the average detection times when design teams used any of the other three technologies. Design teams were able to detect design errors faster when using the HMD system. These results may be attributable to the effects of immersion that the visual display device creates. Stuart (1996) defines immersion as the presentation of sensory cues that convey perceptually to users that they are surrounded by the computer-generated environment. Visual display devices can be categorized and defined by the level of immersion they provide to the user. These are immersive, semi-immersive, and non-immersive.

The HMD device creates an immersive environment where the user experiences the virtual world and is not cognizant of the real world. This level of immersion provides the user with a maximum level of presence in the environment. Hendrix and Barfield (1996) define one aspect of presence in a VE as the sense of "being there." The effect of a person being immersed in the virtual design may have some value to the CDR process.

The downside of using a single HMD system for team activity is that not all participants are able to share the same experience. Current technology is capable of networking multiple persons in a VE, where all the users could wear HMDs and achieve this greater level of immersion. Researchers are developing the infrastructure to accomplish this goal by improving communication protocols, creating database management procedures, and computer operating systems.

In contrast, the BOOM and stereoscopic glasses are considered semi-immersive systems, thus creating an environment where the user sees and experiences the virtual world but is cognizant of the real world. A user can easily remove the device and can use the real world as a reference. The findings conclude that the BOOM and stereoscopic glasses perform similarly and differed significantly from the performance when teams used the non-immersive, monoscopic CRT monitor. Design team performed the worst when using the BOOM and stereoscopic glasses systems.

One conclusion drawn from these findings is that users prefer the sense of total presence in the environment and if they can not obtain that level of immersion they prefer to revert back to their more familiar technology, the monoscopic CRT monitor.

The experimental design maintained equivalence between design teams and between TFTS subassemblies, and the design maximized randomization of the experiment order, yet the four-way ANOVA yielded significant statistical differences between all three blocking factors. Differences in the performance of the design teams can be attributed to the inability to control variation in personality types and logic methods individuals use to detect problems. The TFTS subassemblies chosen for this study contained similar design problems based on an evaluation from a senior level designer. However, differences where identified between the TFTS subassemblies. This finding can be attributed to the navigation required for a design team to get to a subassembly location. Least mean square graphs for the subassembly factor shows that the average time to detect a design error was longer for the TFTS suspension subassembly than the other three subassemblies. One obvious interpretation of this finding is that evaluating the suspension system required design teams to navigate to the underside of the TFTS model so that they had the correct view of the suspension system. This maneuvering could account for the differences experienced between the subassemblies. The least mean square graph for the experiment order factor show that design teams preformed worst for the third experiment in their testing sequence. One possible cause for this finding is that design teams were given a short break at the end of their second treatment, which could have resulted in a break in continuity.

Time to Resolve

No significant differences were revealed for the average time to resolve a detected design problem. This study failed to find any significance between the four visual display technologies on the time it took the design teams to resolve a detected design problem.

One possible reason is that after a problem was identified the design teams solved the problem without the assistance of any of the four visual display systems. Team members reverted back to basic communication skills and practices, at this stage of the CDR activities. It is apparent that problem resolution within teams requires face to face communications. The value of human interaction through gestures, eye contact, and mannerisms is crucial in consensus forming tasks. Outside observation concluded that after a period of time the design team members did not use the technology as the focus of their attention. Instead they continued discussions to resolve the problem without much emphasis on viewing the model.

In addition, some team members who were using stereoscopic glasses removed them while continuing to have team discussions. This action demonstrated a lack of need to use the technology during team discussion activities. At the extreme, one user who was not wearing stereoscopic glasses explained his point of view by pointing at the model on the monitor even though the image was blurred and distorted. This action support earlier research which identifies a users need for face-to-face communication to include gesture and expression when discussing and solving design problems.

Perception: VE Assessment Survey Two -- The Individual Technology

VE Assessment Survey Two was designed to obtain design team participant's subjective feelings on the value and usefulness of each of the four visual display technologies. The questionnaire addressed four areas: technology-training, CDR process, quality, and physiological effects. Some additional questions were also included to determine how long users were willing to use the technologies and if they thought the systems were better adapted for individual use.

Technology Training

The results indicate that the standard 15 minute training period was adequate for the design teams to conduct the design review task. Subjective data indicate that design team participants received a sufficient level of training prior to the experimentation. Based on frequency of responses, 87.5% "found the training to be sufficient", 85.4% "thought that they fully understood the correct operating procedures, and only 20.8% "felt they were not prepared." Most negative responses were associated with the stereoscopic glasses and monoscopic CRT monitor systems. This can be related to the navigation method employed in these two configurations. The mouse device was more difficult to learn and operate because it required more finesse. From this finding, it can be concluded that caution must be made when integrating simple mouse devices as navigation tools for virtual environment-based CDRs. More training may be required in order for users to grasp the functionality of panning in the environment, a task easily accomplished in the real world with normal head movements. It is important to understand that novice users get frustrated easily and can experience anxiety when using new computer systems (Shneiderman, 1993).

Concept Design Review Process

Results from the Kruskal-Wallis analysis and Bonferroni pairwise comparison tests on the cumulated CDR process data reveal differences between the four test visual display systems. User perceptions indicate that design team participants felt that stereoscopic glasses have the least effect on the design process. It is supported by descriptive analyses performed on the data. Only 16% (2/12) felt that it "assisted the design process", only 58% (7/12) thought it "helped describe problems to other team members," and only 41% (5/12) felt it "assisted in team consensus building." In contrast, users felt that the HMD, BOOM, and monoscopic CRT monitor were more helpful and useful to the CDR process. Eighty-three percent (10/12) of the users felt that the HMD and BOOM helped them identify problems. Caution needs to be used when interpreting these results. There is a much promoting, and hype about VR technology in the media, and this was the first exposure to these devices for some of the test participants. Novice users may have been more intrigued with the more novel visual VR display technologies and felt that they have a better effect on the CDR process.

Quality

Results from the Kruskal-Wallis analysis and Bonferroni pairwise comparison tests on the cumulated quality data reveal differences between the four test visual display systems. Participants felt that the stereoscopic glasses had the least effect on the quality of the CDR process. This is supported by the descriptive analysis findings. Where user perceptions indicate that only 33.3% (4/12) of the participants felt that stereoscopic glasses impacted the quality of the design process in a positive way, only 16.67% (2/12) thought that using stereoscopic glasses were satisfying and wonderful, and only 25% (3/12) thought they were stimulating. This finding can be attributed to the fact that users seemed uncomfortable in wearing the stereoscopic glasses. One commented that " they wouldn't want to use the technology for a long period of time." Again caution needs to be used when interpreting these results. Novice users may think the more complex systems, the HMD and BOOM, are better merely because of their higher cost, larger size, and promotion. This study did not explore this issue further.

Physiological Effects

The information collected in this section of the questionnaire addressed the physiological state of the users after exposure to the four visual display systems. The actual duration of usage for each participant for each technology was relatively short (approximately three to four minutes); therefore, a comprehensive evaluation of the mental and physical state of the design team participants was not feasible. However, descriptive analyses indicate that the majority of design team participants did not experience any simulator sickness symptoms. Only four of the design participants experienced any symptoms after exposure to the visual display systems. Of the affected participants only one person experienced any symptoms using the HMD, two using the BOOM, and zero using the monoscopic CRT monitor. However, thirty-three percent of the participants felt some form of eyestrain when using the stereoscopic glasses. A more in-depth study is required to determine the physiological effect of using these systems for CDR processes. These studies could focus on determining the optimal exposure time for these technologies applying simulator sickness assessment techniques as described by Kennedy et al. (1992).

Additional Questions

Individual design participants were asked how many hours they would be willing to use each of the four test visual display technologies. Descriptive statistics concluded that on average users are willing to use a traditional monoscopic monitor 34% longer than a HMD and 55% longer than either the BOOM or stereoscopic glasses. User comments support this finding. Some of these comments were: "it was familiar as using a PC," "easy to use," and "less tasking on one person." This finding identifies a typical interface design problem faced by new technology developers. New interface paradigms must compete with standard computer interfaces. According to Nielsen (1993) new interfaces need to be intuitive to users to provide them with consistency especially if these new interfaces take the place of existing ones. The researcher defines an intuitive interface as one that is easy to learn and easy to remember, and consistency can enhance the user's ability to transfer a skill from one system to another or from one task to another. This is a logical rationale to explain why users have a tendency to revert back to what they know -- more familiar ground. If VEs are to become the next generation interactive interface, it will be necessary to closely match functionality with user expectations.

Participants were also asked whether they thought the visual display systems were more beneficial for single use rather than team work. Statistical analysis revealed that no significant differences exist between the four tested visual display systems with regard to this issue. There was no evidence that the four tested technologies were more useful for single person usage.

Preferences: VE Assessment Survey Three -- Technology Comparisons

Usefulness

Results from the Freidman analysis indicate that individual preference for usefulness of the technologies differed significantly between the four visual display technologies. Post-hoc pairwise comparison tests revealed that when participants were asked to compare the four visual display technologies, they felt that the usefulness of the HMD and the monoscopic CRT monitor were equally useful and better than both the BOOM and stereoscopic glasses systems. Outside observation and user comments support these findings. HMD comments include: “Seems good because it raised many questions regarding the concept in a short time,” and “you are able to see 3-D and can really concentrate on the design.” Monoscopic CRT monitor comments include: “less tasking on one person, allowing the group to interact more,” “provides a better understanding of the concept,” and “it was as familiar as using your PC.” In contrast, user comments about the BOOM were more negative and include: “device doesn't lend itself to office use,” and “equipment was cumbersome and difficult to maneuver.” Stereoscopic glasses comments include: “glasses didn't seem to make much of a difference or assist in the design process,” “glasses are hindersome,” and “wouldn't want to use this technology for a long design review.”

Difficulty

When individual team members were asked to compare how difficult the technology was when applied to the CDR process, the Freidman analysis concluded no significant statistical differences between the four visual display technologies. All four of the evaluated technologies gave the users some difficulty in operating the system. Users experienced problems with using all of the navigational devices: the mouse, the 3-D pointer, and the BOOM functional buttons. User comments include: "difficult to use the mouse to maneuver to a desired angle", "difficult to move vertically with the BOOM", and "when using the HMD locking in on a single view is hard."

Practicality

The Freidman analysis results reveal significant differences for how practical the technology is for CDR. Pairwise comparison results indicated that practicality of using the monoscopic CRT monitor differed from all other evaluated technologies. Users believed that this system was the most practical and that the BOOM and stereoscopic glasses were the least practical technology to use. These findings are supported by user comments. One person commented on the BOOM saying " I could not use this on a daily basis." Another said "Wouldn't want to use this for long reviews" when talking about the stereoscopic glasses. These findings demonstrate that immaturity of the technologies may have a negative impact on real world applications. Comment analysis leads to the conclusion that users realize that the monoscopic CRT monitor is the most practical device because it is the most mature and familiar.

Team Interactivity

Results from Freidman analysis indicated that individual preferences for how the technology assisted in stimulating team interactivity between the technologies differed significantly between the four visual display technologies. It was found that the HMD and the monoscopic CRT monitor were preferred similarly and were ranked higher for helping stimulate team interaction. Users felt that the BOOM and stereoscopic glasses systems performed similarly and were ranked the worst. Even though the HMD system did not allow all the test participants to use the virtual display device simultaneously, users still felt that this technology helped in team interaction.

Team Consensus

Design team participants were asked to compare how useful they felt the technologies were in developing design team consensus. Friedman analysis results indicated that significant differences exist between the four visual display technologies.

Results from the pairwise comparison analysis show that the monoscopic CRT monitor differed from the other three visual display technologies and that the BOOM and stereoscopic glasses were similar. Design team participants thought that the monoscopic CRT monitor was the best for helping design teams form consensus and that the stereoscopic glasses and BOOM systems were the worst. This finding indicates that the CRT monitor configuration was better suited for team communication. When all team members were able to simultaneously view the same perspective of the TFTS model team consensus building was enhanced.

Recommendations

Machover (1997) provides worldwide forecasts for the year 2000 for commercial and industrial computer graphics applications and are shown in Table 20. These projections demonstrate expanded growth and strong emphasis on computer display systems. As shown, CAD/CAM, while small compared to other technologies, will grow 22% and VR applications will grow 81% by the year 2000. This is the largest projected growth of all computer applications.

Table 20.

Worldwide Forecasts for Commercial and Industrial Computer Graphics Applications

Application	1995 ($billion)	2000 ($billion)	Percent Growth (forecasted)
CAD/CAM	$11.9	$15.2	22
Art/animation	$ 3.4	$ 7.4	54
Multimedia Presentation	$14.7	$29.5	50
Real-time Simulation	$ 0.7	$ 1.3	46
Scientific Visualization	$ 2.9	$ 6.5	55
Graphic Arts	$ 4.0	$11.2	64
Virtual Reality	$ 0.4	$ 2.1	81
Other	$ 5.3	$ 8.7	39
Total	$43.3	$81.9	47

Note: Modified from **How Applications Have Driven Display Requirements** (p. 4), by C. Machover. In L. W. MacDonald & A. C. Lowe (Ed.) Display Systems: Design and Applications. Chichester, UK: John Wiley & Sons; 1997.

In light of these projections, research is needed to gain a better understanding of how to apply display technologies to these application areas while maintaining and improving performance of the users. Based on the results of the research study, this section offers recommendations for application to CDRs and user interface design and usability engineering practices. This section also presents recommendations for future studies in these two areas.

Application to Concept Design Reviews

This study has shown that VE technology has a potential to reduce development costs by identifying design problems early in the design process through the ability of cross-functional design teams simultaneously interacting in virtual prototypes of future designs. This section reflects on the results of this study and offers some recommendations for design trade-off, software issues, and dynamic modeling -- a concept referred to as VE-CAD.

Today, wide ranges of visual display devices and VE tools are available in the market. Similarly, cost of these systems varies widely. The risk organizations face is they must make decisions on which VE tools to invest in and which tools are most appropriate for the tasks they wish to accomplish. This requires organizations to make design trade-offs based on the state of the current technology, the task to be accomplished, demands on human perceptual and motor capabilities, and cost.

Based on empirical findings, it can be inferred that the best approach to using the commercially available visual display systems tested in this study for CDR activities is a combined technology approach. Before the CDR process begins using virtual visual display technologies, design team members should clearly understand the objectives of the CDR and the requirement specification of the system they are evaluating. Once team members possess this understanding, the CDR process can be initiated using a combined technology approach. The following recommendation is made based on the findings of this study.

First, using an HMD system, allow design team participants to review the conceptual virtual model individually. This complies with the second empirical finding, that design teams were able to identify design errors faster with this system. When selecting a HMD system it is important to purchase a system that has a higher resolution, greater FOV, and less physical weight because these three technical features help improve the sense of immersion in the virtual world and minimize ergonomic problems. Normally these systems are more costly because of the more sophisticated optics.

After individual evaluation, teams should meet to discuss problems they found during their individual investigation using the stereoscopic glasses system. This supports the first empirical finding, that design teams were able to detect more errors when using the stereoscopic glasses system. This will allow the teams to assemble in a more team-like environment and will promote interaction, stimulation of new ideas, and further detection of potential design problems. It is suggested that during this phase of the CDR process, a monitor larger than 21-inch be used. The reason for the larger monitor is that when more than two or three people are viewing the stereoscopic image generated from the stereoscopic glasses and emitter system, it is critical that viewers are in a frontal position to the emitter to achieve the correct 3-D perception. However, based on the subjective data collected and evaluated in this study, caution must be taken when using the stereoscopic glasses systems. Users did not perceive the value of this technology and in some cases experienced eye fatigue when using it. The implication of using the stereoscopic glasses systems will require shorter usage times and they should not be used for extended CDRs. It is also suggested that better navigational methods be provided to improve the likelihood of user acceptance of this technology for CDRs. If design team members were able to move quickly to a selected location, the time in the system could be reduced and the likelihood of user acceptance would be improved.

Lastly, after exposure to the conceptual model as an individual and as a team member, teams should resolve problems with their improved knowledge base using face-to-face communication. At this phase of the CDR activity, the design participants have developed an improved understanding of the concept model and the potential problems that exist. It is suggested that a team leader facilitate the process during this phase of the CDR. This leader would be responsible for focusing the discussion, keeping team members on track, and helping design team members formulate consensus on problem resolutions in real-time.

Also, when using virtual visual display systems for CDR activities, it is recommended that novice users get adequate exposure to the technologies prior to conducting the actual CDR. This will eliminate potential problems with navigating in the virtual environment and reduce potential anxiety when using the systems.

The problem faced in creating a good VE is important to the success of the virtual representation of a concept design. The problem faced in creating good VEs with today's tools, is that the translation from CAD data formats into virtual world software formats is a time consuming and sometimes difficult process. CAD data formats contain larger amounts of information than are necessary for VE developments. User comments obtained in this study indicate that some users expected a higher level of detail in the virtual model. Yet the current state of computer technology limits the level of detail that is feasible. VE models require less detail in order to provide the correct visual rendering of the virtual objects. Less detail minimizes latency, problems associated with slow processing power. Current computer processing power restricts the ability to have a one to one matching between CAD and VE file formats.

Another important technology issue is that equipment set-up is not trivial. Required are computer programming, hardware integration, and computer trouble-shooting skills. This issue is brought up because it is important to realize that design teams are comprised of individuals with varying levels of technical expertise who most likely do not have all the skills needed to develop or use these tools without the assistance of experienced technical specialists.

In addition, it is strongly recommended that future design tools possess the technical characteristics necessary to give users the ability to move and interact with the data model, and to make changes dynamically in a more intuitive manner. User comments indicate that a future tool that would allow them to dynamically make changes while they were conducting the design review would greatly benefit the CDR process. This tool could be a VE-based CAD tool, which provides users with the capability to make design changes in 3-D and still maintain the level of engineering data necessary to build the end product. An extension to research in haptic interface applications to design, would be the capability to dynamically make changes to the virtual design by grabbing an object, scaling it, moving it, and making final decisions during the CDR. This capability does not presently exist in today's systems.

User Interface Design and Usability Engineering

Understanding the task and who will be using the technology is important in selecting which display system is appropriate. It is critical to remember that not all potential users have experience with VEs or with computer technology, and new experiences may be intimidating at first. Shneiderman (1993) indicates in a book preface that "fighting for the user" is important because frustration and anxiety are a normal part of daily life for many computer users. People struggle to learn command language and menu selection systems that are supposed to help them do their job. Some people encounter such serious cases of computer shock, terminal terror, or network neurosis that they totally avoid using computers. The researcher also indicates that these electronic-age maladies are growing more common.

Future VE tools need to be intuitive to the user and need to closely match the task they are trying to accomplish. User comments obtained in this study identified limitations of current computer-based systems and offered some insight into possible interface improvements. Users want improved resolution of displays, improved navigation techniques, incorporation of touch and more intuitive ways to grasp objects, and the inclusion of some form of dynamic modeling. The closer systems capabilities match the real world, the more likely VE systems will give users the better performance capabilities. Navigation is a critical function in VEs, allowing users to move and change points of view. Current systems accomplish this task by using methods that often do not closely relate to natural or expected actions in the real world. Navigational devices must be improved if they are to become more widely and successfully used. This researcher strongly agrees with Bryson (1996) who identified two primary difficulties impeding the development of VR applications. They are: VR interfaces are a new paradigm to which 2-D interface paradigms do not easily apply, and VE systems need to deliver high performance in order to achieve user expectations.

Recommendations for Future Research

On the basis of the findings and observations gathered from this study, recommendations for future research in two major areas are presented. These are: applications to CDRs, and user interface design issues and usability engineering practices.

Application to Concept Design Reviews

This study examined the use and value of some commercially available 3-D visual display systems to the CDR process. These systems will continue to mature and evolve over time.

User comments obtained in this study have also lead the researcher to believe that physical interaction with a virtual model is necessary during CDR activities. Haptic devices have been suggested for medical, entertainment, and military applications (Burdea, 1996) because they provide the user with the sense of touch. These haptic devices may also have the potential to provide interesting insight into whether design team members would gain improved performance. With this capability design team members may intuitively grasp, touch, and move objects – much more than can be accomplished using current navigational techniques such as a 3-D mouse.

Burdea (1996) also found that the sense of presence might serve an important role in VE-based design review activities. Researchers have initiated efforts to develop an understanding of the sense of presence in virtual environments but much of this work has not yet been focused on specific application areas. A better understanding of how important the sense of presence is in product design review environments would be beneficial.

The inclusion of more technologies (e. g., CAVE, ImmersaDesk, Immersive WorkBench, and holographic imaging systems) for testing is needed as these technologies mature and become more affordable for CDR use. As these tools enter the commercial market it is necessary for organizations to understand the performances and task utilization of these systems in order to make correct trade-off determinations.

Lastly, this study was based on the performance of U. S. Army design teams. Test replication in other environments (e.g., NASA space element design, Air Force or Navy weapon system development review, and civilian consumer product development) is needed to provide validation and understanding for the entire product design community.

User Interface Design and Usability Engineering

"Knowing the user" is one of the most fundamental of all human interface usability guidelines (Shneiderman, 1993; Nielsen, 1993). Future studies focusing on the "people" in the product development community are needed to gain a better understanding of the differences between product design review participants, the dynamics of team interaction, the complexity of the process, and the required tasks. These discoveries could then be translated into improved VE interface designs for the general product design and development community. Nielsen (1993) suggests that more formal, systematic task and functional analyses can be fruitful, providing interface designers with information regarding what users want to accomplish, how they will accomplish it, and what the relationships are between the tasks and the actions in the application. These methods can help determine the correct functionality of the interface and help identify occasional and exceptional tasks which are more difficult to discover (Shneiderman, 1993).

One issue that was not addressed in this study is the effect of differing personalities among design team participants. These personality differences may have an effect on how users performed and how they felt about the visual display systems. An approach that merits further investigation, as described by Shneiderman (1993), is to focus on measuring the cognitive and personality styles of the product design team community and translating these findings into improved VE interface designs.

Summary

Demands and technological advances for sophisticated methods of collaborative interaction have led to great interest in the techniques and applications of 3-D imagery. Few researchers and organizations have the opportunity to make direct comparisons of different 3-D systems used for CDRs. Because of this limitation, their choice of display systems maybe arbitrary. This study was conducted to evaluate, through comparative empirical testing and data analysis, how commercially-available virtual 3-D display systems contribute to cross-functional team collaboration in a product design review environment.

Applications of VR to the product design and development process have intrigued many. A majority of today's organizations are exploring the possibility of designing products only in the virtual sense. VE technology allows for persons to experience a new product concept prior to building costly physical prototypes. Through the use and testing of four different visual display systems, the results in this study serve to strengthen the premise that VEs improve the effectiveness and efficiency of the design review process. Data collection, which applied the four visual display systems in an experimental setting, produced results identifying the strengths and weaknesses of each visual display system. These findings are important because they lead to a better understanding of the trade-off required when selecting a VE visual display system, and they provide insight for consideration and testing of future interface designs.

APPENDICES

Appendix A

Abbreviation of Terms

Abbreviation of Terms

BOOM	Binocular Omni-Orientation Monitor
CAD	Computer aided design
CAE	Computer-aided engineering
CAM	Computer-aided manufacturing
CAPP	Computer-aided process planning
CAVE	Cave Automatic Virtual Environment
CDR	Concept Design Review
CRT	Cathode Ray Tube
CSCW	Computer Supported Cooperative Work
DC	Direct Current
DMD	Digital Micromirror Device
DOD	Department of Defense
FOV	Field of View
HDTV	High-definition television
HMD	Head Mounted Display
IR	Infrared
LAN	Local Area Network
LCD	Liquid Crystal Display
NASA	National Aeronautics Space Administration
PC	Phase Coherent
QUIS	Questionnaire for User Interface Satisfaction
SE	Synthetic Environment
SGI	Silicon Graphics Incorporated
TACOM	Tank-automotive and Armaments Command
TOF	Time of Flight
TFTS	Tracked Fuel Trailer System
VE	Virtual Environment
VP	Virtual Prototyping
VR	Virtual Reality
WAN	Wide Area Network
2-D	Two-dimensional
3-D	Three-dimensional

Appendix B

Tracked Fuel Trailer System (TFTS) Requirements

TRACKED FUEL TRAILER SYSTEM (TFTS)

Concept Philosophy

A new tactic of fighting being evaluated is to engage two opposing forces within a range of 50 to 100 kilometers. The way to defeat an Army using this strategy would be to disrupt the logistics resupply line. DSOPS believes that digital voice and data communications would enable this to work. This requires the ability for ground vehicle systems to continually be on the move. Providing extended range capability and minimizing logistic supply interruptions.

REQUIREMENTS

- 600 Gallon Fuel Pod
- Trailer to be towed behind a tracked (Abrams M1 Main Battle Tank) or tactical wheeled vehicle
- Continuously provide fuel to the prime mover when in tow
- Remotely activated & quick disconnect of the fuel delivery system and trailer
- Convertible for water and/or palletized load
- Capable of external helicopter lift
- Towed safely at speeds of prime mover
- Equipped with essential operational safety features
- Recoverable and reusable without repair or preparation

Appendix C

Test Plan Summary

Test Plan Summary

1. **Participants:**
   1.1. Participants for the experimentation are personnel at the U. S. Army Tank-automotive and Armaments Command in Warren, Michigan. Specifically, the following operational organizations; New Equipment Training, Human Factors, Safety, Logistics, Maintenance, Quality Assurance, and Design
   1.2. Test participants will fill out VE survey one (1), Participant Background Data prior to any experimentation. The survey contains data on educational, professional, and computer literacy of each participant.
   1.3. Participants will be tested for color deficiency and visual acuity prior to experimentation using a standard Ishihara Color Deficiency test and a Snelling Chart examination. Tests take 5-10 minutes each.
   1.4. Subjects that are tested positive for color deficiency will be eliminated from the subject pool.

2. **Design Team Composition:**
   2.1. Identification of representative design team members. Teams are composed of designers and non-designers. A total of 3 subjects for each team; 1 designer and 2 non-designers.
   2.2. Test participants will be pre-assigned to a design team, based on data from the VE Assessment Survey One. The purpose is to create teams with similar backgrounds & characteristics based on an aggregation of experience, computer literacy, and education. Balancing the teams.
   2.3. The designer will act as the team leader.

3. **Pilot Test:**
   3.1. Conduct orientation and pilot test in one (1) day.
   3.2. The pilot test will be done at on-site laboratory. The purpose of the pilot test is to evaluate test procedures, VE assessment surveys, and test model.
   3.3. The test will use the same procedures and data collection mechanisms as the experimentation. Based on the pilot, modifications to the procedures and surveys will be done.

4. **Experimental Design:**
   4.1. 4X4 Graeco-Latin Square
   4.2. Four variables each with four levels. Teams = T_1, T_2, T_3, T_4; Experiment Order = E_1, E_2, E_3, E_4; Technology = A, B, C, D; and Subassembly = 1. 2. 3, 4
   4.3. Design teams will be randomly assigned to a test sequence, a column in the Graeco-Latin Square.
   4.4. Time order will be randomly assigned to a row in the Graeco-Latin Square
   4.5. Where Technology A, B, C, D are defined as HMD, BOOM, Stereoscopic

Glasses, and Monoscopic 3-D respectively.

4.6. Where Subassemblies 1, 2, 3, 4 are defined as fuel transfer subsystem, fuel container subsystem, towing subsystem, and suspension subsystem respectively.

4.7. Purposeful assignment to prevent confounding.

5. **Subassemblies (problem/issues):**

5.1. Four (4) different subassemblies of the concept trailer will be used for the experimentation. Each subassembly contains problems or issues with similar levels of complexity.

5.2. The subassembly issues are related to mechanical, ergonomic, maintenance, or operational issues.

6. **Experiment**

6.1. **Pre-test Orientation:**

6.1.1. Conduct pre-test orientation on the day of the experiment in a local conference room.

6.1.2. Orientation Agenda:

6.1.2.1. General purpose/objective of the experiment (i.e. the purpose is evaluate the usefulness of a variety of VE based visualization technologies on the product design review process)

6.1.2.2. Describe Tracked Fuel Trailer System requirements

6.1.2.3. Provide an overall schedule of day's events (logistics)

6.1.2.4. Description of Test Conduct (Protocol)

6.2. **Test Protocol:**

6.2.1. Groups will move between technology stations.

6.2.2. Groups will have a time limit (one-hour) at each technology station.

6.2.3. Each technology station will have a technology test observer.

6.2.4. System familiarization (training) will be conducted at each technology station

6.2.4.1. Standard 15 minute training session

6.2.4.2. An alternate model will be used for training.

6.2.5. Design reviews will be conducted at each technology station

6.2.6. Test Teams will be told subsystem of focus at each technology station.

6.2.7. Test Teams will be told that there are at least 3 problems or issues in each subassembly.

6.2.8. The designer will act as the team leader and discussion facilitator.

6.2.9. Participants will be asked to identify an issue, and to resolve the issue before moving on to the next problem (sequential). The purpose is to reach consensus on problem identification and possible resolution

6.2.10. It is suggested that each team use the technology in anyway they feel is appropriate.

6.2.11. The test observer will take continuous clock times of problem identification times and resolution times. Documented on a standard quantitative data Collection Sheet.

6.2.12. The test observer will document solutions.

6.2.13. The test observer will document anything unusual that may effect the data

6.2.14. After experimentation, each person will complete VE Assessment Survey Two – Individual Technology. Participants will be given 15 minutes to complete the survey

6.2.15. After completion of all technologies, each participant will complete VE Assessment Survey Three -- Technology Comparisons. Participants will be given 15 minutes to complete the survey

Appendix D

VE Assessment Survey One -- Participant Background Data

Virtual Environment Assessment Survey One
Participant Background Data

Name: ____________________
Participant Number __________

Part 1.1 Personal Information

Sex: ____ Male ____ Female

1.1.1 Do you wear corrective glasses (not contact lenses)? ____ Yes ____ No
1.1.2 Have you ever experienced simulator (motion) sickness? ____ Yes ____ No

Part 1.2 Educational Background

1.2.1 Identify the highest level of your education
___ High School ___ Bachelors Degree ___ Doctoral Degree
___ Associates Degree ___ Masters Degree ___ Post Graduate Study

1.2.2 Identify the field of your study
___ Engineering ___ Business ___ Quality Assurance ___ Psychology
___ Other What is your field of study? ____________________

Part 1.3 Professional Experience

1.3.1 How many years have you been working in your field?
___ Less than one year ___ 3 to 5 years ___ 10-15 years
___ 1 to 3 years ___ 5-10 years ___ Greater than 15 years

1.3.2 In what area have you spent most of your career?
___ Project Management ___ Research ___Engineering
___ Manufacturing ___ Quality
___ Other What area? ____________________

Part 1.4 Computer Usage

1.4.1 How many different types of computer systems (e.g. main frames and personal computers) have you worked with?
___ None ___ 1 ___ 2 ___ 3-4 ___ 5-6 ___ more than 6

1.4.2 Of the following devices, software, and systems, check those that you have personally used and are familiar with:

__ keyboard	__ text editor	__ color monitor
__ numeric key pad	__ word processor	__ time-share system
__ track ball	__ file manager	__ workstation
__ mouse	__ electronic spreadsheet	__ personal computer
__ light pen	__ electronic mail	__ floppy drive
__ joy stick	__ graphics software	__ hard drive
__ touch screen	__ computer games	__ compact disk drive

1.4.3 Of the following types of visualization devices and systems, check those that you have personally used and are familiar with:

__ Helmet Mounted Display (HMD)	__ Stereoscopic Glasses
__ Binocular Omni-Orientation Monitor (BOOM)	__ 3-D Solid CAD Models

Part 1.5 Design Review Experience

1.5.1 How many design and/or concept reviews have you participated in?

___ None   ___ 1   ___ 2   ___ 3-4   ___ 5-6   ___ more than 6

Please leave blank, a standard eye examination and color deficiency test will be given prior to the experimentation.

Visual Acuity ______________
Color Deficiency ______________

Appendix E

Test Presentation

Appendix F

Outside Observer Comments

Technology A, HMD

User wants to point at a certain location in the design, and at first doesn't think that it is possible then notices the virtual hand makes pointing easy.
User commented that he was just as comfortable viewing the computer monitor and didn't want to use the HMD.
Participants had used the HMD and pointing devices fairly easily to locate problem areas and to bring others into individual perspectives.
Participants followed design protocol, but it was difficult for them to focus on one issue. sometimes they sidetracked into several issues, but where brought back into focus by the team leader.
Issues that were solved were sometimes re-opened
Team made a summary at the end of the session, recapping their conclusions.
The person in the HMD seemed isolated from the conversation. The two persons looking at the monitor where engaged in conversation and the HMD user was busy looking around the model. HMD User seemed intrigued with the technology and was not directing the others to specific problem areas. HMD user would interject once in awhile.
User used physical hand gestures to explain his idea to his partners. He never used the virtual hand to point and explain his perspective.
Users sometimes re-iterated their findings to the HMD user after exchanging positions.
Users asked the HMD user to navigate to a certain part of the model.
When switching the HMD from design member some users lost their place in the model. Not enough experience with how these systems work and didn't realize he was out of the trackers range. Simply fixed when he moved forward.
Some users didn't navigate around in the model; they remained in a fixed position. I think he didn't want to disrupt what the remaining members were looking at and discussing.
Teams kept conversing without using the HMD. This seems typical for design reviews. people look at a concept then prefer to discuss with face to face contact. In fact the model wasn't even in focus on the external monitor.
User made a comment that all the team members should have HMDs.
HMD user asked the others to navigate him to where they wanted to look.
Group outside of the HMD seemed frustrated because the person in the HMD was busy looking at what he wanted and kept moving around especially when they were trying to point to and discuss a specific thing.
One team member made a comment that this is definitely not good for group interaction, or group work. "The guy in the HMD is like in the closet"
The team member in the HMD, flipped up his visor so he could be part of the discussion, then the dialogue continued with gestures and face to face discussions.
Most of the discussion was without using the HMD
Users want to focus on a detailed level design and not a conceptual level.

Technology B, BOOM

Users had increased difficulty in maneuvering in the virtual design space. Especially when it comes to leveling your personal height in the world. Sometimes they couldn't get the exact view they wanted and discussed issues from their best attempt

Comments on difficulty to use

Comments on grainy resolution

One user commented that it is easier to move around by looking at the monitor and physically moving the boom device. He preferred to focus on the monitor and use the boom as the navigation device.

Teams seem to be quite comfortable talking around the monitor, without any stereoscopic perspective.

After a period of time the users did not use the system as the focus of their discussion. They kept the model in view of the monitor, by one person holding the device steady. Discussions continued without the BOOM device, allowing more face to face interaction.

Not every one used the technology for a long duration of time, they preferred to look at the monitor.

One user commented that the BOOM seemed more intuitive to operate and navigate.

One user commented that the BOOM user the odd man out, this is a problem with this technology.

Technology C, Stereoscopic Glasses

Participants made comments on the quality of the visual system.

Using single monitor participants seemed very comfortable and the dialogue flowed. There was no need for participants to switch devices, or places, or seats.

Some users took off their glasses towards the end of the session, they continued to discuss problems and issues. They would put the glasses when they want to point at something,

All participants were able to view the same monitor. It seemed easier for them to share, or take charge of the discussion, or show an individual perspective. This differed from the HMD where the HMD user was looking at what he wanted to independent of the group discussion.

In one case, one user pointed at a specific part of the model without using his glasses. Without the glasses the monitor picture appears distorted and offset, but he didn't put the glasses back on to get his point across.

Participants had difficulty navigating with the mouse device.

One participant commented, "does anyone know how to move around?"..."3-D might be good but it seems you can't see the detail, maybe the dimension is more a problem than its worth."

The pintle seems very detailed and the glasses make it hard for them to actually see the detail, eyestrain.

Participants used gestures and natural pointing when discussing problems and solutions.

One participant commented in relation to 3-D drawings..."that if he had a 3-D drawing he would know immediately how the pintle worked."

One participant said he would prefer to have the monitor divided with the same views as 3-D drawings.

Technology D, Monoscopic CRT Monitor

All design team members seemed comfortable

Sometimes participants continued discussing issues without even looking at the monitor, they preferred to make eye contact with each other.

Using a single monitor participants seemed very comfortable and the dialogue followed. There was no need for participants to switch devices, or places, or seats.

Participants frequently used physical hand gestures to describe their issue or problem. Often pointing to the monitor to specifically point out what they wanted to discuss.

Difficulty using mouse device.

Discussions where natural with face to face dialogue and gesturing. You get the sense that the participants felt as if this is more appropriate.

Participants used pointing and natural gestures to help explain their position.

A lot of face to face dialogue

When looking at the regular monitor, it appears that the participants love to discuss all kinds of multi-issues

After a period of looking at the model, the discussions continued without looking at the model itself. The group was in deep conversation about the issues without the model assisting them.

Appendix G

Data Collection Sheet

Quantitative Data Collection Sheet

This form will be used to collect data during group experimentation with each of the technologies. This information will be collected by trained observers.

Identification number: Group _______ Technology ______ Subassembly ________
Date ________
Start Time ___________

Problem/Issues	Resolution	Detection Time (mins)	Resolution Time (mins)

Did the design team follow the suggested test protocol? ___Yes ___No
If no, what strategy did they use?

____
____
____
____

How did the design team use the technology? (Did each person use the technology before consensus?)

____
____
____
____

Provide comments regarding the experimental sessions.

Appendix H

VE Assessment Survey Two --The Individual Technology

Virtual Environment Assessment Survey Two
Individual VE Technology

This survey will be administered after completion of each individual technology concept design review.

Identification number: Group ______ Participant ________ Subassembly ______
Visualization Technology:
__ HMD __ Stereoscopic Glasses
__ BOOM __ 3-D Monoscopic CAD

For the following questions please circle the number which most appropriately reflect your impressions about this visualization technology. NA = Not Applicable

Part 2.1 Training

2.1.1 Was the training you received on the visualization technology adequate?	Insufficient ... Sufficient 1 2 3 4 5 NA
2.1.2 Did you understand the correct operating procedures for the technology?	Misunderstood ... Fully understood 1 2 3 4 5 NA
2.1.3 Were you sufficiently prepared to conduct a concept review exercise?	Insufficiently prepared ... Totally prepared 1 2 3 4 5 NA
2.1.4 Learning to operate the system was:	difficult ... easy 1 2 3 4 5 NA

Provide comments regarding the training you received prior to the test phase.

____
____
____
____
____

Part 2.2 The Concept Design Review Process

2.2.1 Did the technology assist you in conducting your team concept review?	Not at all ... Totally assisted 1 2 3 4 5 NA
2.2.2 Did the technology assist in detecting design problems or issues?	Not at all ... Totally assisted 1 2 3 4 5 NA
2.2.3 Did the technology help in describing issues to your team members	Not any help ... Totally helpful 1 2 3 4 5 NA
2.2.4 Did the technology stimulate creativity and problem solving?	Not at all ... Totally stimulating 1 2 3 4 5 NA

2.2.5 Did the technology assist group interaction and discussion?	Not at all 1 2 3 4 Totally Assisted 5 NA
2.2.6 Did the technology help develop a group consensus?	Not at all 1 2 3 4 Totally helped 5 NA
2.2.7 Did the technology provide a better understanding of the concept (configuration)?	Not at all 1 2 3 4 Totally Assisted 5 NA
2.2.8 Did the technology provide easier recognition of form & pattern?	Not at all 1 2 3 4 Totally Easier 5 NA
2.2.9 If this technology became a standard for concept design reviews do you think that the product development time would decrease?	Not at all 1 2 3 4 Decreased time 5 NA
2.2.10 If this technology became a standard for concept design reviews do you think that the final product quality would be improved?	Not at all 1 2 3 Totally improve quality 4 5 NA

Provide comments regarding the effect of this visualization tool to perform concept design review tasks.

____

____

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____

____

Part 2.3 Quality

2.3.1 Was the technology helpful as a common platform for group discussion?	Not at all 1 2 3 4 Totally helpful 5 NA
2.3.2 How useful do you think this technology is in the product design review process?	Not at all 1 2 3 4 Totally useful 5 NA
2.3.3 Did you feel that your time using this technology was well spent?	Waste of time 1 2 3 4 Totally well spent 5 NA
2.3.4 Did you feel that you had adequate time using this technology?	Inadequate 1 2 3 4 Adequate 5 NA
2.3.5 Did you feel that any time was wasted waiting for use of the technology?	Wasted time 1 2 3 4 No time wasted 5 NA

2.3.6 Does this technology positively affect the quality of the design review process?	Negative affect 1 2 3 4 5 Positive affect NA
2.3.7 Overall reactions to the system:	Terrible 1 2 3 4 5 Wonderful NA
	Frustrating 1 2 3 4 5 Satisfying NA
	Dull 1 2 3 4 5 Stimulating NA
2.3.8 Operating the system was:	Difficult 1 2 3 4 5 Easy NA

2.3.9 How many hours a day are you willing to use this technology?

__ none __ 2 __4 __6 __ 8

__ 1 __3 __5 __7 __ more than 8

2.3.10 Do you believe this technology is more beneficial for individual use?

_____Yes ____No

If yes, Why?

____

____

____

____

Provide comments regarding the quality of the technology as it applies to product design and your overall reaction to the technology.

____

____

____

____

____

Part 2.4 Physiological

2.4.1 Is the system mentally demanding?	undemanding 1 2 3 4 5 demanding NA

2.4.2 Do you have **any** of the following symptoms (**Check all applicable**)?

__ General discomfort __ Fullness of head __ Vertigo

__ Fatigue __ Blurred vision __ Stomach awareness

__ Headache __ Dizzy (eyes open) __ Burping

__ Eye strain __ Dizzy (eyes closed) __ Nausea

__ Difficulty focusing __ Increased salivation __ Sweating
__ Difficulty concentrating

Provide comments regarding your physical or emotional state after using this technology.

____
____
____
____
____

Part 2.5

Is there any aspect of the visualization tool that could be improved to enhance the concept design review activity? ___ No ___ Yes If yes, please explain.

____
____
____
____

Appendix I

VE Assessment Survey Three -- Technology Comparison

Virtual Environment Assessment Survey Three
VE Technology Comparison

This survey will be administered after completion of all individual technology concept design reviews have been completed.

Identification number: Group _______ Participant ________

Part 3.1 Comparison

3.1.1 Please rank the **usefulness** of the four visualization technologies on the concept design review and evaluation process, where one (1) is considered the most useful and four (4) is the least useful.
__ HMD __ BOOM __ Stereoscopic Glasses __3-D Monoscopic CAD Model

3.1.2 Please rank the **difficulty** of using the technologies on the task of concept design review and evaluation, where one (1) is considered the most difficult and four (4) is the least difficult.
__ HMD __ BOOM __ Stereoscopic Glasses __3-D Monoscopic CAD Model

3.1.3 Please rank the **practicality** of using the technologies for concept design and evaluation, where one (1) is considered the most practical and four (4) is the least practical.
__ HMD __ BOOM __ Stereoscopic Glasses __3-D Monoscopic CAD Model

3.1.4 Please rank the **stimulation of group interactivity** when using the technologies for concept design review and evaluation, where one (1) is considered the most stimulating group interaction and four (4) is the least stimulating group interaction.
__ HMD __ BOOM __ Stereoscopic Glasses __3-D Monoscopic CAD Model

3.1.5 Please rank the **usefulness for developing group consensus when using the technologies** in concept design review and evaluation, where one (1) is considered the most useful for developing group consensus and four (4) is the least useful for developing group consensus.
__ HMD __ BOOM __ Stereoscopic Glasses __3-D Monoscopic CAD Model

Part 3.2

Answer the following question: In **retrospect**, after experiencing all four visualization technologies would you make any changes to your previous responses to your individual technology surveys? If yes, explain.

Appendix J

Data for Design Problem Detection Time and Resolution Time

Team	Experiment Order	Technology	Subassembly
T_1	E_1	A	1

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
The angle of the transfer boom has too much play in it.	Did not resolve, but decided to move to next problem	30	118	30	88
How is the fuel pumped?	Need mechanical fuel pump inside of or in the bottom of the fuel pod?	130	300	12	170
The angle of the transfer boom has too much play in it.	Use a flexible hose that will allow quick connect	318	353	18	35
The exit point of the fuel pod is too high, may cause improper fuel release.	Move the exit point to the bottom or front side of the fuel container	464	473	111	9

Team	Experiment Order	Technology	Subassembly
T_1	E_2	B	3

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
There will be a problem when turning the M1 with the trailer attached (problem with the turning radius.	Extend the pintle on the M1 tank	120	150	120	30
There is no quick release mechanism on the hitch itself.	Did not resolve, but decided to move to next problem	210	420	60	210
What kind of power is going to the trailer, no 24V cable	Provide the trailer with an electrical harness that will provide 24V	450	477	30	27
The lift handles do not look adequate to carry the entire weight of the system	Need to strengthen the handles using a different lift handle design in order to allow for air transportability	599	921	122	322

There is no quick release mechanism on the hitch itself.	Provide a quick release in the electrical harness of the trailer	960	1242	39	282

Team	Experiment Order	Technology	Subassembly
T_1	E_3	C	4

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
It appears that there will be torsion on the axle which can cause excessive twisting on the leaf springs	Utilize the same axle	195	655	195	460
Should the beams between the wheels be changed?	Use a fixed beam system	664	780	9	116
Why re-invent the suspension for the trailer system?	Use an existing trailer system's suspension	822	860	42	38
Is the leaf spring system adequate to carry the load?	Incorporate a shock absorber system	930	979	70	49
What type of brake system is on the trailer?	Need some method of braking the trailer system, especially if being pulled behind a wheeled tactical vehicle.	998	1088	19	90
Need to drop on the move for survival purposes.	Need some type of skid plate to allow you to drop and continuously move	1413	1453	325	40
At what speed is it safe to drop the trailer system	Need to look at more detailed operational requirements for the move dropping speeds	1467	1610	14	143

Team	Experiment Order	Technology	Subassembly
T_1	E_4	D	2

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
The profile of the tank is too high	Did not resolve, but decided to move to next problem	30	38	30	8
Need a method to fill, drain and vent the fuel	Incorporate a vented design into the gas cap	65	118	27	53
There is no disconnect where the fuel transfer enters the fuel pod	Need to add a quick disconnect mechanism at the pod connection	166	177	48	11
What kind of feature for changing from water, fuel, or ammo	Did not resolve, but decided to move to next problem	201	233	24	32
Is there any armor protection required?	No, armor is not an operational requirement	540	593	307	53
The profile of the tank is too high	Lower profile of the fuel pod to reduce the trailer silouhette, reduce vulnerability	598	659	5	61
What kind of feature for changing from water, fuel, or ammo	Need to have more distinction on the pod as to what it carries	670	874	11	204

Team	Experiment Order	Technology	Subassembly
T_2	E_1	B	2

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
The trailer needs to be protected	Does not appear to be any way to armor the trailer fuel pod	114	432	114	318
Profile of the tank is too high	Make fuel pod longer and lower to reduce vulnerability	489	505	57	16

Does the fuel pod need separate lifting hooks?	Did not resolve, but decided to move to next problem	598	622	93	24
There is an issue when air lifting the fuel pod when it is full, as far as the rigidity of the pod (should it be flexible or rigid	This is an issue that needs to be addressed in further concept work.	644	663	22	19
The fuel pod needs some sort of venting system	Provide a venting system in the fuel pod itself, to eliminate combustion	706	760	43	54
Does the fuel pod need separate lifting hooks?	Put hooks on the fuel pod or provide some type of track so that it can be removed easily (slide on and off)	802	834	42	32

Team	Experiment Order	Technology	Subassembly
T_2	E_2	A	4

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
All the concept has is springs and one axle, this won't work	Did not resolve, but decided to move to next problem	105	108	105	3
There appears to be no break system	Did not resolve, but decided to move to next problem	140	185	32	45
Only one axle with 600 gallons on top of it	Did not resolve, but decided to move to next problem	203	260	18	57
No tail lights on trailer	Did not resolve, but decided to move to next problem	269	293	9	24
Still concerned about the springs	Did not resolve, but decided to move to next problem	320	331	27	11
Back to 600 gallon fuel pod	Need a two axle system	336	349	5	13
Back to tail lights on trailer	Need to put a set of rear lights on the trailer	356	374	7	18

Tank assembly is short	Make it longer, but this is not a big deal	488	547	114	59
Can't tell dynamically how is will hold up	Need some dynamic modeling conducted	868	908	321	40
There appears to be no break system	Recap - Need to design a braking system that will brake in cooperation with the prime mover	970	1008	62	38
Only one axle with 600 gallons on top of it	Recap-Need a two axle system to carry weight	1048	1064	40	16
No tail lights on trailer	Recap-Need to put a set of rear lights on the trailer	1082	1096	18	14
All the concept has is springs and one axle, this won't work	Recap-Need some kind of air suspension system	1121	1163	25	42

Team	Experiment Order	Technology	Subassembly
T_2	E_3	D	3

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
Does the tow pintle rotate?	Never Resolved	105	120	105	15
Is there a tow hitch on the M1?	Did not resolve, but decided to move to next problem	147	180	27	33
Needs to be some landing mechanism	Incorporate a landing leg into the design	189	197	9	8
Is there a tow hitch on the M1?	Use an inventory hitch system	200	221	3	21
Needs to be some landing mechanism	Incorporate a landing leg into the design	257	332	36	75
Problem with turning radius when turning the trailer	train crew how to drive when trailer in tow	347	486	15	139
Lifting eyes not visible	Need eyehooks with chain spreaders or a flexible lifting belt	643	711	157	68
Shorter trailer may be better	Need a better turning radius	811	851	100	40

Is the quick disconnect adequate	Appears to be OK	1063	1083	212	20
Lifting eyes on back end of the trailer seem as if it would unbalance the trailer	Extend the back of the trailer out a little bit to stabilize the load when airlifting	1100	1135	17	35
Backend of the trailer looks too light	Extend the solid metal sides on the trailer to the back end	1280	1313	145	33

Team	Experiment Order	Technology	Subassembly
T_2	E_4	C	1

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
The piping is too rigid	Need a flexible hose	71	96	71	25
Why fill fuel from the top?	Use a bottom filler cap	173	197	77	24
Where should the bottom cap be place?	Use a hose from bottom and boom it up like a flexible joystick	247	267	50	20
There is a lot of heat coming out of the M1 exhaust system	This needs to be addressed with some sort of heat shielding mechanism	376	386	109	10
When the turret rotates, the gun tube will rip off the fuel transfer line	The hose needs to come out of the bottom	394	411	8	17
Is there quick disconnects at tank side and pod side?	Need to have flexible, rotatable disconnects at both ends	505	517	94	12
Is fuel sucked out or pumped out?	Include a pony engine on the trailer to pump the fuel if it's not using a suction device	528	650	11	122
Is it constantly fueling or not?	Provide a sensor on the M1 tank so that it knows the fuel level and when it is completely out	733	794	83	61

Should a remote control be placed on the M1 tank to turn the pump on or off?	$$$ vs. ease of installation vs. automatic continuous fueling	841	922	47	81
Does the driver need two fuel gauges?	No, the driver's primary concern is the fuel in the M1 and not the fuel pod	952	1044	30	92

Team	Experiment Order	Technology	Subassembly
T_3	E_1	C	3

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
Are there any airlift holds on the trailer and are they enough?	Located 4 hold points, this seems sufficient	113	164	113	51
Is the pintle on the tank the normal M1 pintle?	not resolved	190	410	26	220
How does the hitch work?	Eyelet on the trailer hooks onto the lower portion of the pintle	420	468	10	48
Fluctuations in terrain are going to cause problems in the hookup as far as rotation, bouncing off the hitch	Need a pivotable hitch and one that clamps and locks down	470	480	2	10
There are no safety chains	not resolved	489	665	9	176
Is the hitch position locked	Not resolved	678	970	13	292
How do the pintle jaws work?	Need to look at the existing M1 pintle and compare	1024	1159	54	135
Eyelet on the trailer isn't bolted to the frame	Bolt or weld it to the frame	1284	1298	125	14
How is the trailer leveled to the pintle height?	Need something to level the trailer to the height of the pintle in order to connect it easily	1360	1368	62	8

Team	Experiment Order	Technology	Subassembly
T_3	E_2	D	1

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
There is going to be a fatigue problem with the rigid z-curve of the fuel transfer system	Replace rigid pieces with flexible tubing	25	56	25	31
How is attached to the tank?	No resolution	59	90	3	31
Where is the fuel pump? How is the fuel pumped into the M1 tank?	Did not resolve, but decided to move to next problem	94	120	4	26
Why is the fuel line coming out of the top?	Did not resolve, but decided to move to next problem	124	183	4	59
Where are the electrical connections for the trailer subassemblies?	Provide an electrical harness of some kind to the trailer system	216	386	96	170
Where is the fuel pump? How is the fuel pumped into the M1 tank?	Need something in the M1 to suck or suction the fuel out or even a pump in the fuel tank itself	390	428	4	38
Why is the fuel line coming out of the top?	Locate fuel line towards the middle or bottom of tank	440	526	12	86
The manhole cover in the fuel pod is too small for conducting any maintenance on the pod	Enlarge the manhole cover	620	638	94	18
How is the fuel filtered from the trailer to the M1 tank?	Put a filter in the fuel line of the tank for filtering all the fuel	706	716	68	10
Diameter of the fuel transfer rod is too small	Widen the diameter of the hose feeding the tank	768	798	52	30

Team	Experiment Order	Technology	Subassembly
T_3	E_3	A	2

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
How is the pintle attached to the trailer?	Did not resolve, but decided to move to next problem	63	240	63	177
How is the fuel pod removed?	Provide a mounting feature on the fuel pod itself	288	338	48	50
How is the pintle attached to the trailer?	Need a quick method for attaching and detaching the trailer from the pintle	345	379	7	34
Logistics is a problem when changing from fuel to water.	Probably will not do this during battle this will be done easily in non-battle conditions	485	586	106	101
Does the fuel pod need to be a lower profile?	Did not resolve, but decided to move to next problem	587	615	1	28
How are gas fumes in the pod taken care of?	Need baffles installed on the fuel pod	628	648	13	20
The fuel pod is too much design in the shape of a fuel tank and thus making it more vulnerable for attack	Redesign the pod to resemble something else that the M1 normally tows	819	880	171	61
Does the fuel pod need to be a lower profile?	No profile change is really needed, it is not higher than the M1 tank	900	940	20	40

Team	Experiment Order	Technology	Subassembly
T_3	E_4	B	4

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
Do we want wheels with the rubber tracks?	Keep the concept as it is, it should work	36	70	36	34

Use of leaf springs only, is this adequate?	Did not resolve, but decided to move to next problem	120	148	50	28
Detail of model doesn't show how spring is attached to the axle	Need more detail to determine how they are connected	288	317	140	29
Use of leaf springs only, is this adequate?	Some type of shock absorption is required	320	374	3	54
How is the track taken off or replaced?	Provide some type of mechanical system to aid in the removal of the track	458	498	84	40
Mud splashing will be a problem	Provide some type of fender system to keep the mud splashing contained	540	556	42	16

Team	**Experiment Order**	**Technology**		**Subassembly**	
T_4	E_1	D		4	
Problem/Issues	**Resolution**	**Detection Time (Sec)**	**Resolution Time (Sec)**	**Times to Detect (Sec)**	**Times to Resolve (Sec)**
Why do they have tracks on the trailer?	Study needs to be done on whether the track possibility is required	24	279	24	255
Why tandem wheels on each side?	Did not resolve, but decided to move to next problem	293	316	14	23
No oscillation ability	Did not resolve, but decided to move to next problem	504	810	188	306
Height of trailer, is it O.K.?	Good height from the ground clearance of ground obstacles	840	862	30	22
Spring hangers look flimsy	Re-look at the design of the hangers, they need to be strengthened	888	960	26	72
Why tandem wheels on each side?	Look at using an in stock large wheel that are being used on other vehicles (one vs. two)	970	982	10	12
What holds the track on?	No sign of a track guide, one needs to be inserted	1203	1228	221	25

Tires are very wide	Relief of ground pressure a possibility, need to conduct an analysis	1290	1324	62	34
Axle meeting wheel bar, no pivot on bar	How are bars attached to the wheel, need something to attach them	1357	1505	33	148
How are things attached?	Need more detail in the design	1548	1610	43	62
Will track wear be an issue?	Conduct a durability analysis.	1622	1670	12	48

Team	Experiment Order	Technology	Subassembly
T_4	E_2	C	2

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
Profile of pod is too high	Reduce the height, spread out over the length of the frame making it more stable	46	64	46	18
What is the tank made of?	Need to determine a suitable material	142	156	78	14
Why not a fuel bladder, why use a trailer at all?	A bladder directly on the tank may be a better solution	167	208	11	41
Is there a pump?	Needs to be a pumping system	226	248	18	22
Attachment to trailer, stress points	Did not resolve, but decided to move to next problem	316	328	68	12
How is it vented?	Need baffles to vent it	361	410	33	49
How do determine the fuel level?	Place a fuel gauge on the pod	468	471	58	3
Need to drain the fuel	Add a drain to the fuel pod	478	490	7	12
Need identification of what is in the pod	Add ID plate	708	721	218	13
Attachment to trailer, stress points	Need to place a damper between the fuel pod and where it rests on the trailer	748	791	27	43

Lifting eyes or track for interchangeability	Need a way to change the tank, lift off the pods	899	929	108	30
Overpressure valve is not apparent	Make sure to include an overpressure valve	948	969	19	21

Team	Experiment Order	Technology	Subassembly
T_4	E_3	B	1

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
Hard piping/line size flow not good	use a flexible hose and increase the diameter of the line	145	158	145	13
Engine heat exhaust will be a problem	Use thermal hosing	190	197	32	7
How often running the transfer system	Felt all fuel should be transferred and then the trailer should be jettisoned	252	336	55	84
How do quick disconnects work remotely?	Did not resolve, but decided to move to next problem	356	420	20	64
Square transfer pipe?	Use the flexible hose method	489	511	69	22
How do quick disconnects work remotely?	Possibility of using a pressure disconnect of some type	677	870	166	193
Corrosion problems	Need to use materials that are non-corrosive	878	895	8	17

Team	Experiment Order	Technology	Subassembly
T_4	E_4	A	3

Problem/Issues	Resolution	Detection Time (Sec)	Resolution Time (Sec)	Times to Detect (Sec)	Times to Resolve (Sec)
Where the pintle bar meets the trailer frame, tension and sheer will cause it to fail and it may snap.	Lengthen the bar into the eyelet and fasten it down	25	160	25	135

Eyelet is too small	Needs to be reworked	170	240	10	70
No auto disconnect	Need a remote disconnect, solenoid of some type may be the solution	251	275	11	24
No pincer to drop the pintle	Need something that disconnects and lets the pintle loose from the eyelet	449	548	174	99
Pintle is too high on the back of the tank	Lower the pintle on the tank	571	604	23	33
Should the entire are flex?	Yes, or cracking will occur in the towing structure if there is no flex	668	721	64	53

Appendix K

Number of Design Error Detected

Number of Design Errors Detected for Each Treatment

Team	Experiment Order	Technology	Subassembly	Errors
T_1	E_1	A	1	3
T_1	E_2	B	3	4
T_1	E_3	C	4	7
T_1	E_4	D	2	5
T_2	E_1	B	2	5
T_2	E_2	A	4	6
T_2	E_3	D	3	9
T_2	E_4	C	1	10
T_3	E_1	C	3	9
T_3	E_2	D	1	8
T_3	E_3	A	2	6
T_3	E_4	B	4	5
T_4	E_1	D	4	10
T_4	E_2	C	2	11
T_4	E_3	B	1	6
T_4	E_4	A	3	6

Appendix L

Design Problem Detection Time

Mean and Standard Deviation for Each Treatment on Detection

Times (Seconds)

Group	Experiment Order	Technology	Subassembly	Mean	SD	N
T_1	E_1	A	1	42.75	46.11	4
T_1	E_2	B	3	74.2	44.09	5
T_1	E_3	C	4	96.29	119.76	7
T_1	E_4	D	2	64.57	107.79	7
T_2	E_1	B	2	61.83	34.79	6
T_2	E_2	A	4	60.23	85.89	13
T_2	E_3	D	3	75.09	72.78	11
T_2	E_4	C	1	58	34.529	10
T_3	E_1	C	3	46	46.29	9
T_3	E_2	D	1	36.2	38.15	10
T_3	E_3	A	2	53.63	58.99	8
T_3	E_4	B	4	59.17	47.373	6
T_4	E_1	D	4	55.25	73.211	11
T_4	E_2	C	2	57.58	58.97	12
T_4	E_3	B	1	70.71	58.52	7
T_4	E_4	A	3	51.17	63.3	6

Appendix M

Data for Design Problem Resolution Time

Mean and Standard Deviation for Each Treatment on the average time to resolve design errors (Seconds)

Group	Experiment Order	Technology	Subassembly	Mean	SD	N
T_1	E_1	A	1	75.5	71.06	4
T_1	E_2	B	3	174.2	138.93	5
T_1	E_3	C	4	133.71	149.38	7
T_1	E_4	D	2	60.29	66.74	7
T_2	E_1	B	2	77.17	118.77	6
T_2	E_2	A	4	29.23	18.50	13
T_2	E_3	D	3	44.27	37.61	11
T_2	E_4	C	1	46.4	39.77	10
T_3	E_1	C	3	106	104.28	9
T_3	E_2	D	1	49.9	47.43	10
T_3	E_3	A	2	63.88	52.17	8
T_3	E_4	B	4	33.5	12.80	6
T_4	E_1	D	4	91.55	101.31	11
T_4	E_2	C	2	23.17	14.47	12
T_4	E_3	B	1	57.14	66.5	7
T_4	E_4	A	3	69	42.03	6

Appendix N

Participant Comments from VE Assessment Survey Two

Technology A, HMD

Provide comments regarding the effect of this tool to perform concept design review tasks, the quality of the technology as it applies to product design and your overall reaction to the technology, and any comment regarding your physical or emotional state after using the technology.

Should be able to zoom in an out of model components in order to examine them more thoroughly.
The HMD is not useful for the actual design because the design can not be modified.
HMD allows for easy maneuvering around the concept.
You are able to see the design in 3-D and really concentrate on a specific area of the design.
Seems good because it raised many questions regarding the concept in a short time.
I feel that this technology greatly improves the overall product design.
Easy to learn and utilize.
If properly developed this tool has the potential to enhance the design process. However, in its current state it has little use.
Particularly difficult in team reviews since you can not point at things.
The person wearing the device is not part of the group; perhaps each group member should be wearing a device.
No eye contact when wearing the device, so you can't understand what others are referring to.
Locking in on a view is hard to due.
Easiest device to use.
Clear picture and ease of use are positive attributes

Is there any aspect of the visualization tool that could be improved to enhance the concept design review activity?

Improve component level detail and exploration.
Smooth the movement of the model.
Improve resolution.
If the tool really allowed you to touch the object under study it would be very useful.
Have the ability to lock in a view.

Technology B, BOOM

Provide comments regarding the effect of this tool to perform concept design review tasks, the quality of the technology as it applies to product design and your overall reaction to the technology, and any comment regarding your physical or emotional state after using the technology.

The low image resolution makes it difficult to determine the details of the concept; it was easier to see it on the monitor.

It is difficult to maneuver into the viewing angle you desire.

The image seems jumpy.

Very poor image.

Difficult to move around the model.

Horizontal movement is ok, but vertical movement is difficult.

Image very grainy.

Some feelings of nausea.

More stimulating than looking at drawings, it could make work more interesting.

It does not appear to be a viable tool since the user must stand up in a relatively uncomfortable posture.

Can not quickly view what you want to see.

The BOOM was hindersome; once we got the object in view we stepped away and discussed.

No physical or emotional effects.

Mouse is better to accomplish same task of moving.

Easy to learn.

Without the external monitor the team would not be able to communicate or see the same item at the same instance.

Very useful, freedom to move is easy and concise.

User doesn't get frustrated trying to aim where they would like to be located.

Easy flowing.

My eyes were unaffected by the technology, the updates were slow enough not to make me dizzy.

Device doesn't lend itself for office use.

I could not use on a daily basis.

Felt that it required too much movement of the users' head and I think that would be uncomfortable.

Equipment is cumbersome.

Is there any aspect of the visualization tool that could be improved to enhance the concept design review activity?

Image quality.

Improve vertical movement for ease of operation.

Keep bumping into BOOM arm.

The structure of the BOOM causes the user problems because one keeps hitting it with their head when turning at certain times.
Attach it to a swivel chair so the user can sit down while operating it.

Technology C. Stereoscopic Glasses

Provide comments regarding the effect of this tool to perform concept design review tasks, the quality of the technology as it applies to product design and your overall reaction to the technology, and any comment regarding your physical or emotional state after using the technology.

Difficult to use the mouse to maneuver to desired viewing angle.
Mouse functions difficult.
Model too slow.
Need to focus better, resolution.
The glasses did not assist in my concept review using the monitor.
Glasses didn't seem to make much difference to me.
Glasses didn't seem to help in the discussion.
A good tool if used in accordance with a 2-D drawing.
Had a problem with "ghost" images.
Difficulty in focusing on the solid model.
Developed a bit of eyestrain trying to focus.
The current state of the technology does not appear to be efficient tool to evaluate design problems; it may be useful to look at the overall design after the problems have been resolved.
Problem is getting in close.
The benefit of 3-D glasses did not add to enhancing our ability to visualize our sample. Maybe this is more suited for more complex or detailed designs.
More eye demanding than a simple monitor does.
Wouldn't want to use this technology for a long design review.
Glasses are hindersome at times.

Is there any aspect of the visualization tool that could be improved to enhance the concept design review activity?

Make it easier to change viewing orientation.
Actually get rid of the glasses.
Difficulty to position at the correct spot to get the best 3-D.

Technology D, 3-D Monoscopic CRT Monitor

Provide comments regarding the effect of this tool to perform concept design review tasks, the quality of the technology as it applies to product design and your overall reaction to the technology, and any comment regarding your physical or emotional state after using the technology.

Difficult using the mouse to maneuver to desired viewing angle.
The stereo effect would be more useful for more complex models.
Less tasking on one person, allowing the group to interact more.
Slow updating causes group to lose focus.
The mouse was the easiest device to use.
Helped me pinpoint design problems.
Helps other people visualize what the engineer is trying to develop.
Provides a better understanding of the concept.
The tool was more difficult to use due to inexperience, than using drawings and appropriate design parameters. However, the future designer may use this type of technology in conjunction with other equipment to optimize the design process.
Was easy to move around and look at different views of a picture.
It was as familiar as using your PC.
No physical or emotional effects.
One can see how subsystems interface with each other.
The quality of the graphics was crisp, clear and allowed for any flaws to be detected easily.
Great tool for assisting in the design process.
Networking the design review through a series of screens integrating the engineer. logistician, maintenance and cost estimator will result in optimal designs that are both user friendly in terms of operation, maintaining, and cost effective.
Command controls are slow and awkward to use (at least initially) this can become tiresome and can exuberate an already difficult task like a design review.

Is there any aspect of the visualization tool that could be improved to enhance the concept design review activity?

Make it easier to change views.
Would like to make design changes on the spot (cut, paste. and delete).
A large monitor screen with more details including both the electrical and mechanical portions of the system.

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