Development of a virtual laboratory for the study of complex human behavior

Jeff B. Pelz,*[a,b] Mary M. Hayhoe,[b] Dana H. Ballard,[c] Anurag Shrivastava,[b] Jessica D. Bayliss,[c] and Markus von der Heyde[d]

[a]Carlson Center for Imaging Science, Rochester Institute of Technology, Rochester, NY 14623
[b]Dept. of Brain and Cognitive Sciences, University of Rochester
[c]Dept. of Computer Science, University of Rochester
[d]Max-Planck-Institute for Biological Cybernetics

ABSTRACT

The study of human perception has evolved from examining simple tasks executed in reduced laboratory conditions to the examination of complex, real-world behaviors. Virtual environments represent the next evolutionary step by allowing full stimulus control and repeatability for human subjects, and a testbed for evaluating models of human behavior.

Visual resolution varies dramatically across the visual field, dropping orders of magnitude from central to peripheral vision. Humans move their gaze about a scene several times every second, projecting task-critical areas of the scene onto the central retina. These eye movements are made even when the immediate task does not require high spatial resolution. Such "attentionally-driven" eye movements are important because they provide an externally observable marker of the way subjects deploy their attention while performing complex, real-world tasks. Tracking subjects' eye movements while they perform complex tasks in virtual environments provides a window into perception. In addition to the ability to track subjects' eyes in virtual environments, concurrent EEG recording provides a further indicator of cognitive state.

We have developed a virtual reality laboratory in which head-mounted displays (HMDs) are instrumented with infrared video-based eyetrackers to monitor subjects' eye movements while they perform a range of complex tasks such as driving, and manual tasks requiring careful eye-hand coordination. A go-kart mounted on a 6DOF motion platform provides kinesthetic feedback to subjects as they drive through a virtual town; a dual-haptic interface consisting of two SensAble Phantom extended range devices allows free motion and realistic force-feedback within a 1 m^3 volume.

Keywords: virtual reality, eye tracking, EEG, motion platform, driving simulator, haptic interface

1. BACKGROUND

The study of human behavior is challenging for many reasons. Historically, experimenters have attempted to make such studies tractable by reducing the complexity of both the environment and the task under study. As a result, much of what is known about human behavior is restricted to over-simplified tasks, such as single eye movements made in response to the onset of a signal light, or a reach to an isolated target in a dark field. We have been striving to expand the range of behaviors to include the kind of complex behavior that makes up daily life. In that effort, we are developing a virtual reality laboratory in which the behavior of human subjects can be studied as they perform arbitrarily complex tasks.

*Correspondence: pelz@cis.rit.edu

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A concern about such experiments is the ability to make meaningful conclusions about human performance because of the very complexity we are striving to understand. The use of virtual environments allows us to maintain enough control over the visual, kinesthetic, and haptic environment to permit meaningful analysis. In addition to traditional metrics of performance (such as reaction times, success rates, etc.), we monitor subjects' eye movements to provide an externally observable marker of attention. Electroencephalograph (EEG) recordings can also be used to provide multiple indicators of cognitive state.

In order for the lab, funded as part of the National Institutes of Health National Resource Lab initiative, to accomplish its goal, many component subsystems must be successfully integrated. It is necessary to generate complex, stereo virtual environments contingent on the subjects' head position, position in the virtual environment, and in some cases hand position. The generated images must be displayed with sufficient fidelity to provide a strong sense of immersion so that natural behaviors can be observed. While visual simulation is the heart of the virtual environment, full immersion requires kinesthetic and/or haptic feedback. The visual, kinesthetic, and haptic simulations comprise the perceptual 'input' to the subject – a critical aspect of the lab's goal is the ability to monitor subjects' cognitive state as they perform complex tasks in the virtual environment. That is accomplished by the use of integrated eyetrackers in the virtual reality HMDs and concurrent EEG recordings. Each of these elements is discussed in the following sections.

2. GRAPHICS GENERATION AND DISPLAY

2.1 SGI Multi-Processor Onyx

The heart of the graphics generation system is a Silicon Graphics Onyx processor equipped with four R10,000 processors and an Infinite Reality rendering engine. The system generates stereo image pairs at up to 60 Hz, depending on the complexity of the scene. Figure 1 shows a stereo pair from a sequence that was generated at 30 Hz.

Figure 1 Driving environment stereo pair (crossed disparity)

In addition to generating the graphics for the head-mounted displays (HMDs), the Onyx is responsible for interfacing with other computers and equipment in the laboratory. The Onyx is equipped with a high-speed serial interface board capable of simultaneous communication with head trackers, motion platform, haptic interface, eyetrackers, and EEG systems. A special-purpose 12-bit analog-to-digital board reads steering, accelerator, and brake signals from the driving simulator

2.2 Virtual-Reality Head-Mounted Displays (HMD)

Achieving the goals of the laboratory requires the presentation of as realistic an environment as possible. It is important that the mode of display have the best combination of spatial, temporal, and spectral resolution, along with as large a field of view as practical while maintaining a lightweight HMD that will not fatigue subjects during experiments. We have chosen to use HMDs for image presentation for several reasons. Retinal projection systems are not yet practical, and VR rooms that project images onto the walls, ceiling and floor are expensive and the areas where multiple images meet can lead to a loss of the sense of immersion. The tradeoff is that HMDs require high-accuracy, low-latency head tracking in order to avoid delays that lead to side effects ranging from a loss of immersion to nausea (see section 2.2, below). The lab is currently equipped with two HMDs manufactured by Virtual Research. The *VR4* has dual back-illuminated 1.3" LCD displays with a resolution of 640x480 pixels. Color images are created by addressing color triads on the LCD, effectively reducing the spatial resolution by a factor of three. The *VR4* has a 60 degree (diagonal) field of view at full ocular overlap, and accepts standard interlaced NTSC video signals. The interpupillary distance (IPD) is adjustable from 5.2 to 7.4 cm. The *VR4* is integrated with an eyetracking system that monitors the eye position of the left eye (see 4.1 below).

In addition to the VR4 HMD, the lab is equipped with a Virtual Research *V8* HMD. The *V8* is similar mechanically and optically to the *VR4*, but is based on a higher resolution LCD display. The *V8*'s display is made up of a pair of 1.3" LCD panels, each with a resolution of 1920x480 pixels. The display is grouped horizontally into RGB triads, yielding a true 640x480 VGA display. The higher resolution requires dual standard VGA video feeds in place of the *VR4*'s NTSC video signal. The V8 is also equipped with an integrated eyetracking system (see section 4.1 below).

2.3 Motion-Tracking Systems

Central to all HMD-based virtual environment systems is the ability to track the position and orientation of the subject's head in order for the graphics engine to render the appropriate scene given the current viewpoint. The ideal head-tracking system would have infinite resolution, no error, and zero lag. Several technologies exist for tracking the position of the HMD. We are evaluating magnetic field, inertial, and hybrid systems in the laboratory.

The Polhemus Fastrak 3-SPACE motion tracking system is the lab's primary system. The system has a fixed transmitter consisting of three mutually orthogonal coils that emit low-frequency magnetic fields, and receivers containing three mutually orthogonal Hall-effect sensors. The system controller cycles the three transmitting coils and sensors, taking nine measurements in each cycle. The relative and absolute field strength measurements are sufficient to determine the orientation of the receiver, and position within a hemisphere. The 6DOF measurement is then transmitted *via* a serial connection to the Onyx. In the basic configuration we use a single receiver operated at 120 Hz. The working volume of a single transmitter is a sphere with a radius of ~75cm for maximum accuracy, or a radius of up to ~3m with reduced accuracy. Up to four receivers can be used within the working volume of a single transmitter with reduced temporal resolution (2 receivers at 60 Hz each, 3 receivers at 40 Hz, 4 receivers at 30 Hz). If more receivers and/or a higher temporal sampling rate are required, up to four controller/transmitter systems can be operated within the same workspace. The spatial resolution of the system is approximately 0.15mm at 75cm; angular resolution is approximately 2 arc minutes. The static spatial accuracy of the system is rated at 1mm (RMS), static angular accuracy is rated 10 arc minutes. Because the system's position and orientation coordinates are based on measurements of the magnetic fields created by the transmitter, the system is susceptible to systematic errors when ferrous metal is in close proximity to the transmitter and/or receiver. To minimize these errors, the transmitter is mounted on a wood support and the receiver is mounted on the HMD so that it is at least 1cm from any large metal pieces. Tests in our laboratory show that the accuracy varies from better than the rated values when the transmitter-to-receiver distance is less than 10cm to errors greater than 1cm at distances approaching the recommended 75cm limit.

Another critical characteristic of tracking devices used to monitor HMD motion is the delay imposed by the system. Any delay between sensing the position of the HMD and the arrival of the signal at the rendering engine will induce a lag in the display. These lags result in a mismatch between the subject's efferent and proprioceptive information about head position and the visual signal delivered by the HMD's display. This mismatch can lead to discomfort and nausea. The Polhemus has a stated latency of 4ms, defined as the elapsed time from the center of the receiver measurement period to the beginning of the associated record's transmission from the serial port. As a result, it is clear that the latency does not equate with the temporal delay between HMD movement and the appropriate image update. At the maximum sample rate of 120Hz, there is a variable delay between the desired and actual samples that can be as high as 8ms. Even at a serial transfer rate of 115Kbps there is an additional delay of approximately 5ms for transmission of the data packet containing position and orientation information. Calculating and displaying the environment takes a variable amount of time; at a minimum it is the period of frame display, or 17msec for 60 Hz displays. Further delays are inevitable, as calculations required for image display cannot begin until the HMD's viewpoint is received from the tracking system. It is clear, then, that even a tracking system with zero latency can't eliminate the problem of display lag.

One approach to minimizing the problems associated with delay between position sensing and image display is to implement a predictive algorithm. The mass of the head and HMD are sufficient that inertial damping limits the maximum acceleration of the HMD. We are now evaluating the IS-600 hybrid head-tracking system manufactured by Intersense. The IS-600's primary tracking is performed by a tri-axial inertial sensor. Rather than rely on a transmitter/receiver pair to monitor field strength, the IS-600 is a 'dead-reckoning' device that constantly updates its position based on the integrated acceleration values. In this mode, the tracker has an unrestricted range and is unaffected by metal in the environment. A room-referenced ultrasonic time-of-flight system can be used to prevent errors from building up over time if the system is used in stationary mode. In this 'fusion' mode, the workspace is restricted to a volume of approximately 1.25m x 2.5m x 1.25m. The sampling rate is 150 Hz with one sensor and an integrated predictive filter can be set from 1-50ms. In fusion mode, orientation measurements have a resolution of 0.02 degrees, static accuracy of 0.25 degrees, and a dynamic accuracy (during rapid motion) of 1.5 degrees. Position measurements have an RMS jitter of 0.5mm and a static accuracy of 5mm.

3. KINESTHETIC AND HAPTIC INTERFACES

3.1 DRIVING SIMULATOR

One of the virtual environments we use to study complex behavior is a driving simulator. The simulator is based on a racing go-kart frame in which the steering column has been instrumented with a low-noise rotary potentiometer and the accelerator and brake pedals are instrumented with linear potentiometers. A constant voltage supply across each potentiometer produces a variable voltage from each control that is read by a multi-channel sample-and-hold 12-bit A/D board on the SGI's VME bus.

Subjects drive in "PerformerTown," an extensible environment designed by Silicon Graphics. Figure 1 shows a sample from the environment. We have added cars and trucks to the environment that move along pre-defined or interactively controlled paths. These objects, as well as "DI-Guy" people can be placed in the environment through a configuration file that makes it easy to customize the environment. The visual environment is also easily modified to simulate lighting at any time of day or night, and the addition of fog.

3.2 MOTION PLATFORM

To aid on our goal of making experiences in the virtual environments as close as possible to those in the real world, the driving simulator is mounted on a motion platform. The McFadden Systems Inc. 6-12AL Motion Simulator System, is a 6DOF platform constructed of 6 independent hydraulically actuated cylinders, each with a 30 cm stroke. With a payload of 900kg the platform can generate linear accelerations of ±0.75g for heave and surge and ±1g for sway, and angular accelerations of ±200 degrees/sec^2 for pitch, roll, and yaw. The platform produces maximum linear velocities of ±20 inches/sec for heave, surge, and sway, and angular velocities of ±20 degrees/sec for pitch, roll, and yaw. The platform is controlled by a host PC that is connected to the SGI via serial interface. The host PC accepts acceleration values and calculates optimum linear and angular values for the platform actuators.

Figure 2 Driving simulator on 6DOF motion platform

Most motions are made up of a combination of linear and angular movement designed to provide a realistic sensation of motion. An extended forward acceleration, for example, would be 'written out' to the platform as an initial forward linear acceleration coupled with an upward pitch designed to provide additional stimulus to the subject's vestibular system. Without this cross-stimulus matching, linear accelerations would be limited to relatively short-lived actions that wouldn't exceed the platform's range. After delivering the initial linear acceleration, the platform is moved back toward its neutral position at a washout rate that is below the threshold of detection in preparation for the next motion.

A Fastrak transmitter is mounted rigidly to the platform so that angular motion designed to stimulate the vestibular organs does not induce a change in the rendered environment. Because of the effect of metal between the Fastrak's transmitter and receiver, the transmitter is mounted approximately 1m above the motion platform.

3.3 SensAble Technologies, Phantom haptic feedback devices

Head-mounted displays can provide a rich visual environment that offers a strong sense of immersion, but the ability to *interact* with the environment is a crucial element in developing a laboratory in which complex behaviors can be studied. While the driving simulator allows subjects to guide their travel through the virtual town, they are unable to interact with elements in the environment. In order to expand the range of experiments that can be run in the lab to include manual interaction, we have integrated a dual haptic interface into the lab. Two extended-range Phantom haptic feedback devices from SensAble Technologies are mounted so that the thumb and index finger can be tracked and force-feedback applied.

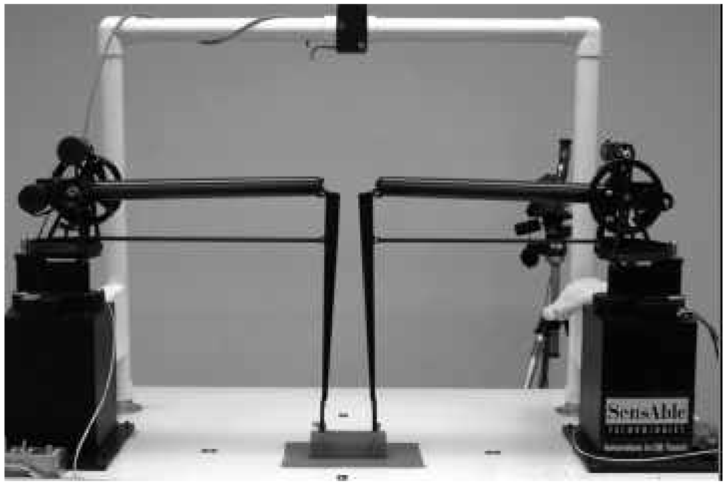

Figure 3 Dual haptic interface workspace

The workspace of the combined Phantoms, shown in Figure 3, is approximately 40cm x 60cm x 80cm. Optical shaft encoders at the devices' joints track the fingertips' position at 1000Hz. Powerful DC motors are capable of exerting over 20N of force to the fingers. If either or both fingers move into a volume occupied by a virtual object, the Phantom haptic interface exerts an opposing force proportional to the relative distance between the fingers and the virtual object. The result is a very compelling sense of immersion in a world in which objects can be seen, felt, and manipulated. Walls, floor, and ceiling can be defined as objects to restrict the range in which motion is allowed. The physics of the virtual world is under experimenter control, so gravity can be turned on or off, or inverted; a variable "force-field" can be applied to simulate a rotating environment's centrifugal force; and the mass, color, and size of individual objects can be varied during a movement. Because of the high spatial and temporal tracking capabilities of the Phantom haptic interface, the SGI's graphics rendering is 'slaved' to the Phantom's reported position.

4. INDICATORS OF COGNITIVE STATE: EYETRACKING AND EEG

4.1 EYETRACKING CAPABILITIES

Central to the lab's goal of studying complex behavior is the ability to monitor subjects' use of attention and other aspects of their cognitive state. Monitoring eye movements is a powerful tool in understanding behavior. The viewer's point of gaze within a virtual environment has been used to reduce computational or bandwidth demands;[1,2] our goal is different. In previous work with real tasks, we have shown that eye movements are a reliable metric of subjects' use of attention and as a gauge of cognitive state[3]. Recorded eye movements provide an externally observable marker of attentional state and of strategies employed in solving complex, multi-step problems. Particularly important is the fact that eye movements can sometimes reveal low-level strategies that are not available to the subject's conscious perception. Complex tasks are often 'serialized' into simpler sub-tasks that are then executed serially[4]. In some cases rapid task-swapping is observed between multiple subtasks[5]. While this is evident in the eye movement record, subject's self-reports in such tasks reveal that they are unaware of the strategy.

Tracking subjects' eye movements in virtual environments presents a special challenge. We have worked with Applied Science Laboratories (ASL), ISCAN Inc., and Virtual Research to develop two HMDs with integrated eyetracking capabilities. Both systems employ infrared video-based eyetrackers that determine the point-of-gaze by extracting the center of the subject's pupil and the first-surface reflections from video fields. Tracking both pupil and first-surface reflections allows the image-processing algorithms to distinguish between eye-in-head movements and motion of the eyetracker with respect to the head. An infrared-emitting diode (IRED) is used to illuminate the eye; in the ISCAN system the IRED is off-axis, yielding an image in which the pupil is the darkest region, the iris and sclera are intermediate in value, and the first-surface reflection is brightest.

The ASL system uses a beam-splitter to provide co-axial illumination. While the human eye absorbs most light that enters the pupil, the retina is highly reflective in the extreme red and infrared regions of the spectrum. This phenomenon, which leads to 'red-eye' in photographs taken with a flash near the camera lens, leads to a 'bright-pupil' eye image in the ASL tracker. In this image, the iris and sclera are the darkest regions; the pupil is intermediate, and the first-surface reflection of the IR source off the cornea is the brightest.

The eye image is processed in real-time by both systems to determine the pupil and corneal reflection centroids, which are in turn used to determine the line-of-sight of the eye with respect to the head. Figure 4 shows an eye image captured with the ASL bright-pupil system. The image on the left shows the raw IR illuminated image; the image on the right shows the image with the superimposed cursors indicating pupil and first-surface reflection centroids.

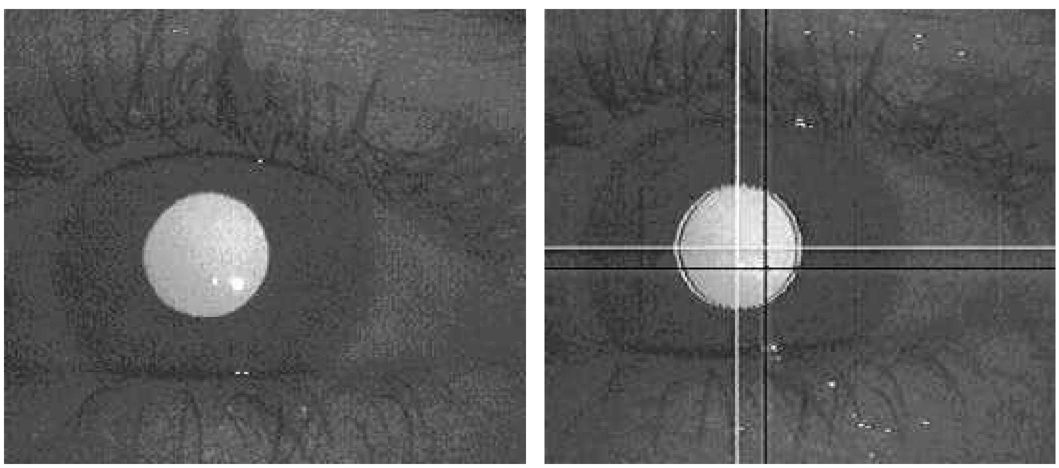

Figure 4 Image of the eye captured by the ASL eyetracking system

Figure 5 shows a Virtual Research VR4 HMD (see 2.2, above) that was modified to incorporate an ISCAN RK-426PC/520PC eyetracker. In order to capture an image of the eye, the HMD display was adapted to allow the video camera to view the eye through the HMD's viewing optics. The video signal from the integrated eyetracker is captured by the ISCAN PCI boards installed on a Pentium-based PC. The system calculates an eye position signal on each video field (i.e., 60 Hz). Single measurements can be read out at that rate or averaged over multiple fields to reduce signal noise. The system also digitizes the rendered image from the SGI and overlays a cursor indicating the subject's point-of-gaze on that field. In addition to the video record showing gaze on the virtual scene, the eye position signal from the ISCAN system is sent via serial port to the SGI. Accuracy of the eye position signal is approximately 1 degree in the central 20 degrees and 2 degrees in the periphery.

Figure 5 VR4 HMD with integrated ISCAN eyetracker

Figure 6 shows a Virtual Research V8 HMD (see 2.2, above) that was modified to incorporate an ASL Series 501 eyetracker. A miniaturized illuminator/video camera assembly is mounted below the left ocular, which has a dichroic beamsplitter mounted at its face. The signal from the eye camera is digitized by the eyetracker controller, which is powered by a DSP and two microcontrollers. The controller communicates with a host PC over a serial link for calibration and monitoring. The eye position signal is transmitted to the SGI through the controller or PC. Like the ISCAN system, the ASL superimposes a cursor indicating eye position on the rendered image from the SGI.

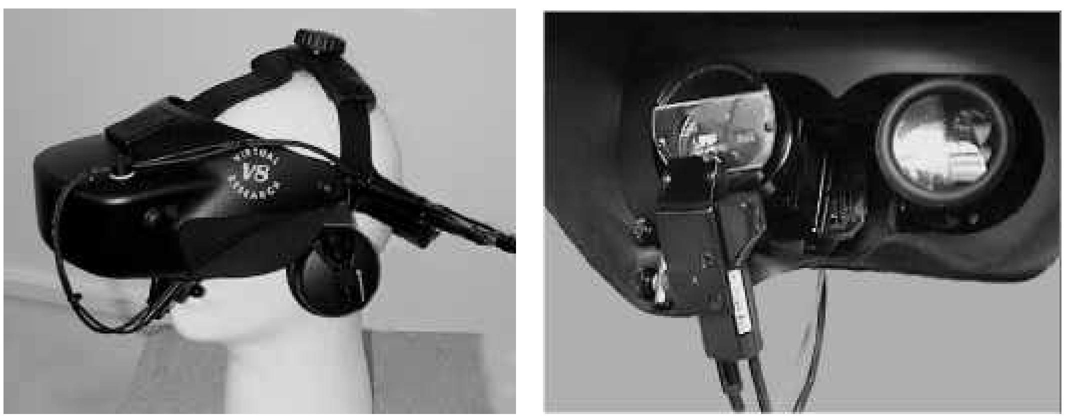

Figure 6 V8 HMD with ASL Model 501 eyetracker

Both ISCAN and ASL systems are capable of tracking eye movements at rates greater than 60 Hz with special eye cameras whose vertical scanning can be controlled externally. By limiting the vertical scan to half the normal image height, two scans can be made in the time usually used for a single scan. The controllers analyze both images in each field, providing a 120Hz sample rate. The increased temporal frequency comes at the cost of vertical field. The higher temporal sampling rate is important for "contingent display" – when the eyetracker signal is used to initiate changes in the virtual environment based on eye position or eye movements.

4.2 Electroencephalogram (EEG) Signals in Virtual Reality

While the main emphasis in our lab has been eye tracking, our interest in multiple indicators of cognitive state has led to the integration of EEG acquisition equipment into the lab. Virtual Reality (VR) expands the bounds of possible evoked potential experiments by providing complex, dynamic environments in order to study decision-making in cognition without sacrificing environmental control. We have integrated the use of a NeuroScan acquisition system with eye tracking inside of an HMD in order to obtain multiple indicators of cognitive state.

The most important consideration in this integration was whether or not the HMD would cause undue noise in the EEG signal acquisition. Since scalp EEG recordings are measured in microvolts, electrical signals may easily interfere during an experiment. The results from a test for such noise showed that there was no obvious noise increase caused by the helmet[6].

The setup for EEG acquisition starts with a 32-channel electrode cap from NeuroMedical Supplies, Inc. This cap fits snugly over the head and holds the electrodes in place while the subject is wearing the HMD. The cap feeds into a set of analog Grass amplifiers. These amplifiers have a minimum low cut-off frequency of 0.01 Hz and a maximum high cut-off frequency of 20 kHz.

The Grass amplifiers in turn feed into a NeuroScan acquisition system located on a mid-range Pentium PC. The NeuroScan acquisition program *Acquire* allows regular EEG signal acquisition and performs on-line averaging and frequency analysis. A separate NeuroScan dynamic linked library (DLL) allows EEG data to be read by a user-created program on-line.

Figure 7 Subject driving with EEG electrode cap

This has allowed the creation of an evoked-potential recognition and online feedback system. The program receives the amplified EEG signal input as well as integer stimulus ‘trigger codes’ from either the Silicon Graphics Onyx machine or another PC with the NeuroScan Stim package. The stimulus codes are normally used to trigger EEG recording (although not necessarily), and so are commonly known as trigger codes. After the EEG signal and trigger codes enter the *Acquire* program, they are grabbed from the acquisition buffer via the DLL provided by NeuroScan.

This DLL is called from within the *Recognition and Biofeedback* program. The *Recognition and Biofeedback* program chooses which data (in a continuous recording) need to be sent for further processing via the Matlab program. This program also gives audio feedback to the user after recognition occurs; may send return information to the SGI through a serial port interface; saves recognition data; calculates whether correct recognition has actually occurred (using available trigger codes); and may read previously processed data from a Matlab file for a demonstration of recognition speed. We use the Matlab program because it enables the rapid prototyping of algorithms for use in the system and because it allows the easy swapping of algorithms for recognition/feedback/analysis. All routines are Matlab M-files to enable easy use of different recognition routines. While compiled programs are faster than m-files, we have not had a problem with speed yet and find the general interface encourages the use of new computer algorithms for processing.

The ability of the system to give quick feedback enables it to be used in brain-computer interface (BCI) research, which is aimed at helping individuals with severe motor deficits to become more independent. For example, the lab has been used to show that the P300 EP, a positive waveform occurring about 300 ms after an infrequent task-relevant stimulus, occurs at red stoplights in the dynamic VR Performer Town. This information has been used for on-line recognition of red vs. yellow traffic lights, which enables the graphics car to stop for red but not yellow traffic lights[7].

Off-line analysis of the recorded EEG signals is also available. NeuroScan has programs which come with the acquisition system for analysis (Edit, Stats, Win) and other analysis is done with a library of Matlab algorithms created in the lab and at other research laboratories.

5. SUMMARY

Virtual environments provide a valuable tool in understanding complex human behaviors because they offer a unique combination of flexibility and control. State-of-the-art graphics generation and displays coupled with kinesthetic and haptic interfaces create a rich family of virtual environments for psychophysical experiments. The use of integrated eyetrackers and concurrent EEG recording gives us a window into subjects' use of attention and their cognitive state as they complete complex, multi-step tasks. The inherent flexibility of virtual environments allows us to study complex behaviors in realistic and novel worlds. Realistic environments, such as the driving world, permit experiments without concern for the subjects' or the public's safety, while the Phantom haptic workspace can create novel environments where the laws of physics can be manipulated at will to study the way subjects adapt to new environments. Together, the lab's suite of virtual environments, eyetracking and EEG capabilities for measuring behavior provide a unique tool that is allowing us to extend our understanding of human behaviors into the realm of complex task performance.

6. ACKNOWLEDGEMENTS

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