Published in final edited form as:

J Neurosci Methods. 2008 January 15; 167(1): 2–14. doi:10.1016/j.jneumeth.2007.09.025.

Virtual reality hardware and graphic display options for brain-machine interfaces

Amar R. Marathe¹, Holle L. Carey¹, and Dawn M. Taylor^{1,2}

¹Case Western Reserve University, Department of Biomedical Engineering, Cleveland, Ohio

²Louis Stokes Veterans Administration Medical Center, Cleveland Functional Electrical Stimulation (FES) Center of Excellence, Cleveland, Ohio

Abstract

Virtual reality hardware and graphic displays are reviewed here as a development environment for brain-machine interfaces (BMIs). Two desktop stereoscopic monitors and one 2D monitor were compared in a visual depth discrimination task and in a 3D target-matching task where able-bodied individuals used actual hand movements to match a virtual hand to different target hands. Three graphic representations of the hand were compared: a plain sphere, a sphere attached to the fingertip of a realistic hand and arm, and a stylized pacman-like hand. Several subjects had great difficulty using either stereo monitor for depth perception when perspective size cues were removed. A mismatch in stereo and size cues generated inappropriate depth illusions. This phenomenon has implications for choosing target and virtual hand sizes in BMI experiments. Target matching accuracy was about as good with the 2D monitor as with either 3D monitor. However, users achieved this accuracy by exploring the boundaries of the hand in the target with carefully controlled movements. This method of determining relative depth may not be possible in BMI experiments if movement control is more limited. Intuitive depth cues, such as including a virtual arm, can significantly improve depth perception accuracy with or without stereo viewing.

Introduction

Virtual Reality in Brain-Machine Interfacing and Motor Control Studies

The fields of brain-computer interfacing (BCI) and brain-machine interfacing (BMI) have grown rapidly due to advances in cortical sensing technologies, in real-time signal processing and decoding, and in the development of new devices that can utilize cortically-derived movement commands. The combined effect of these advances is an increase in the sophistication of the movement-related command signals extracted from the brain and an increase in the complexity of the devices that can be driven by these neural signals. The real

Corresponding Authors information: Dawn Marie Taylor, PhD, Department of Biomedical Engineering, Case Western Reserve University, Wickenden Building 101, 10900 Euclid Avenue, Cleveland, OH 44106, email: dxt42@case.edu, Phone: (216) 368-2476, Fax: (216) 778-4259 or (216) 368-4969.

All Authors' contact info

Amar Ravindra Marathe, Graduate Student, Department of Biomedical Engineering, Case Western Reserve University, 10900 Euclid Ave, Wickenden Building #119, Cleveland, OH 44106, Phone: (216) 368-2948, Fax: (216) 368-4969, amar.marathe@case.edu
Holle Lujah Carey, Graduate Student, Department of Biomedical Engineering, Case Western Reserve University, 10900 Euclid Ave, Wickenden Building #119, Cleveland, OH 44106, Phone: (216) 368-2948, Fax: (216) 368-4969, holle.carey@case.edu

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

benefit of this increase in sophistication is the potential to provide paralyzed individuals with more effective options for interacting with the world.

Many BCI systems focus on restoring communication and computer access. With point-and-click or menu-driven control of a computer interface, even the most severely paralyzed individuals can run typing software, send emails, surf the internet, and control their environment through customized software interfaces (Kennedy, et al., 2000; Hochberg, et al., 2006; Wolpaw, et al., 2002). For these standard computer-based functions, a two dimensional (2D) computer screen is adequate for training, evaluation, and daily use of the BCI system. However, for applications where the brain signals are used to drive a device that interacts in three-dimensions (3D) with the physical world, a development platform that uses a 3D virtual environment for initial training and evaluation may be more appropriate than a 2D computer interface.

Various BMI systems are currently being developed to restore reach and grasp function to motor-impaired individuals (Taylor, et al., 2002, 2003; Carmena, et al., 2003; Schwartz, et al., 2006). For people with high-level spinal cord injuries, implanted stimulation systems can directly activate peripheral nerves and generate the coordinated muscle contractions needed to achieve functional movements of the paralyzed limbs (Keith & Hoyen, 2002; Peckham, et al., 2002). For people with missing limbs, advanced prosthetics are being developed with the capabilities of generating independent movement in each of the many joints of the wrist and fingers (e.g. DARPA's 'Revolutionizing Prosthetics' Project). Sophisticated wheel-chair mounted assistive robots can also restore reach and grasp function to people suffering from neurological disorders such as amyotrophic lateral sclerosis (ALS) (e.g. Assistive Robot Manipulator (ARM) from Exact Dynamics and the Raptor from Advance Rehabilitation Technologies).

The common thread between all of these technologies to restore reach and grasp is that these devices must function in a 3D world and that multiple degrees of freedom must be controlled to generate efficient naturalistic movements. A 3D virtual development environment with the appropriate degrees of freedom is useful for testing and evaluating such systems. In this study, we set out to compare different 3D virtual development environments for BMIs designed to restore reach and grasp function. This evaluation includes a comparison of different monitors for 3D stereoscopic viewing as well as different software options for displaying the translational and rotational degrees of freedom that make up basic reach and grasp activities.

When using a virtual BMI instead of a physical BMI, a computer-generated representation of the final intended output device is displayed in a 3D virtual environment and is controlled in real time with the decoded brain signals. This computer 'representation' can be as simple as a neurally-controlled moving sphere that represents hand position in 3D space, or it can be as elaborate as a realistic image of a full arm and hand. Targets for reaching practice can also be as simple as spheres that appear at various locations in 3D virtual space, or they can be realistic computer-generated objects such as a fork or a cup placed on a table in a virtual kitchen.

Using a 3D virtual environment during BMI training and evaluation has a number of advantages over working directly with the actual physical output device of many BMI systems. In a virtual world, objects of any size, shape, and simulated weight can be instantaneously placed anywhere in the workspace to serve as targets for reaching practice and evaluation. Color-change cues can be used to provide feedback of movement accuracy for training purposes. Target objects can also be moved with precisely controlled velocities for continuous target tracking tasks. Executing a thorough set of movement tests in the

physical world using a wide range of precisely placed target objects would be much more time consuming, expensive, and inefficient.

The virtual image of the BMI output device can either be moved directly using the brain-based movement commands or the neural command signals can be used to drive a mathematical model of the final output device, and the model's output would then be used to update the virtual display of the device (Chadwick, et al., 2007; Hauschild, et al., 2007). The mathematical model would ensure the virtual version of the device has the realistic dynamics and unique control properties of the actual physical system. The first option (controlling the virtual image directly) allows one to assess the brain-based movement command signals alone without confounding the assessment with the added variability inherent in the output device. A majority of BCI experiments are currently conducted in this manner. The second option (controlling a model of the physical system with the virtual display driven by the model output) enables one to simulate a more realistic control environment to see how users adapt their command strategies to the unique dynamic properties of the specific BMI system. Alternatively, one can control the output device with brain signals directly, but still view the device through the virtual environment (Taylor, et al., 2003). This combines the best of both worlds by incorporating the actual dynamics and inaccuracies of the physical output device, while still enabling convenient computer-controlled display of virtual reach targets within a virtual environment. In this case, position sensors on the output device would control the position of the virtual device in real time (Taylor, et al. 2003).

With virtual reality, different work environments can be easily tested without ever leaving one's lab or home. Although it is possible to set up a variety of realistic physical workspaces, the use of virtual environments is necessary with some types of test subjects if transporting them to the desired physical environments is not possible (e.g. people with implanted subdural grid electrodes who are confined to a hospital room; non-human primates).

Virtual interfaces have also been the mainstay of many motor control studies where a subject's actual limb movements are tracked via a motion sensing system and then displayed to the user through a virtual interface. Here again, the convenience of instantly being able to place targets of any size or shape at any location throughout the workspace makes conducting experiments in a virtual environment much more efficient than trying to accomplish the same tests by setting up physical targets. In addition, the virtual world enables the experimenter to skew or perturb the visual feedback of the movement to test different hypotheses about how movements are controlled (Schwartz, et al., 2004).

Pros and Cons of Different Stereo Viewing Systems

A key element in any virtual reality system is the ability to provide the perception of depth by projecting a slightly different view of the computer generated environment to the left and right eye. A number of different options exist for both placement of the viewing screen and for providing different versions of the image to the left and right eye. The specific requirements of the experiment will dictate which option is best for any given virtual BMI system.

One configuration commonly used in non-human primate studies (but also applicable to human tests) is to place a stereo monitor over head and reflect the image to the eyes via a mirror placed at a 45° angle directly in front of the subject's face like the setup shown in figure 1 (specific 3D stereo monitor options are discussed below). The advantage of this setup is that placing the monitor above the head allows unencumbered arm and hand movements in front of the subject while still limiting what the subject sees to only those

virtual images that the experimenter wants the subject to see. This type of system has been used for both BMI studies where the virtual limb image is controlled directly by the decoded brains signals (Taylor, et al, 2002;Schwartz et al., 2006) and for basic motor control studies where the virtual limb image is moved based on actual limb movements captured in real time via position sensors (Moran & Schwartz, 1999;Schwartz, et al., 2004). One disadvantage of this configuration is that the monitor is placed close to the top of the head where it can contaminate the neural recordings with electromagnetic (EM) noise. This is particularly problematic with high-impedance intracortical electrodes which are more susceptible to EM interference. Shielded glass placed between the screen and the subject can reduce EM noise contamination somewhat while allowing the light from the stereo screen to pass through. The use of lower-noise LCD monitors instead of CRT monitors will also serve to improve neural recording quality in this configuration.

Head-mounted displays also allow human and animal subjects to freely move their arms while ensuring only the experimenter-controlled virtual limb image is seen. These systems have a separate miniature screen for each eye and provide more immersive viewing as all extraneous peripheral visual input is blocked out. By calibrating these systems with head orientation and position sensors, the virtual image can be made to rotate to give the impression of looking around and moving within the virtual environment (Bayliss, 2003; Hauschild, et al., 2007; Messier et al., 2007). Disadvantages include potential EM interference with neural recordings due to the very close proximity of the display electronics to the recording hardware. These systems also can get heavy and require secure mounting to the head. Therefore, they can be uncomfortable or impractical to use with EEG caps, acute subdural grid electrodes soon after surgery, or implanted electrodes whose percutaneous connectors interfere with the head straps.

The simplest viewing option is to use a stereo monitor placed in front of the subject on a desk or table top. This configuration puts distance between the monitor and the recording hardware thus eliminating the monitor as a source of EM contamination of the recorded neural signals. Desktop monitors provide the perception of 3D only within the limited viewing area of the monitor screen. Therefore, this configuration does not immerse the user in a 3D virtual world, and the users can still see their own limbs and surroundings.

Large wall-sized projection screen and virtual reality rooms are an option for conveying a person's place within a larger virtual environment. These virtual wall displays can be useful for safely evaluating brain-controlled wheel-chair navigation in a realistic world (Scherer et al., 2007).

There are two primary types of desktop monitors that provide 3D stereo viewing. (Note the desktop monitor options described below are the same monitors one would use in the overhead/mirror configuration described above). The first type projects differently-polarized light when displaying the image intended for the left versus the right eyes. The user must then wear a pair of lightweight glasses, similar to sunglasses, with polarized filters in the lenses. These filters only allow through the appropriate left or right eye images. For animal studies, the light-polarizing filters can be mounted in front of the animal's face and do not have to be worn as glasses. The light polarizing shutter screen in the monitor can be a significant source of EM noise when used in the overhead configuration. EM shielded glass can reduce this noise, but any smudges on the monitor, the shielded glass, or the filter glasses can diffuse the polarized light and reduce the selectivity of the filters. Filtering is usually less than 100% effective and faint 'ghost' images from the other eyes can often be seen.

Another common type of desktop stereo monitor displays the left and right eye images simultaneously but on alternating columns of pixels. These monitors have an array of thin built-in vertical bars embedded in front of the screen to block the light from either the even or odd columns of pixels when viewed from the left or right eye position. However, in order for the fine bars to completely block light from all odd columns of pixels when viewed from one eye and block light from all even columns of pixels when viewed from the other eye, the head must be placed at a very precise location relative to the monitor. Any head motion or deviation from this 'sweet spot' will cause the subject to lose stereo viewing. The brightness and resolution of the image is substantially reduced over a standard LCD screen because only half of the pixels are seen by each eye.

Perceptual Concerns with the Use of Stereo Monitors

When viewing objects in the physical world, our brains perceive depth based on a variety of cues including the relative size of the object in relation to its surrounding, the different convexity adjustments the lens of the eye needs to make in order to focus light onto the retina from objects at different distances (accommodation), and the angle at which the two eyes must be turned toward the midline in order to center light from one object onto the fovea of both eyes (vergence). People naturally differ in the degree to which they rely on each of these cues for depth perception, and this can cause some people to have more difficulty and require more effort than others in perceiving depth with stereoscopic viewing systems (Miyao et al., 1996).

Some users of virtual reality systems have reported experiencing motion-sickness-like symptoms often called 'cybersickness' (i.e. nausea, vomiting, headache, loss of balance, and altered eye-hand coordination). This is more common with the more immersive display technologies and is relatively uncommon with desktop displays (Holden, 2005). However, one problem that is common to almost all stereoscopic display systems is the unnatural disassociation between 'vergence' and 'accommodation'. The vergence or eye angle needed to foveate on objects changes when viewing stereoscopic images at different depths. However, the lens convexity in the eyes must still be adjusted to focus on an image at the actual fixed distance to the display. This discrepancy between the changing vergence angle and the fixed focal distance to the viewing screen can cause visual stress, fatigue, and perceptual problems (Wann, et al., 1995; Miyao, et al. 1996; Schowengerdt & Seibel, 2004). Binocular deficits in real world vision have also resulted from stereo viewing even after as little as ten minutes of use of a head-mounted display (Mon-Williams, et al., 1993). Studies of long-term effects of stereoscopic viewing are needed as relatively little is known (Rushton & Riddell, 1999). Potential issues with cybersickness and binocular vision problems should be taken into consideration when designing studies that use stereoscopic viewing systems.

More complex viewing systems are currently being developed that can project images with varying focal distances to better link accommodation and vergence (Schowengerdt & Seibel, 2004). These newer systems may improve depth perception and reduce fatigue as they become available and affordable in the future.

Options for Displaying Reach and Grasp Movements

The most appropriate display options for conveying brain-controlled reach and grasp movements will depend on the specific goals of the training or evaluation process. Brain-controlled movement parameters can be conveyed either by simplified abstract representations of the BMI output device (e.g. moving spheres or geometric shapes) or by realistic representations of the actual device in its natural environment (e.g. a realistic image of an arm and hand). Realistic representations are best for providing practice and assessment

in executing functional tasks because they represent what the user will actually see when using the real BMI. However, more stylized representations may be better for accuracy training and for assessing command signal precision in each movement degree of freedom because realistic representations often do not allow for consistent viewing of all movement degrees of freedom. For example, precision control of finger flexion angle cannot easily be assessed using a realistic representation of the hand because the user cannot always see the finger flexion angle when the hand is in certain configurations. Also, for assessing movement precision, the 'goal' or 'target' hand position and configuration must be adequately conveyed to the user in order for the user to move their virtual hand to that position and configuration. Precise movement goals are difficult to convey in a realistic virtual environment because hand position and configuration is only suggested in more general terms by the size, shape, and location of the virtual objects presented for the person to acquire.

Command signal precision is much easier to assess using stylized geometric shapes designed to show all translational and rotational degrees of freedom simultaneously. With simplified shapes, 'target' hand positions and configurations can easily be displayed using the same stylized image as the brain-controlled hand. The user simply tries to move the brain-controlled hand representation to align with the position/configuration of the target hand representation for precise assessment of the user's control accuracy.

Purpose of This Study

Our colleagues at the Cleveland Functional Electrical Stimulation (FES) Center have designed implanted stimulation systems capable of restoring reach and grasp function to individuals with spinal cord injuries at the C4 level and above. We are funded by NICHD to combine this movement restoration technology with emerging intracortical microelectrode recording technology (contract # N01-HD-5-3403; RF Kirsch PI). The end goal of this project is to implement direct brain control of arm and hand movements in spinal cord injured individuals. As part of this contract, we are to refine control algorithms for transforming the recorded brain signals into effective stimulation parameters that will generate the desired limb movements. This refinement process will utilize a virtual testing environment that incorporates a dynamic musculoskeletal model of a paralyzed arm and hand to simulate direct brain control of a paralyzed limb activated via our implanted stimulation technology. By using this virtual development environment, we can engage the small population of human study participants that currently have an intracortical implant system but do not yet have an upper limb stimulation system. This will allow us to refine the control system using the virtual development environment before combining the intracortical recording technology with the implanted limb stimulation system in the same individuals.

We are further funded by NINDS (contract # N01-NS-5-2365; RF Kirsch PI) to make this virtual development environment available to the BCI/BMI community to encourage researchers working with a wide range of neural recording technologies to focus their development efforts on the difficult problem of restoring reach and grasp to paralyzed individuals via brain control of implanted stimulation technology. Therefore, the virtual development environment should be of a form that is usable by people working in a variety of research settings including those working with nonhuman primates and those using surface or implanted EEG and ECoG electrodes. Therefore, we have focused our assessment on desktop monitors which do not require mounting electronics on the head, but could be used with a mirror in an overhead configuration, such as for animal work, if desired. Information on getting access to this virtual development environment can be found at <http://TaylorBMILab.case.edu>.

In the study presented in this article, we compared errors in depth perception conveyed via three types of monitors. One stereo monitor used light polarization technology. One stereo monitor utilized the fine bars that blocked light from every other column of pixels to each eye, and one monitor was a plain 2D monitor. The 2D monitor was included to quantify how much benefit 3D viewing really provides. Including a 2D option was important given that some people can have problems (eye strain, headaches, fatigue, etc.) with stereoscopic monitors.

These monitors were tested using three different virtual display options that we have developed for conveying arm and hand movement degrees of freedom. The first display option is simply a moving sphere that can only represent hand position in 3D space. This was included because 2D circles or 3D spheres have been the gold standard of many BMI and motor control studies with both human and nonhuman primates to date (Georgopoulos, et al. 1982; Schwartz, et al. 1988; Moran & Schwartz, 1999; Serruya et al., 2002; Taylor et al., 2002; Carmena et al. 2003; Hochberg, et al., 2006). The second display option is a realistic arm and hand intended for practicing functional tasks in a realistic environment. The third option is a stylized hand that can simultaneously convey all the degrees of freedom that our implanted upper-limb stimulation system is intended to restore (i.e. hand position in 3D space, finger flexion/extension, and two rotations about the wrist). By comparing the three types of monitors with each of these three virtual display options, we hoped this study would provide guidance in the selection of viewing hardware as well as provide information on the relative functionality of these three different display options.

Materials and Methods

Experimental Setup

Able-bodied subjects performed a visual depth discrimination task and two target matching tasks in a virtual environment. In the visual depth discrimination task, subjects were asked to determine the relative depth of two spheres. Errors in subjects' ability to accurately discriminate the relative positions of the spheres were compared between three different desktop monitors. In the target matching tasks, able bodied subjects used their own 3D hand movements to control the movement of a virtual hand representation. Errors in matching the position/configuration of the subject-controlled virtual hand to the position/configuration of the target hands were compared between the same three desktop monitors and between three virtual hand representations to identify significant differences in target matching accuracy.

Display options included a simple translucent shaded sphere, a realistic virtual human arm and hand with an identical translucent shaded sphere attached to the tip of the index finger, and a stylized 'pacman' hand of an equivalent size and translucent shading as the spheres in the other two display options. See figure 2.

Desktop monitors tested were the 21" NuVision mx5-21 stereo shutter screen monitor (McNaughton Corp), the 17" DTI Virtual Window LCD autostereo monitor (Dimension Technologies Inc.), and a standard 2D 17" LCD monitor (Dimension Technologies Inc.). Note the DTI autostereo monitor generates stereoscopic viewing using a fine array of vertical bars to block light from alternating columns of pixels from reaching the left and right eyes. This same monitor was also used as the standard 2D LCD with the monitor put in its 2D viewing mode (i.e. light blocking bars turned off and single image projected). Subjects were seated 30" from the 17" DTI monitor, which was the manufacturer's recommended distance for best stereo viewing. For a fair comparison, subjects were seated farther away (42") from the larger 21" NuVision monitor to ensure the size of the virtual images were equivalent in the subject's visual field for all monitors. All monitors were set to a screen resolution of 1024×768. Experiments were conducted in a dimly lit room to

minimize interference from screen reflections. The center of each monitor was placed at eye level for each subject. Displays were generated using Matlab's Virtual Reality Toolbox (Mathworks), and stereo mode viewing used the BS Contact VRML plugin (Bitmanagement). Arm movements were tracked via an Optotrak motion capture system (Northern Digital Inc.) and sampled at 20Hz by Matlab software running on a dual processor PC. This study was approved by the Institutional Review Board of MetroHealth Medical Center, Cleveland, Ohio.

Visual Depth Discrimination Task

The ability to visually discriminate relative depth differences between two target spheres was tested using a two-alternative forced choice paradigm. Five subjects were asked to determine whether peripheral target spheres appeared in front of or behind a central target sphere on each of the three monitors.

A trial began with a target sphere in the center of the virtual workspace. After a 750ms delay, the peripheral target appeared at one of the designated locations in the workspace. After a two-second delay, both the central and peripheral target disappeared, and the subjects were given two seconds to verbally identify the peripheral target as being in front of or behind the central target. After the two second response period, the next trial began.

Peripheral targets were situated at 12 locations evenly distributed throughout the workspace. Each location was displayed at three depth magnitudes (± 2.5 , ± 10 , and ± 17.5 cm) in front of and behind the central target, which was 70 cm from a virtual view point. The combination of 12 locations in the viewing plane of the screen and six depths (three in front, three in back) resulted in 72 distinct peripheral target positions per block of trials. To separate the perception of depth due to stereo cues from depth perception due to perspective size cues, blocks were presented either with perspective size cues or without perspective size cues. In blocks with perspective size cues, closer targets were drawn larger on the screen and more distal targets were drawn smaller on the screen to reflect the naturally occurring size difference due to perspective. When size cues were removed, the radius of the peripheral target spheres were adjusted so that all spheres had an identical size on the screen (i.e. spanned the same number of pixels), which forced the subjects to make a determination of depth based solely on the stereo cues.

Subjects completed three blocks of trials with perspective size cues on each of the monitors, and also completed three blocks of trials without size cues on the two 3D monitors. Since depth disparity should not be detectable on a 2D monitor without perspective size cues, subjects were only asked to complete one block without size cues on the 2D monitor. The 2D monitor trials verified that the subjects performed at chance level when all perspective cues were removed.

Translational Movement Task

Perception of virtual hand position in 3D space was tested using a 3D center-out movement task (translational task). The same five subjects were asked to move the virtual hand representation from a central target to one of eight peripheral targets located at the corners of an imaginary cube. Targets appeared in random order, and the subject would return the virtual hand back to the center target after attempting to hit each peripheral target. Subjects controlled the position of the hand representation in a virtual workspace by moving their own hand within an analogous 3D workspace. Radial distance from the center target to each peripheral target was 17.3 cm. Each center-out movement (trial) was considered a 'hit' when subjects positioned the virtual hand to within 6.8 cm of the center of the target hand. When the virtual hand was within this limit, the target color changed from light blue to red.

However, once within this hit range, subjects were asked to continue refining the position of the virtual hand representation to match the target hand position as closely as possible. Holding the virtual hand within the hit range for three seconds triggered the end of that movement trial. Trials in which the three-second hold time was not met within ten seconds of the target being displayed were considered 'misses'.

For each subject, all nine possible combinations of the three monitors and three displays were tested. The order of testing was randomized for each subject, and subjects were given ample breaks as needed to prevent fatigue. Movement trials were conducted in blocks, which consisted of one center-out movement to each of the eight targets. With the 3D stereo monitors, the first block was discarded because subjects often took up to a half a minute to fuse the left and right eye images into a single perceived 3D image at the start of each session. Therefore, this first block provided practice before collecting data for actual analysis. A total of eight complete usable blocks of movements were collected from each subject for each of the nine monitor and display combinations.

Rotational Movement Task

The ability to perceive key hand degrees of freedom (two wrist rotations plus finger flexion/extension) was tested with a rotational target matching task using the pacman hand and each of the three monitors. The task was analogous to the translational center-out task in that subjects would start by matching their virtual pacman hand to a 'center' pacman target hand that had each of its three movement degrees of freedom at the center of the rotation range. Then one of eight 'target' hand configurations would appear and the subjects would rotate the configuration of the pacman hand to match the target hand configuration as closely as possible. Target hands consisted of all eight possible combinations of the three rotational degrees of freedom at $\pm 45^\circ$ from the central starting angles.

Initial testing used the same pacman hand representation that was used during the translational movement tasks (shown in figure 2C). Rotational degrees of freedom consisted of finger flexion/extension represented by the degree of opening of the pacman 'mouth', and two wrist rotations. One wrist rotation representing pronation/supination was around an axis running from the small 'wrist' sphere located at the bottom of the disk to the top of the pacman head. The other wrist rotation was around an axis through the 'wrist' sphere and perpendicular to the pacman disk. Rotations into and out of the screen of the flat pacman disk were difficult to discriminate on all of the monitors tested. Therefore, the pacman hand was modified by adding a triangular pyramid extending out of the lower half of the pacman structure to provide more directional information when looking at the disk from side angles. The modified pacman hand can be seen in various configurations in figure 3. Although it is difficult to visualize the 3D shape and orientation of the pacman hand from the static line drawings shown here, study participants reported that orientation of the pacman hand was actually easy to perceive during the movement tasks because the line drawings rotated in unison as one solid object, which helped convey the shape and orientation. This figure shows the configuration of the central target (in the center of the figure) along with four of the eight rotated target configurations. The additional four rotated targets not included in the figure are similar to the outer targets in figure 3, except that the 'mouth' of the pacman hand is closed.

Trials were considered a 'hit' when the subject rotated the pacman hand to within 18° of the target hand angles in each rotational degrees of freedom. This triggered the target to change from light blue to red. Once within the hit range, subjects were instructed to continue refining the hand configuration to match the target configuration as closely as possible. Holding the pacman hand within the 'hit' range for 3.5 seconds triggered the end of a trial.

Trials in which the 3.5 second hold time was not achieved within 30 seconds of the target being displayed were considered misses.

Only three of the original five subjects were able to come back to participate in the rotational task. To make the best use of the subjects' time, data for the rotational task were collected in conjunction with a separate on-going experiment where subjects used linear translations of their actual hand to control the rotational degrees of freedom of the pacman hand. This transformation did not affect the ability to view the hand configuration on the three monitors, which was the focus of the assessment in this study. However, subjects did take extra time to learn to make the transformation between their linear hand movements and the rotational movements on the screen. Therefore, data used in this study were only collected after each subject had performed at least 30 blocks of practice movements to remove any confounding effects of learning this unnatural linear-to-rotational transformation. Linear movements in the horizontal plane were transformed into the two wrist rotations. A 17cm linear hand movement equaled a 45° angular movement in each wrist degree of freedom. Hand movements were not used to control the opening/closing of the pacman 'mouth' (finger flexion/extension degree of freedom) because this degree of freedom was quite easy for subjects to perceive accurately and should not have been significantly affected by the different stereo viewing options. Perceiving the two wrist rotations that brought the pacman disk into or out of the screen were the main concern in this analysis. Eliminating that third finger flexion/extension degree of freedom from the task made learning the transformation much easier for the subjects.

Each of the three subjects completed the rotational task using each of the three monitors, but each subject did them in a different order. Movement trials were conducted in blocks, which consisted of one movement from the center start configuration to each of the eight target configurations (rotational analog to a center-out movement task). Subjects were given ample breaks as needed to prevent fatigue. Even though subjects did not control the opening/closing of the pacman 'mouth' themselves, targets were presented that had the mouth in both the open and closed configuration. The pacman mouth in the virtual hand was automatically set to match the mouth configuration in the target hand in each trial. With the 3D stereo monitors, the first block of movements for each session was thrown out to allow subjects time to fuse the left and right eye images into a single stereo image. A total of nine complete usable blocks of movements were collected from each subject for each of the three monitors.

Data Analysis

During the visual depth discrimination task, subjects' verbal responses were recorded by the experimenter. Verbal responses were compared to the actual position of the peripheral target for each trial to determine the percent of the responses that were correct under each viewing condition.

For the target matching tasks, hand and target positions and configurations were recorded every 50ms throughout each set of movements. Offline analysis was performed to determine the average target matching error for each movement as the subjects tried to hold the hand representations stationary at the targets. For the translational task, target matching errors were computed as the straight line distance between the center of the subject-controlled hand representation and the target hand in 3D space. A single radial error value per trial was calculated by averaging the radial error at each sampled time point during the final 1.5 seconds of the trial when the subject was already at the target and trying to match the hand position to the target position as closely as possible (last 30 samples). These radial errors per trial were used in all further statistical analyses.

Each movement block consisted of one movement to each of the eight peripheral targets and eight movements from the peripheral targets back to the central target. Because the central target was presented eight times as often in each block as any single peripheral target, the mean radial errors for the eight iterations of the central target within each block were averaged together to yield a single average radial error measure for the central target. This resulted in nine target matching error values for each block. Blocks where any of the 16 movements resulted in a 'miss' were discarded, and subjects continued to perform the task until eight blocks of error-free data were obtained for each monitor and display combination.

Mean radial target matching errors were calculated for each monitor type and for each display option for each subject individually and for all subjects combined. Radial error data from all monitors were pooled to identify significant differences in the mean error attributable to display type, and data from all three display options were pooled to identify significant differences that could be attributed to the different monitors.

Statistical significance of the differences between monitors or display options were calculated by two different methods, which yielded similar results. In both cases, the natural log of the radial error data was first taken to transform the data to a normal distribution (Kolmogorov-Smirnov normality test). In the first case, a one-way analysis of variance (ANOVA) and a Tukey-Kramer multiple comparisons analysis was conducted using all data points to determine which monitors or which display options were statistically different. In the second method, mean radial errors were averaged by target across all eight blocks to provide one error value per monitor, per display option, per target, per subject. Significant differences between monitors or display options were then determined using paired T-tests conducted with analogous pairs of data. In each case, significance was determined at the 95% and at the 99.5% confidence levels.

Target matching errors in the two wrist rotation dimensions were also calculated using only the final 1.5 seconds (30 samples) of each trial. The magnitude of the rotational errors were computed for each wrist rotation degree of freedom separately and then summed. The sum of the two wrist rotation errors were then averaged across the last 30 samples of each trial and those error values were analyzed to determine any significant differences in target matching accuracy across the three monitor options. Statistical tests used were similar to those used for the translational data (i.e. ANOVA and paired T-tests) and also required a natural log transformation to convert the data to a normal distribution.

Results

Radial movement errors in the translational task are shown averaged by monitor type in figure 4A. Means are shown for each subject individually and for all subjects combined. Pairs of monitor or display options with significant differences are indicated by the lines and asterisks below each set of three bars. Longer lines indicate significant differences between pairs represented by the outer two bars. Shorter lines indicate significant difference in the pair of adjacent bars directly above the line. One asterisk denotes the difference was significant at $\alpha = 0.05$, and two asterisks denotes the difference was significant at $\alpha = 0.005$. Significance shown was determined by paired T-tests. Significance results calculated via the Tukey-Kramer multiple comparisons analysis were nearly identical to those shown with only minor differences (i.e. a few pairs changed from being significant at $\alpha = 0.05$ to $\alpha = 0.005$ and vice versa).

Figure 4B shows the percent of trials where the relative difference in target depth was incorrectly perceived in the visual depth discrimination task. The upper row of bars in figure 4B show the results from trials where normal size perspective cues were given in addition to

stereo cues. Therefore, targets located at different depths also changed size on the screen. The bottom row of bars in figure 4B show results from trials where the target size on the screen was held constant (perspective size cues removed) and only the stereo cues were provided. Subjects that tended to do well in either visual depth discrimination task also tended to do well in the physical target matching task. The correlation coefficient between subject performance in the physical target matching task and the visual perception task with size perspective cues present was 0.62 ($P < 0.006$). Without size perspective cues, the correlation coefficient between the physical target matching task and the purely visual depth perception task was 0.63 ($P < 0.03$). This correlation suggests the target matching errors in the physical movement task were significantly affected by the person's ability to accurately perceive target depth.

Although most subjects did quite well with size cues (figure 4B, upper row), three of the five performed very poorly with stereo cues alone while two subjects were able to use the stereo cues fairly effectively alone (figure 4B, bottom row). The two best-performing subjects reported that an unexpected size illusion was perceived when perspective size cues were removed and only stereo cues were present. Closer targets would be perceived as being smaller on the screen and distal targets would appear to be larger on the screen even though they were drawn as identical sized spheres spanning the same number of pixels. This shift in perceived size is an appropriate perception if the brain is expecting to see perspective size differences accompanying the stereo cues (e.g. the closer target appears as the same size as the distal target; therefore the closer target must really be smaller).

However, this illusion of a size difference due to stereo cues produced a perceived size change that could also generate a conflicting perspective cue. For example, the closer target is presented as the same size as the distal target; therefore stereo cues generate the illusion that the close target is smaller. However, a smaller target size is what one would observe if the target was farther away). Subject S2 reported seeing the peripheral target position flip randomly between being in front of or behind the central target while looking at a constant screen image. S2 also reported that the size difference illusion between targets would go away each time the perceived target position would flip to the incorrect depth. The implications of this phenomenon on the design of a 3D target matching task are discussed in the next section.

Figure 5 indicates each subject's depth discrimination accuracy as a function of the size of the depth difference between the pairs of presented targets. Even with size cues provided, all subjects had some difficulty at the smallest depth difference (2.5 cm). However, without size cues (stereo cues alone), even depth differences as large as 17.5 cm had an accuracy rate that was not much better than chance for some individuals while other individuals perceived the larger depths fairly well.

Radial movement errors in the translational task are shown averaged by display option in figure 6. Means are shown for each subject individually and for all subjects combined. Significant differences between display options are indicated by the lines and asterisks below each set of bars in the same manner as was done in figure 4A. Adding a realistic arm and hand to the moving sphere significantly reduced target matching errors when compared with the sphere alone or the pacman hand.

The mean radial error in the translational target matching task is made up of three components—a vertical, a horizontal, and a depth component. The depth component made up 55.59% of the total radial error when all translational error data was pooled. When broken down by display option, trends in the relative magnitudes of the error in the depth component reflected the relative differences in magnitude in the radial errors (i.e. percent of

radial error due to depth component: spheres = 57.24%, arm/hand = 51.75%, pacman = 57.27%). When comparing errors in the depth component by monitors, we also see trends similar to those in the mean radial error (i.e. percent of radial error due to depth component: 2D = 56.2%, 3D DTI = 56.79%, 3D NuVision = 53.61%).

Figure 7 shows the mean errors for the rotational task averaged by monitor type for each subject individually and for all subjects combined. Surprisingly, rotational errors were lowest with the 2D monitor for all subjects and this difference was significant in each subject compared to one or both of the 3D monitor options. In the pooled data, rotational errors were significantly lower with the 2D monitor than either of the 3D options.

Discussion

Overall movement accuracy in the target matching task was high but varied substantially among the different subjects (figure 4A). These differences could be due to differences in each subject's physical movement capabilities. However, the relative movement accuracy across subjects for each monitor was significantly correlated with these subjects' ability to discriminate depth differences (figure 4B) suggesting that the ability to perceive depth had an impact on the target matching accuracy.

In the translational task, all subjects performed best (lowest radial errors) with the 3D NuVision stereo shutter screen monitor except one subject which had a significantly larger error with the NuVision monitor (figure 4A). This type of intersubject variability is consistent with the expectation that different people will emphasize different aspects of the visual cues to perceive depth (e.g. size cues versus focal distance versus vergence angle) (Miyao, et al. 1996). The very large differences among subjects in the visual depth discrimination task when perspective size cues were removed confirms that even this small pool of subjects included people with a diverse range of natural tendencies to rely on different aspects of the visual cues for depth perception.

In the visual depth discrimination task, when the naturally occurring perspective size cues were removed, substantial perceptual illusions were generated (i.e. perceived relative target size changes; random flipping of target depths between being in front of or behind the central target). In some individuals these illusions caused substantial perceptual errors that made depth discrimination only slightly better than chance, even for large depth differences of 10-17.5 cm. All subjects' depth discrimination was significantly improved by the inclusion of perspective size cues, and most 3D BCI movement experiments are likely to include these beneficial perspective size cues. However, the size of the brain-controlled hand and the corresponding target may inadvertently generate illusions in some BCI experiments. If the target and brain-controlled hand representation have slightly different sizes, then the brain may confuse these native differences in size as differences generated due to perspective, thus skewing the perceived depth. This problem may be further compounded in experiments where the target size is changed regularly throughout the experiment. For example, in some studies the target size is gradually reduced as the subject improves in order to maintain a consistent level of difficulty (Taylor, et al., 2002). Grip force has also been represented by a changing cursor size in conjunction with a 2D target matching task (Carmena, et al., 2003). This representation of grip force could not be used effectively in conjunction with a 3D target matching task as the cursor size changes would interfere with perspective size cues.

Although the pooled data indicated a small but significant advantage when using the NuVision monitor over either the 2D or the 3D DTI monitor in the target matching task, there was no significant difference between monitors in the visual depth discrimination task.

The 3D DTI monitor may have performed more poorly in both the translational and rotational target matching tasks because the subjects' physical motion could have caused shifting of the head position which would bring the eyes out of alignment from the optimal stereo viewing location. For BCI experiments where the subject is immobile, maintaining alignment with monitors that require precise head placement is not a big concern, although initial alignment can be problematic in itself. But for studies that require physical movements of the limb, a stereo monitor that does not require precise head placement may be advantageous.

Almost all subjects also reported a strong dislike of the 3D DTI monitor due to difficulties maintaining stereovision and the requirement of keeping the head stationary at a fixed location relative to the screen. One subject referred to the 3D DTI monitor as 'the mind cage' and another had to take extended breaks between blocks to rest her eyes. Subjects generally took longer to initially fuse the stereo image and lost fusion more often when using the 3D DTI monitor. In spite of carefully measuring each subject's monitor-to-eye distance and placing the monitor at the manufactures recommended 'optimal' distance, some subjects reported that stereo viewing fell apart at the edges of the screen (i.e. both left and right images were seen by the same eye toward the edges of the screen). This may be due to the subjects having a different inter-eye distances than the average distance for which the monitor is calibrated. It may also be due to the inability of the subjects to maintain their head position at the precise optimal distance from the monitor during the extended length of the experiment. One subject learned to keep the relevant parts of the screen in stereo by moving her head slightly to the right when the targets were on the left side of the screen and moving her head to the left for target on the right side of the screen. This strategy, however, would not work when trying to view an entire virtual scene at once.

Different subjects reported using different strategies for matching the hand representation to the target in the translational target matching task, and these strategies may be more suited to one type of monitor over another. Strategies subjects adopted included slowly moving toward the target and stopping when the hand appeared to passed through the target as indicated by the change in color from hand to target color (for distal targets) or from target to hand color (for proximal targets). Another subject reported intentionally overshooting the depth dimension and then moving the hand back and forth over smaller and smaller distances to refine the point in space at which the hand surface crossed the target surface—again using color change cues to determine if the hand was in front or behind the target. Another strategy was to focus on aligning the edges of the spheres or pacman hands with the edges of the targets. The different strategies adopted by different subjects may have contributed to the large differences among subjects in the overall magnitude of the matching errors.

All subjects reported needing to use some trick or strategy to match the depth component of the hand to the target instead of just relying on an impression of depth generated by the stereo image. These strategies can be applied with either the 2D or 3D monitors, and this may explain why there did not appear to be a consistent benefit of using either 3D monitor over the 2D monitor in this study. The need for stereo viewing may be different for non-human primates than with the human subjects studied here. Although we have not done a carefully controlled study, at least one of our monkeys had substantial problems using visual perspective and occlusion cues to gauge depth on a 2D monitor during an arm movement task even though these same visual cues provided what seemed to be obvious depth cues to the human observers. Further studies are needed to clarify the value of stereo viewing in animal experiments.

Although movement errors in the translational target matching task were generally small (i.e. a few millimeters), the visual depth discrimination task showed all subjects had some problems perceiving depth differences at distances of 2.5 cm, even when both stereo and perspective size cues were provided (figure 5). These results may explain why all subjects still needed to conduct active movement tricks to fine tune the alignment of the hand to the target. The stereo and perspective cues were too subtle at those small depth differences to enable accurate matching of target depth.

Some of the tricks people relied on for fine tuning depth location may not be possible when moving the virtual hand representation using brain signals, especially if the brain-based movement commands are less accurate than the actual hand movements used here. A person's movement control may not be good enough, for example, to move the cursor back and forth through the target multiple times to fine tuning the depth with each pass, or to fine tune depth by carefully aligning the hand with the target along all edges. In able bodied individuals, proprioceptive feedback provides information on which direction the hand is moving. However, in many BCI studies as well as actual neuroprosthetic applications this proprioceptive feedback is either missing entirely or replaced artificially by some lower resolution sensory feedback signal. This inability of perceive fine gradations of depth may pose some inherent limits on the movement accuracy that can be expected in these 3D BCI studies as well as in real world applications.

Surprisingly, rotational task performance was significantly better with the 2D monitor than with either of the 3D monitors. One explanation may be that, in the rotational task, subjects relied on aligning the lines that made up the pyramid on the bottom half of the pacman hand and on aligning the edges of the pacman target and hand disks. However, in the translational task, most subjects used strategies that relied on the color change of the surface to indicate whether the target was in front of the hand or vice versa. Therefore monitors that display lines more clearly may have had an advantage in the rotational task. The 2D DTI monitor was substantially brighter than the other two monitors; making fine lines show up very clearly. The 3D NuVision had a lower contrast between the lines and the background and the 3D DTI monitor lost brightness because every other column of pixels was blocked.

Although the 3D DTI performed significantly worse than the 3D NuVision monitor in the translational task, there was no significant difference between 3D monitors in the rotational task. This may be due to the fact that both the pacman hand and targets were located in the center of the screen throughout the rotational tests, so any problem with stereo viewing at the outer edges with the 3D DTI monitor was no longer a factor.

When comparing the three display options, pooled data showed a significantly lower radial error when the realistic arm and hand was added to the simple sphere representation even though subjects still had to match the sphere at the tip of the finger to the target just like when using the sphere alone. The realistic looking arm changed elbow extension/flexion angle as the finger tip and sphere moved along the depth component of the workspace. This likely provided an easily understandable visual cue that mimicked what subjects were used to seeing in every day life when pointing at different distances.

Three of the five subjects show a significant reduction in radial error when using the plain sphere over the pacman hand, and two of the five subjects had just the opposite results. This disparity between subjects again may be due to differences in the visual cues people naturally use to perceive depth and in the specific strategies subjects adopted in this study to match the various types of targets.

In the translational target matching task, the mean radial error magnitude was only about 2% of the total center-to-target distance (i.e. ~3.5 mm out of 17.3 cm). In the rotational task, the

mean summed rotational error was about 8% of the rotation range ($\sim 3.75^\circ$ out of 45°). However, this rotational error is no larger than the translational error when the rotational error is expressed in terms of millimeters in Cartesian space. In the translational task, a radial error of 3.5 mm means that every point of the user-controlled sphere or pacman is 3.5 mm away from its intended target location. However, in the rotational task, the straight-line distance between the user-controlled pacman and the target pacman will vary for different points on the pacman. This straight-line error distance will continuously vary between zero at the center of rotation and some maximum value at the farthest point on the disk from the center of rotation. For a total rotation error of 3.75° , the maximum possible deviation of any point on the disk ranged from 2 mm to 4mm depending on which of the two rotation angles contributed more to the summed rotational error value. All other points on the disk had smaller linear deviations that diminish to zero at the wrist.

In spite of the diminished visual error cues near the wrist, the subjects did relatively well in the rotational task (max error was 2-4 mm for the rotational task versus 3.5 mm in the translational task). The good performance in the rotational task may be due to the four thin lines that were added to form the pyramid on the lower half of the pacman. Any error significantly greater than the thickness of these lines was likely to be very apparent, and these lines provided additional clear visual points at which to match the hand to the target. As in the translational target matching task, the alignment tricks used in the rotational matching task may not be as easily accomplished if the brain-based movement command is not very accurate. Input from individual users on what visual cues work best will help guide the further development of effective hand movement display options for training and evaluation of different BCI systems.

Conclusions

This study suggests that a good 2D desktop LCD monitor may be just as effective as a 3D desktop monitor for use in human virtual BMI studies. Perspective size cues play a large role in the perception of depth, and target and cursor sizes should be carefully chosen so that they do not disrupt the natural illusion of depth generated by size differences on the screen. The true resolution of depth differences that can be inherently perceived in a static 3D image is an order of magnitude lower than the actual movement accuracy that can be achieved through active movements and interactions with a target. This fine tuning of the alignment of the depth component in a target matching task was achieved by active movement tricks such as repeatedly moving in and out of a target to fine tune the depth. However, these movement tricks for target matching may not be possible when controlling movements with less-than-perfect brain signals, and inherent depth perception limitations may impact the accuracy of movements in virtual environments as well as real world environments.

The 3D DTI monitor was not tolerated very well by any of the subjects, and stereo monitors that rely on this same pixel-blocking technology should be used with caution, especially if subjects are not able to easily tell you when they are having trouble seeing the stereo image or when they are getting a headache from the display (i.e. non-human primates, people with locked-in syndrome).

With both 2D and 3D monitors, subjects relied heavily on non-stereo cues to provide information on 3D position and degree of rotation. Therefore, hand and target representations that provide easily discernable non-stereo position and configuration cues can improve movement accuracy (e.g. an arm and hand with realistic joint angles; thin lines at different angles that can convey fine details of alignment status from any viewing angle). These principles should guide virtual display development for assessment of realistic functional tasks and for high resolution accuracy future BMI systems.

Acknowledgments

This work was funded by the National Institutes of Health (NICHD # N01-HD-5-3403; NINDS # N01-NS-5-2365), the Department of Veterans' Affairs (# B4195R), the Department of Education (GAANN, Neural Engineering Training Grant), Medtronic Scholars Program, and Case Western Reserve University.

References

- Bayliss J. Use of the Evoked Potential P3 Component for Control in a Virtual Apartment. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. 2003; 11(2):113–116. [PubMed: 12899249]
- Carmena JM, Lebedev MA, Crist RE, O'Doherty JE, Santucci DM, Dimitrov DF, Patil PG, Henriquez CS, Nicolelis MAL. Learning to control a brain-machine interface for reaching and grasping by primates. *Public Library of Science*. 2003; 1(2):1–16.
- Chadwick, EK.; Blana, D.; Kirsch, RF.; van den Bogert, AJ. Dynamic Arm Simulator: A real-time model of the upper limb. *Conference Proceedings of the International Society of Biomechanics; Taiwan*. July 2007; CD
- Georgopoulos AP, Kalaska JF, Caminiti R, Massey JT. On the relations between the direction of two-dimensional arm movements and cell discharge in primate motor cortex. *Journal of Neuroscience*. 1982; 2(11):1527–1537. [PubMed: 7143039]
- Hauschild M, Davoodi R, Loeb GE. A virtual reality environment for designing and fitting neural prosthetic limbs. *IEEE Transactions on Neural Systems and Rehab Eng*. 2007; 15(1):9–15.
- Hochberg LR, Serruya MD, Friehs GM, Mukand JA, Saleh M, Caplan AH, Branner A, Chen D, Penn RD, Donoghue JP. Neuronal ensemble control of prosthetic devices by a human with tetraplegia. *Nature*. 2006; 442:164–171. [PubMed: 16838014]
- Holden MK. Virtual environments for motor rehabilitation: Review. *CyberPsychology & Behavior*. 2005; 8(3):187–211. [PubMed: 15971970]
- Keith MW, Hoyen H. Indications and future directions for upper limb neuroprostheses in tetraplegic patients: a review. *Hand Clin*. 2002; 18(3):519–28. viii. [PubMed: 12474601]
- Kennedy PR, Bakay RA, Moore MM, Adams K, Goldwithe J. Direct control of a computer from the human central nervous system. *IEEE Transactions on Rehabilitation Engineering*. 2000; 8(2):198–202. [PubMed: 10896186]
- Messier J, Adamovich S, Jack D, Hening W, Sage J, Poizner H. Visuomotor learning in immersive 3D virtual reality in Parkinson's disease and in aging. *Experimental Brain Research*. 2007; 79:457–474.
- Miyao M, Ishihara S-Y, Saito S, Kondo T-A, Sakakibara H, Toyoshima H. Visual accommodation and subject performance during a stereographic object task using liquid crystal shutters. *Ergonomics*. 1996; 39(11):1294–1309. [PubMed: 8888641]
- Mon-Williams M, Wann JP, Rushton SK. Binocular vision in a virtual world: Visual deficits following the wearing of a head-mounted display. *Ophthalmic and Physiological Optics*. 1993; 13:387–391. [PubMed: 8278192]
- Moran DW, Schwartz AB. Motor cortical representation of speed and direction during reaching. *Journal of Neurophysiology*. 1999; 82(5):2676–2692. [PubMed: 10561437]
- Peckham PH, Kilgore KL, Keith MW, Bryden AM, Bhadra N, Montague FW. An advanced neuroprosthesis for restoration of hand and upper arm control using an implantable controller. *American Journal of Hand Surgery*. 2002; 27(2):265–276.
- Rushton SK, Riddell PR. Developing visual systems and exposure to virtual reality and stereo displays: some concerns and speculations about the demands on accommodation and vergence. *Applied Ergonomics*. 1999; 30:69–78. [PubMed: 10098818]
- Serruya MD, Hatsopoulos NG, Paninski L, Fellows MR, Donoghue JP. Instant neural control of a movement signal. *Nature*. 2002; 416(6877):141–142. [PubMed: 11894084]
- Scherer R, Schoegl A, Lee F, Bischof H, Jansa J, Pfurtscheller G. The Self-Paced Graz Brain-Computer Interface: Methods and Applications. *Computational Intelligence and Neuroscience*. 2007 Online Article ID 79826, 9 pages.

- Schowengerdt BT, Seibel EJ. True three-dimensional displays that allow viewers to dynamically shift accommodation, bringing objects displayed at different viewing distances into and out of focus. *CyberPsychology & Behavior*. 2004; 7(6):610–620. [PubMed: 15687795]
- Schwartz AB, Kettner RE, Georgopoulos AP. Primate motor cortex and free arm movements to visual targets in three-dimensional space. I. Relations between single cell discharge and direction of movement. *Journal of Neuroscience*. 1988; 8(8):2913–2927. [PubMed: 3411361]
- Schwartz AB, Cui XT, Weber DJ, Moran DW. Brain-controlled interfaces: movement restoration with neural prosthetics. *Neuron*. 2006; 52(1):205–220. [PubMed: 17015237]
- Schwartz AB, Moran DW, Reina AG. Differential representation of perception and action in the frontal cortex. *Science*. 2004; 303(5656):380–383. [PubMed: 14726593]
- Taylor DM, Helms Tillery SI, Schwartz AB. Direct cortical control of 3D neuroprosthetic devices. *Science*. 2002; 296:1829–1832. [PubMed: 12052948]
- Taylor DM, Helms Tillery SI, Schwartz AB. Information conveyed through brain-control: cursor versus robot. *Neural Systems and Rehabilitation Engineering, IEEE Transactions*. 2003; 11(2): 195–199.
- Wann JP, Rushton SK, Mon-Williams M. Natural problems for stereoscopic depth perception in virtual environments. *Vision Research*. 1995; 35(19):2731–2736. [PubMed: 7483313]
- Wolpaw JR, Birbaumer N, McFarland DJ, Pfurtscheller G, Vaughan TM. Brain-computer interfaces for communication and control. *Clinical Neurophysiology*. 2002; 113:767–791. [PubMed: 12048038]

Figure 1.

Overhead monitor and mirror configuration. A mirror placed at a 45° angle in front of the animal's face reflects the image from an overhead stereo monitor. The animal does not see its own arm or hand and only sees the virtual images from the monitor. In this example, a position sensor on the animal's wrist controls the movements of a virtual sphere, which the animal tries to move to virtual targets by moving its own arm in 3D space. By permission DM Taylor.

Figure 2.

Three ‘hand’ display options compared in this study. The white spheres (A&B) or white pacman (C) are controlled by the user. The full arm and hand move with the white sphere in B and show realistic changes in limb joint angles as the finger tip moves with the sphere. The blue spheres and blue pacman are the ‘target hands’ to which the subject tries to align the user-controlled hands. Configurations shown have the user-controlled hand at the central start position for the center-out movement task. Blue target shown is located at the distal upper left corner for the center-out task. User-controlled spheres & pacman have identical diameters as the target spheres & pacman. Depth can be deduced even on 2D displays by the relative size difference between the user-controlled spheres/pacman and the target spheres/pacman. Target shown is distal to the user-controlled sphere & pacman. Therefore the target appears smaller in the visual field due to perspective effects.

Figure 3.

'Pacman' hand configurations used in the rotational target-matching task. The center pacman shows the central starting configuration for the rotational analog to the center-out task. The surrounding examples represent four of the eight target rotational configurations. The four additional configurations not shown were identical to those shown except that the 'mouth' of the pacman hand was closed rather than opened. These target configurations are the four possible combinations of two wrist rotations at $\pm 45^\circ$ from the starting position. The sphere at the bottom of each pacman represents the stationary wrist about which the pacman hand was rotated. Note, target hand configurations are only shown in separate corners of the figure for easier viewing. Pacman hands were not actually translated to the corners of the workspace during the rotational task but only rotated around a central stationary wrist.

Figure 4.

Error rates for the translational target matching task and for the visual depth discrimination task. A) Mean radial error by monitor type when using arm movements to match the cursor to the target. Means for each subject are shown individually (S1-S5) and for all subjects combined (Total). Error bars represent standard deviation of the mean across display options and targets (individual trials averaged across blocks for each subject). Lines under each set of three bars indicate pairs with significant differences in the means. ‘*’ denotes significance at $\alpha = 0.05$ and ‘**’ denotes significance at $\alpha = 0.005$. B) Percent of targets incorrectly perceived as in front of or behind the central target in the visual depth discrimination task. The upper row of bars is when the normal perspective size cues were included in addition to stereo cues. The bottom row of bars is when the perspective size cues were removed (i.e. all targets were of identical size on the screen) and only the stereo cues remained. In this binary choice task (i.e. in front or behind) chance performance is at 50% (dotted line). Gray area shows lower 95% confidence range for chance performance.

Figure 5. Percent correct in the visual depth discrimination task as a function of depth difference between targets.

Figure 6.

Mean radial error by display option. Means for each subject are shown individually (S1-S5) and for all subjects combined (Total). Error bars represent standard deviation of the mean across monitor options and targets (individual trials averaged across blocks for each subject). Lines under each set of three bars indicate pairs with significant differences in the means. '*' denotes significance at $\alpha = 0.05$ and '**' denotes significance at $\alpha = 0.005$.

Figure 7.

Mean rotational error by monitor type. Means for each subject are shown individually (S1-S3) and for all subjects combined (Total). Error bars represent standard deviation of the mean across targets (individual trials averaged across blocks for each subject). Lines under each set of three bars indicate pairs with significant differences in the means. '*' denotes significance at $\alpha = 0.05$ and '**' denotes significance at $\alpha = 0.005$.