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

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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.

Keywords: Brain–machine interface (BMI); Brain–computer interface (BCI); Neuroprosthesis; Motor control; Virtual reality; Stereoscopic viewing

1. Introduction

1.1. 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 movement-related command signals extracted from the brain and an increase in the complexity of devices that can be driven by these neural signals. The real 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. 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

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generate the coordinated muscle contractions needed to achieve functional movements of the paralyzed limbs (Keith and 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 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. 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 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).

1.2. 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 Fig. 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 experi-