

3D Stereo Viewing Evaluation for the Virtual Haptic Back Project

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ABSTRACT

The purpose of the Virtual Haptic Back (VHB) project is to develop a realistic haptic/graphical model of the human back that can be used for palpation (diagnosis through touch) in medical training. The goal of this research is to design, implement, and evaluate methods to improve viewing realism for the VHB project by applying 3D stereo effects and bringing the virtual model to the user's fingertips like in the real world. Two graphical viewing methods were designed and applied to the VHB project for evaluation along with the standard 23-inch flat-screen LCD monitor: a Head Mounted Display (HMD) with head tracking and a Mirror Viewing System (MVS) which combines graphic and haptic images so that the 3D stereo VHB model appears at the user's fingertips. Evaluations with osteopathic medical students showed that both of these methods (especially the MVS) improve the VHB realism compared to the flat-screen monitor.

Keywords: head-mounted display, mirror viewing system, integration of haptic image and graphical image, PHANToM®, Virtual Haptic Back

1 INTRODUCTION

Haptics is being combined with graphics in virtual reality environments to increase realism. This literature review focuses on visual representations (some combined with haptics). The HiBall Tracking System is a 6-dof wide-area ceiling tracker for use with HMDs (www.3rdtech.com/HiBall.htm). The system uses relatively inexpensive ceiling panels housing LEDs, a miniature camera cluster, and the single-constraint-at-a-time algorithm which converts individual LED sightings into position and orientation data. In the Stanford Visible Female project [4], a 3D stereoscopic visualization of the female pelvis was developed from numerous slices of 2D pelvis data. Haptic feedback was enabled via the PHANToM® haptic interface, allowing the user to interact with and feel the virtual model. The Personal Space Station is a desktop virtual reality viewing system using the mirror reflecting principle with stereoscopic images

(homepages.cwi.nl/~robertl/pss/pss.html). It is used on the Visual Molecular Dynamics simulator to analyze the molecular structure of proteins, nucleic acids and lipids. A mirror reflection viewing system has been made for improved realism in virtual knee diagnosis and simulated surgery via the PHANToM® haptic interface (www.uchsc.edu/sm/chs). A VR simulator for petrous bone surgery with haptic feedback was developed using a glass-reflection device for viewing (uke.uni-hamburg.de/institute/medizinische-informatik). The Virtual Soldier Research Program (digital-humans.org) built a three-wall stereo vision room as a virtual environment to view various anthropometric human models.

Stredney et al. [16] present an overview of integrating visual displays with haptics. Basdogan et al. [2] developed a computer-based training system to simulate laparoscopic procedures in virtual environments for medical training. Authors working in the area of 3D displays include the following: [8] discussed the comfort of 3D viewing; [10] introduced several stereo-display methods; [11] analyzed some display devices for 3D TV systems; and [17] introduced some new no-eyewear stereo viewing technologies. Jones et al. [7] studied the effects of visual-only, haptic-only (blind subjects), and visual-plus-haptic groups for unknown object identification, finding that the visual group was fastest, but the visual-plus-haptic group was the most accurate. Adams et al. [1] have shown a significant improvement in subject performance in a real-world Lego assembly task with VR training including haptic feedback. Inami et al. [6] presented an optical camouflage method to improve the realism in their reflecting system. Reference [9] introduces a software kit for complex modeling in reflecting systems and [12] summarizes the haptic concept and some applications with a stereoscopic mirror reflecting system. Salisbury and Srinivasan [13] explain a PHANToM-based example. IBM [15] did research on stereoscopic vision and HMDs for PCs.

The research reported in this paper grew out of a need for increased visual realism in the Virtual Haptic Back Project [5] at Ohio University. Specifically, the flat-screen monitor in use with two PHANToM® interfaces had the haptic image greatly separated from the graphical image, leading to cognitive dissonance in trainees. In this paper two (separate) additional viewing methods were implemented and evaluated relative to the flat-screen monitor: a Head Mounted Display (HMD, for increased user immersion and natural viewing) and a Mirror Viewing System (MVS, for making the graphical image coincide with the

haptic image at the user's fingertips). While the HMD and MVS have been implemented by others, we have not found evaluations of these devices with stereo vision by trainee subjects, relative to a flat-screen monitor.

This paper is organized as follows: first we present an overview of the VHB Project and the current research objectives, followed by descriptions of the HMD and MVS implementations (including technical problems that arose and their solution), evaluation of all three viewing methods in the context of the VHB project, and then we conclude with limitations of each.

1.1 The Virtual Haptic Back (VHB) Model

The Virtual Haptic Back (VHB) project is an interdisciplinary collaboration at Ohio University wherein haptics is combined with graphics for VR-based training of osteopathic physicians (and related fields) in palpatory diagnosis. The VHB model is a 3D digital model of the human back, applied to palpatory diagnosis training in medical applications [5,18]. The back surface geometry for an adult male of average size was scanned using a 3D digitizer from a live subject. The vertebra, ribs, and scapula models for an were scanned using a 3D digitizer from plastic anatomical models for the model's skeletal structure. By using OpenGL, these data are built as 3D bone models and assembled together into a back structure, along with the surface geometry. The bone movements are restricted and simulated following actual human anatomical limits. This structure is also covered with simulated haptic skin which has spring stiffness characteristics modeling the human back. An operator can feel this virtual back through two PHANToM® 3.0 haptic interfaces, connected to the host computer as shown in Figure 1. Various back problems can be programmed for students to find.

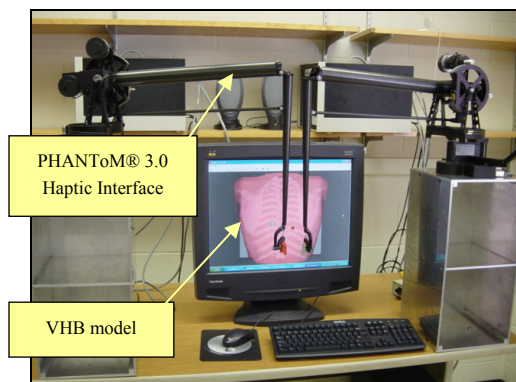


Figure 1. VHB Model with PHANToMs®

1.2 Research Objectives

A 23-inch flat-screen LCD monitor is currently used to display the virtual back image, which is adjusted to real-world size (See Figure 1). But the image of the VHB is fixed and two-dimensional on the screen as the operator uses the PHANToMs® to touch the

VHB model. Also the haptic back model is separated by about 25 cm from the graphic back model. The user has to imagine the shape and size of the back at his fingertips by the force feedback through the PHANToM®, which can lead to cognitive dissonance since the graphics model is not at the same location. The main research goal is to improve viewing realism for the VHB.

When a user puts a finger into the PHANToM® thimble, the PHANToM® gives force feedback to the user's fingertip to make sense of the shape, stiffness and spring of a 3D back model, depending on where the user is navigating. Currently, two PHANToM® 3.0s are used in the VHB project to allow two-fingered (or thumb)ed palpation as shown in Figure 1.

2 HMD VIEWING SYSTEM

The HMD is a popular method for providing immersion in virtual reality. In this research, an HMD (I-glasses 3D pro®) and a Flock of Birds® (FoB) head motion tracker are used together. The images on the HMD change corresponding to the movement of the user's head as determined by the FoB sensor. This HMD gives the viewer a floating screen in front his eyes, just like looking through a small window.

2.1 Coordinate Transformations

This paper uses a right-handed coordinate system. In order to get the position and orientation relationships of the user's eyes and the VHB model (the object), a coordinate space is established that includes world, object, transmitter (the fixed FoB part), sensor (the moving FoB part) and eye coordinate systems, as shown in Figure 2. We assume that the transmitter and the VHB model are fixed in the world coordinate system. The relative coordinates of the eyes and the sensor coordinate system are constant since the FoB sensor is fixed on the HMD. By using conventional coordinate transformation methods we can calculate the relative coordinate change of the eyes in the object coordinates system, which in turn is used to update the scene.

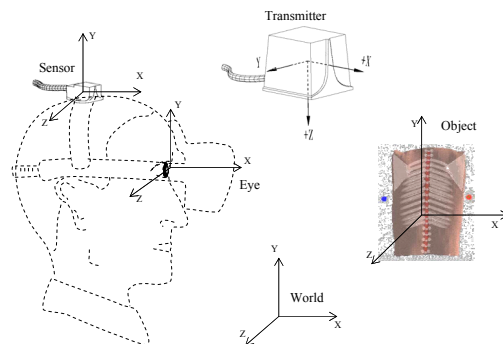


Figure 2. FoB Coordinate Transformations

2.2 Stereo Vision with the HMD

When the user touches the VHB model while wearing the HMD, two small balls (the left one is blue and the right one is red.) are seen on the HMD screens to simulate the operator's two fingertips. The position of each ball represents the position of the user's fingertip in the virtual space. The user cannot see his fingers since the HMD blocks them, but he can see the back of his hand. When the user moves his head, the FoB sends the head position and orientation data to the computer. The VHB image is changed on the screen of HMD in response to user motions. This effect gives the user a feeling that the VHB model is standing still at a fixed pose in space and only the observer is moving, as in the real world. The image of the model is in 3D stereo vision. The user can also turn and move his head to observe the details of the 3D back. When the user moves his fingers onto the virtual back, he can feel the force feedback through the PHANTOMs® while seeing the fingertip-representing ball on the VHB skin. If he pushes a little bit, he can feel the force feedback as the spring of the tissue and muscle. He can move his fingers around on the VHB, feeling the different bumps of the vertebrae and ribs. Figure 3 shows that a user viewing the VHB with the HMD (the screen also shows what the user sees in the HMD).

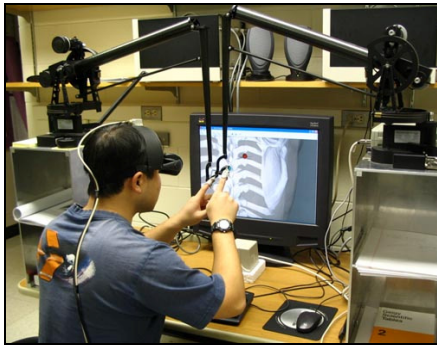


Figure 3. VHB Interaction through HMD and FoB

2.3 Matching Model and Viewer Coordinates

The viewing effect of the current HMD is that of seeing a 1.93m screen from 3.96m. Let us name the viewing angle of the HMD as α_{HMD} .

$$\alpha_{HMD} = 2 \times \arctan \left(\frac{1.93}{3.96} \right) = 27.4^\circ \quad (1)$$

The VHB model is displayed in the size of a real human. In programming, we set the OpenGL camera viewing angles to be the same as the HMD's viewing angle as shown in Figure 4. Since the action of the muscles controlling eye convergence and the muscles controlling eye focusing depart from their habitual relationship, some people may experience an unpleasant sensation when looking at stereoscopic images, especially images with large parallax values. Thus, attention needs to be paid to parallax. Low parallax values will help to reduce viewer discomfort. The purpose when creating stereoscopic images is to provide the deepest effect with the lowest values of parallax. As a rule, the angle of the two viewing axes is not more than 1.5° [14] as shown in Figure 4. This is accomplished in part by reducing the inter-axial separation (s in Figure 4).

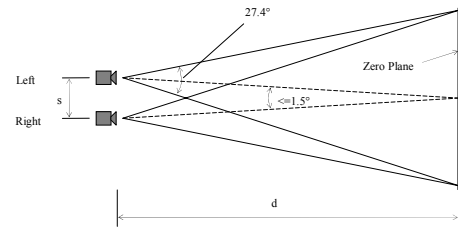


Figure 4. Cameras Settings for HMD

The distance from the eye to the screen of the HMD is about 70 mm. We consider the HMD screens as the zero parallax plane. The two cameras should be set somewhere in front of the zero plane to avoid additional adjustments, i.e. $d = 70$ mm. With the above discussion, the separation s of the cameras should correspond to an angle of less than 1.5° . On the other hand, a bigger s can lead to strong parallax. We hope to see a strong stereo vision effect with little discomfort. Therefore, we derive s by setting the angle equal to 1.5° :

$$s = 2 \times d \times \tan \left(\frac{1.5^\circ}{2} \right) \approx 2mm \quad (2)$$

The values $d = 70$ mm and $s = 2$ mm are applied in stereo vision programming.

2.4 Reducing VHB Model Complexity

The previous VHB model surface had a total of 40,000 triangles. The graphical rendering was too much work for the CPU that had to process the FoB data at the same time. These demanding operations often caused unexpected computer crashes. Our solution was to simplify the VHB model by reducing the number of surfaces on each bone. By trial and error with different reduction rates such as 1/3, 1/4 and 1/10, the best amount of

surface triangles was found to be about 1/4.5 of the original. Hence, the total number of triangles in the reduced surface model is about 9,000. The resulting image quality is still good and the stereo vision effect is able to work normally with the FoB without freezing the computer.

Figure 5 shows a series of HMD screen captures when the user is moving closer to the VHB. The skin of the model can also be set to different transparencies for viewing the bone structure to improve its 3D effect.

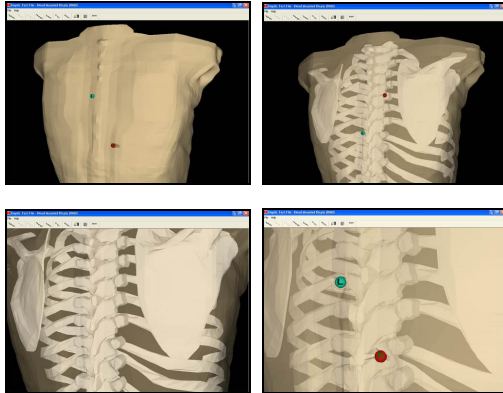


Figure 5. HMD Method Screen Shots

3 MIRROR VIEWING SYSTEM (MVS)

A semitransparent mirror and a display are combined. The basic theory behind this method is optical reflection. A smooth glass is used to reflect the VHB image that is on the screen. In addition, because of the transparency of the glass, when the user's hand is behind the glass, it can be seen at the same time. The two images (the real hands and the virtual back) are combined naturally in the brain, including their shapes and distances. The glass superimposes the reflected VHB image over the hand, which is behind the glass. The user has a strong illusion that he touches what he is seeing, as shown in Figure 6. This significantly reduces the cognitive dissonance caused by our original system where the haptic image was in front of the graphical image by a significant distance.

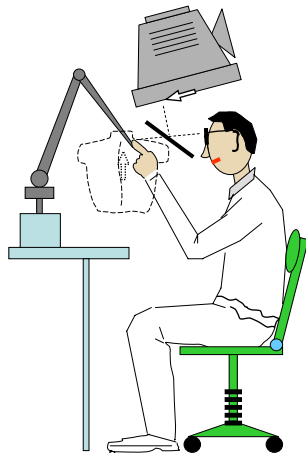


Figure 6. Mirror Stereo Viewing System

When an image is reflected on the mirror, the mirror reverses it. That is, the image flips up and down, but not right to left. We have found two ways to solve this problem. One was using two mirrors to reflect the VHB image twice to get the proper image back. But in this case, the distance between the eye and the reflected image was too long (about 52 cm) for a normal user because of the two reflections. The reflected image was nearly out of reach of the user's arms. The second solution is programming in OpenGL to flip the image (Figure 7) instead of using a second mirror. The VHB image on the screen is already reversed. This solution decreases the distance to about 36 cm between the virtual image and the viewer. In this case the user can feel comfortable without stretching out his hand too far.



Figure 7. Reversing of the VHB Image

3.1 Stereo Vision with the Mirror Viewing System

In the MVS, one big monitor is used to display a life-size VHB image for both eyes. Two cameras in programming generate the left and the right images separately that simulate the human eyes. These two images are displayed to the monitor screen through a special graphics card (which supports OpenGL stereo function) alternately and rapidly. The user wears a pair of 3D shutter glasses to view the left image for the left eye and the right image for the right eye. Usually, the glasses have high-frequency (>120 Hz) electronic shutters (made with liquid crystal material) that open and close in sync with the images switching on the screen automatically. This principle provides the user a 3D stereo VHB image. If the shuttering frequency is not fast enough (<100 Hz), the user can still see a stereoscopic image, but he may also see some unwanted flickering. With this method the user can view the 3D stereo VHB image and touch it with his fingers.

3.2 Use of CRT vs. LCD

The shutter glasses work (opening and closing) at high frequency. To avoid viewing both images simultaneously through both shutters of the 3D glasses, the flickering screen images should appear and disappear as fast as the shutter. LCD monitors have a persistence due to hardware limitations, which causes each of the user's eyes to view two images on the LCD through the shutter glasses so that he cannot see the stereo image properly. But, the persistence of CRT monitors disappears quickly enough to match the shutter glasses, even when operated at more than 120Hz. In this mirror viewing system, the refresh rate of the 19-inch flat-screen CRT is set at 120Hz and 1024×768 pixel resolution. The persistence is hardly noticed.

3.3 The VHB Model and the Display Plane

The PHANToM® haptic image has been adjusted to match the back graphical image. That means the PHANToM® can touch the proper point of the VHB that the user sees. As seen in the left drawing in Figure 8, for example, if there is a bump at point A on the VHB, the PHANToM® can display the bump haptically at the position described by the solid-line eyes.

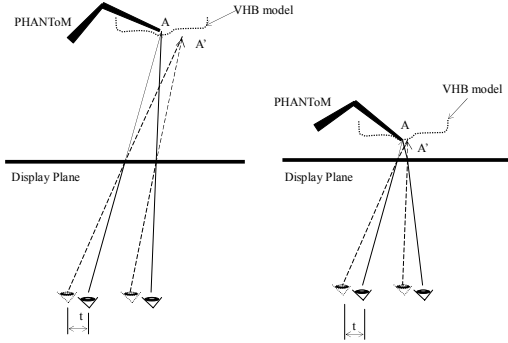


Figure 8. Graphics Excursion

If the user's head moves a small distance t to the left, the proper graphical point A moves opposite (to the right) to point A' (see the left drawing in Figure 8). That means the bump which the user sees is changed to A' . Because the VHB model still stands at its original location while the observer moves, the PHANToM® still feels the bump at point A . Therefore, the haptic image does not match the graphical image at this time. The point which the PHANToM® touches should not have a bump in the dashed eyes' viewing. In the right drawing in Figure 8, we see that A and the A' are very close if the VHB model is very near the display plane. Even though the observer's head moves the same distance t , the haptic and graphical images do not move as far apart as in the left case. The case on the right can reduce the graphics excursion caused by small motions of the user.

3.4 Overlapping Image Problem

When we used regular glass in this system, an overlapping image phenomenon on the glass was found. It is due to the two-surface reflection of the glass as shown in Figure 9 [3].

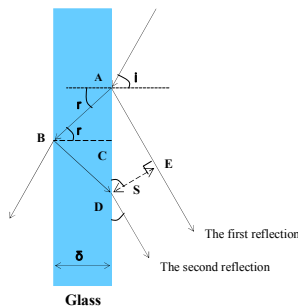


Figure 9. Separation of Double Images

The incident light ray, from air to glass, is also refracted and reflected at the left interface of glass to air. This reflection passes through the glass and refracts into the air on the right again. This is the second reflection. Actually, this ray is reflected and refracted many times on the two surfaces of the glass. But the brightness of the latter reflected lights are reduced sharply. So those reflections which take place after the second reflection can be ignored. But the second reflection is the same brightness as the first reflection, so the viewer sees obvious, separated double images. The relationship of the separation S and the other conditions is shown below:

$$S = \frac{\delta \times \sin(2i)}{\sqrt{n^2 - \sin^2 i}} \quad (3)$$

i is the incident light angle, r is the reflected light angle (drops out in (3)), S is the separation of overlapping images, δ is the of glass thickness, and n is the air refractive index.

The separation S of the overlapping images increases in direct ratio to the thickness δ of the glass. But we cannot use very thin glass because it is broken easily. We choose the glass thickness as 2 mm. Our solution to reduce the unwanted double image that arises from the second reflection of Figure 9 was to use a semitransparent mirror with the coated side upward (facing the user).

3.5 VHB Image on Hands Problem

In the MVS, the VHB graphical image displays on the user's real hands. In the real world, the user's hands obviously should occlude the back under diagnosis, from the user's point of view. With our MVS, this unwanted effect can never go away, but increasing the brightness of the hands by adding auxiliary lighting and adjusting the contrast of the VHB image on the screen helps reduce this unwanted effect dramatically. Also, we found the moving hands capture a person's attention better than the VHB model displayed in the standard manner (with L and R points to indicate the left and right fingertips, but no hand model). Figure 10 shows the mirror stereo viewing system in operation.



Figure 10. Mirror Stereo Viewing System

4 EVALUATION

The two new viewing methods (HMD and MVS) and the previous standard viewing method (23 inch flat-screen monitor) have been evaluated and compared from the subjects' responses.

4.1 Evaluation Method

All three viewing methods were evaluated in the same half-hour session by each individual subject. The three systems were set up one after the other. Every subject tried each of these three viewing systems. The 3D VHB models of each method were set up at about the same position in front of the subject (the subjects were seated and the virtual back was in front of them, corresponding to a standing or seated position of the virtual patient). Three subjective evaluation metrics were used: Realism, Comfort and Easy of Use. Each category was ranked from 1 to 10 (1-worst to 10-best) by each subject. A total of 18 osteopathic medical students participated in this evaluation. There was one treatment group, i.e. all subjects were presented with identical experiments. The test procedure for each subject and viewing method is described below:

The first task: The user explored an opaque VHB model without somatic dysfunctions, with haptic feedback from the PHANToM® interfaces.

The second task: The user explored a transparent VHB model with skeletal structure visible, again without somatic dysfunctions, with haptic feedback from the PHANToM® interfaces

The third task: A somatic dysfunction (bump) was added at the T6 vertebra on the left. The user's task was to find the position of this bump, by exploring an opaque VHB model with haptic feedback, and use a footswitch to confirm it. Since this experiment was to test graphical realism and not palpatory diagnosis, the subject was shown the approximate back area in which to search for the dysfunction.

After finishing these three tests for each of the three viewing systems, each subject filled out an evaluation form regarding his

or her opinions about the graphical quality of the tests. Subjects were also invited to give comments on their form.

4.2 Evaluation Results

The evaluation results are shown in 11. The subjects rated Realism, Comfort, and Ease of Use for each of the viewing methods, all on a integer scale from 1 to 10, with 1 being worst and 10 being best in each case. Above each bar on the graph a number is shown for the average rating in each case from the 18 subjects, and the standard error bars are shown.

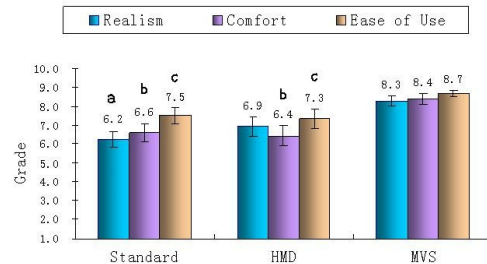


Figure 11. VHB Viewing Evaluation Results

4.2.1 Realism Ratings

The HMD method presents a 3D stereo model and allows the user to view the details of the VHB model closely and from different angles with realistic head motions. However, its realism ranking is not much higher than the standard method, for three reasons. One important reason is that the user can not see his fingers that interact with the PHANToM® haptic interfaces. The second reason is because of the narrow viewing angle limitation of the HMD. The 3D stereo effect of the bones (such as the vertebrae) is better than the back's surface because of their smaller size. The third reason is the different backgrounds. We can not block the real world image completely by adding blinders on the HMD because the user needs to see part of his hand and combine it with the image on the screens of the HMD to increase realism. The user has to view two different backgrounds, leading to unreal perception.

In the MVS, the user views his own fingers combined with the 3D VHB image. This is an important positive factor for realism because the user can touch and feel the virtual model naturally like a real object. Also the VHB model appears to be located in the real world. The virtual environment is pure black and transparent for the reflection. Hence it is mixed with the real environment fairly seamlessly. The user can view the model in a natural viewing angle. These advantages improve the realism significantly. But the phenomenon of the VHB graphics appearing on the user's hands is a weakness of the MVS that cannot be overcome fully.

4.2.2 Comfort Ratings

In the HMD method, the narrow viewing angle sometimes causes the user to lose his finger point on screen. Therefore, the average

comfort rating for the HMD is lower than the other two. There were some interesting results obtained in the Comfort evaluations of the HMD. Some subjects ranked the HMD comfort only 1 and one subject gave it a 10. This indicates that the 3D stereo effect of the HMD gives different people a very different experience. Some subjects are not in the habit of viewing 3D stereo images but others like it very much. Close objects (within 30 cm) show an obvious parallax. Also, with a small viewing angle, the viewer can feel uncomfortable. To improve the comfort with HMD, proper location (proper parallax) of the object and a wide viewing angle are the main factors, as presented earlier.

4.2.3 Ease of Use Ratings

Both the MVS and the Standard System were rated as easier to use than the HMD. When a user sits in front of the MVS and sees the 3D stereo VHB image, she will extend her hand to touch the model spontaneously without guidance. But if she is in front of the Standard and HMD systems, she might need instruction upon the first try. Thus, the MVS was clearly the easiest to use in our evaluations (see Figure 11). The HMD can be uncomfortable, even for short periods of use, since it is like heavy glasses. The HMD and its spring belt must also be adjusted for each new user. The HMD blocks most of the view around the user so it is easy to lose track of where the hands are. All of these factors led to the lowest Ease of Use rating for the HMD of the three methods.

4.3 Statistical Analysis

The Kruskal-Wallis nonparametric test was used to test for significant differences in the ratings of Realism, Comfort, and Ease of Use between the Standard display, HMD and MVS were analyzed using. Post hoc analysis was done using the Mann-Whitney test. Significance for all results was set at $P = 0.05$. Analysis of the data indicates there is no significant difference between the Standard display and the HMD for any of the three measures (Realism, Comfort, Ease of Use). Mean scores from the MVS are significantly higher than the scores for the Standard or HMD systems. Significant differences are as follows:

- a – Realism of the MVS is greater than that of the Standard display ($P < 0.05$);
- b – Comfort of the MVS is greater than that of either the Standard display or the HMD ($P < 0.05$);
- c – Ease of Use of the MVS is greater than that of either the Standard display or the HMD ($P < 0.05$).

The Realism of the MVS just missed being significantly higher than that of the HMD, with a P value of 0.06. Using these tests for significance, the MVS system was clearly the best of the three viewing systems in terms of subjective ratings for Realism, Comfort, and Ease of Use.

5 CONCLUSIONS

The head-mounted display (HMD) and mirror viewing system (MVS) improve the realism of the VHB relative to the flat-screen monitor. On the other hand, the original flat-screen monitor still can be used normally in daily work, programming, testing, etc., because it is easier to set up than the other two. With the HMD, the user can view an object of any size and can be close to the object and see its details, in a natural manner as in the real world. The MVS performs well in short-distance viewing applications. This system, combining a 3D stereo VHB model with the user's actual hands, gives the user a strong feeling of realism. Though the MVS performed the best in our evaluations, it has some limitations, listed below.

- The 3D stereo viewing field depends on the monitor size. Our recommendation is to use a big monitor or projector instead of the small (19-inch) CRT, increasing the image size.
- It is difficult to match the PHANTOM® haptic interface with the VHB image accurately (within 2 mm) because different users sit in different positions. The best accuracy achievable is around 3 mm. Our recommendation is to use a support to fix the user's head.
- The VHB model displays partially on the user's hands.
- The VHB model cannot be viewed naturally when moving the head as in the HMD case since it is a static model with no head tracking.

ACKNOWLEDGMENTS

The authors gratefully acknowledge generous support for this research from the Osteopathic Heritage Foundation of Columbus, Ohio.

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