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A COMPARISION OF LEARNING WITH HAPTIC AND VISUAL MODALITIES[1]

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ABSTRACT

The impact of haptic feedback on the perception of unknown objects (10 without texture, 10 with texture, and 2 complex shapes) was examined. Using a point probe (a PHANTOM), three treatment groups of students (visual, haptic, and visual plus haptic feedback) explored a set of virtual objects. The visual treatment group observed the objects through a small circular aperture. Accuracy of perception, exploration time, and description of objects were compared for the three treatment groups. Participants included 45 visually normal undergraduate students distributed across the three treatment groups and 4 blind students composing a second haptic-only group. Results showed that, within the normally sighted students, the haptic and haptic plus visual groups were slightly slower in their explorations than the visual group. The haptic plus visual group was more accurate in identifying objects than the visual or haptic-only groups. The terms used by the haptic treatment group to describe the objects differed from the visual and visual plus haptic groups, suggesting that these modalities are processed differently. There were no differences across the three groups for long-term memory of the objects. The haptic group was significantly more accurate in identifying the complex objects than the visual or visual plus haptic groups. The blind students using haptic feedback were not significantly different from the other haptic-only treatment group of normally-sighted participants for accuracy, exploration pathways, and exploration times. The haptic-only group of participants spent more time exploring the back half of the virtual objects than the visual or visual plus haptic participants. This finding supports previous research showing that the use of the PHANTOM with haptic feedback tends to support the development of 3-dimensional understandings of objects.

1. INTRODUCTION

Over the last decade there has been rapid development in the number and types of haptic augmented and virtual reality applications. Most of these applications have focused on using haptics to simulate real world situations for training purposes in surgery, dentistry, and air flight navigation. However, recent advances in the technology now allow us to add haptic feedback to a wide range of software applications. For the last five years we have involved middle and high

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school students in remote use of an atomic force microscope with the nanoManipulator (Taylor, et al., 1993) system that provides haptic feedback as students do experiments with viruses (Jones, et al., 2003). In these experiments students can poke, push, and cut adenoviruses or tobacco mosaic viruses and feel the viruses before, during and after manipulations. But how does the addition of haptic feedback impact learning in instructional contexts where an individual would not normally have such feedback?

In our previous research we compared students who received haptic and visual feedback during microscopy investigations with those students who just had visual feedback. We found that students with haptic feedback were significantly more likely to express greater interest in the investigations and were more likely to make 3-dimensional models of viruses than students who did not receive haptic feedback (Jones, et al., 2003). If this finding that haptics promotes 3-dimensional understandings is confirmed by other researchers then there are widespread implications for learning and the design of instructional materials, particularly for science applications where 3-dimensional understandings are critical, such as molecular structure or anatomy.

Historically vision has been reported to dominate haptics for object perception but more recent studies have shown that object perception is more complicated and results vary by condition (Locher, 1982; Sathian & Zangladze, 1997). Some researchers have argued that haptics is particularly effective for the detection of texture whereas vision is better at discriminating details of spatial geometry (Verry, 1998). Other studies have shown that the effectiveness of haptic and visual perception is influenced by situations such as conflict between senses or whether or not individuals can see their hand and use multiple fingers to measure distance. In these conditions, haptic perception may be superior to vision alone (Heller, et al., 1999). Ernst and Banks (2002) suggest that it isn't a case of one modality dominating another but instead they argue that perception is based on a weighted combination of cues from vision and haptics, with the weights determined by the reliability of the cue. The Ernst and Banks model suggests that different behaviors using haptic or visual information will be exhibited depending on the degree of discrepancy between haptic and visual information.

When haptic feedback is available during the exploration of 3 dimensional objects, studies have shown that individuals develop more 3 dimensional understandings than when only visual feedback is available (e.g., Jones, et al., 2003). Furthermore, there is evidence that there may be a preference for haptic exploration of the "back" side of objects whereas visually there is a preference for exploring the "front" of objects (Newell, et al., 2001).

Teachers often talk about the advantages of hands-on experiences in learning, yet the underlying mechanisms for hands-on experiences have not been fully researched. One aspect of haptic experience is active manipulation (as opposed to passive touch) that adds the elements of choice, control, and conscious movement that makes learning tasks more engaging and motivating to students.

Our previous research found that students reported that haptic feedback made learning more interesting. Haptics, as used in our research with students investigating viruses with a nanomanipulator, adds an additional sensory modality and as a result makes the learning more engaging to students. The nanoManipulator uses the PHANTOM Desktop from SensAble Technologies, Inc., www.sensable.com for haptic feedback. This device differs from normal haptic exploration because the PHANTOM stylus limits the exploration of an object to one point at a time. Jansson (2000) has suggested "to get information via a haptic display such as the PHANTOM is in principle similar to getting visual information from a computer screen by moving around a small hole in a paper covering the rest of the screen."

Research with rigid probes like the PHANTOM has shown that that the probe limits the perception of objects. Lederman and Klatsky (2004) compared compliant coverings, rigid finger splits, rigid finger sheaths, and rigid probes and found that the rigid probe provides the most constraints on the user by reducing cutaneous spatial deformation, thermal and kinesthetic cues. Furthermore, Lederman and Klatsky showed that the rigid probe is the least accurate and requires the most response time for the different methods tested. Nonetheless, rigid probe applications are increasing in medical and space applications.

The research reported here has several aims. The first is to compare in controlled settings the modalities of vision, haptics, and a combination of vision and haptics on participants' perceptions of a set of virtual objects. Although it has been argued that texture discrimination is almost as effective when an individual uses a pencil held in the hand as when texture is in direct contact with a finger (Lederman, 1983), there are limited studies involving the PHANTOM or other point probes in educational contexts. A second aim is to explore how the addition of a texture patch to virtual objects impacts how objects are perceived in the three treatment conditions. Texture was added to see if it served as a spatial referent or anchoring point for exploration. Previously we found that when students had haptic experiences with the PHANTOM, they were likely to represent the objects they explored in 3 dimensions. Following up on this finding we sought in the present study to examine the degree to which participants used the haptic feedback to explore the z (depth) dimension of virtual objects. Finally, because teachers typically must teach students with a wide range of abilities and special needs, we compare how blind participants' perceptions and exploration behaviors compared to those of sighted participants.

2. METHODS

2.1 Participants

Sighted participants. Forty-five undergraduate university students participated in the study (21 females, 24 males; 18-22 years of age). Participants were recruited from the university campus, and represented 24 different major courses of study.

Blind participants. Four blind university students (3 females, 1 male) participated in the study. Two were undergraduates and two were graduate students. The blind participants ranged in age from 21-52 years of age. Participants were asked if they had been blind from birth. Two of them were blind since early in life with no memory of images, and two lost their eyesight after having had vision earlier in life. All participants were classified as legally blind and received disability services by the university. However, the degree of blindness was not ascertained except from voluntary self reporting. The rationale for adding the blind participants was to determine if there were differences between the haptic treatments for blind and sighted individuals. There are limited educational materials for teaching spatially complex topics (such as those in science) for students with visual impairment and the present study served as a pilot study to provide data on the effectiveness of the technology across those participants with full vision and those with limited or no vision.

2.2 Procedures

Participants explored a set of virtual objects composed of four connected cubes (Figure 1) with the PHANTOM Desktop. Each cube was 25 x 25 x 25 mm in size. For Session 2 mirror images or rotations of the objects from Session 1 were used and a texture patch was added to one 25 x 25 mm side of one of the cubes. The texture patch was composed of bumps 1.5 mm in diameter. The bumps were randomly distributed within the patches. Individual bumps could be detected with slow movement of the PHANTOM. Presentation order of objects was the same for all participants in all treatment groups to avoid having a practice effect interaction when analyzing results by object.

The sighted participants were randomly divided into three groups of 15 (visual, haptic, and visual plus haptic) who explored the set of virtual objects (Session 1) followed a week later by an exploration of a second set of virtual objects that included a texture patch (Session 2). Objects used in Session 2 were mirror images or rotations of the objects presented in Session 1 to ensure equivalent object complexity across the two sessions. One student in the haptic group was more than three standard deviations above the mean for exploration time and was dropped from subsequent analyses.

The haptic group used the PHANTOM Desktop as a point probe to explore the virtual objects haptically. The virtual objects and haptic components were implemented using the GHOST SDK from SensAble technologies. Visual information was limited to a black window on the laptop computer screen (1600 x 1200 pixels) that displayed the shape number under exploration (to allow students to monitor their progress). The Phantom position was recorded 30 times a second. Students were able seat themselves at a comfortable distance from the computer screen (about .50 to .75 meters).

The participants in the visual treatment group saw a small circular aperture through which they could see portions of the shape (simulating a visual field similar to Jansson's (2000) concept of the PHANTOM as "a small hole in a paper"). The aperture tracked the tip of the PHANTOM stylus, and participants could move the aperture with the PHANTOM (similar to moving a flashlight in a dark room to reveal a large object). The depth position of the PHANTOM had no effect on the aperture or the view through the aperture. The diameter of the aperture was 50 pixels and the width of the component cubes forming the objects was 250 pixels. Thus the aperture area was approximately 4% of the face of the component cube. The diameter of the aperture corresponds to a visual angle of approximately 2 degrees. These participants in the visual treatment group could only see portions of the shape at a time as they moved the aperture around on the screen with the PHANTOM, but could not feel the shapes. Figure 1 shows an example of a test shape shown in full screen and in the reduced-aperture view (reduced in size, test objects filled the screen). Objects were presented in gray scale on a dark red background. Participants could move the PHANTOM arm in any direction – moving the aperture in 2 dimensions (like a flashlight) but they could not move the objects.

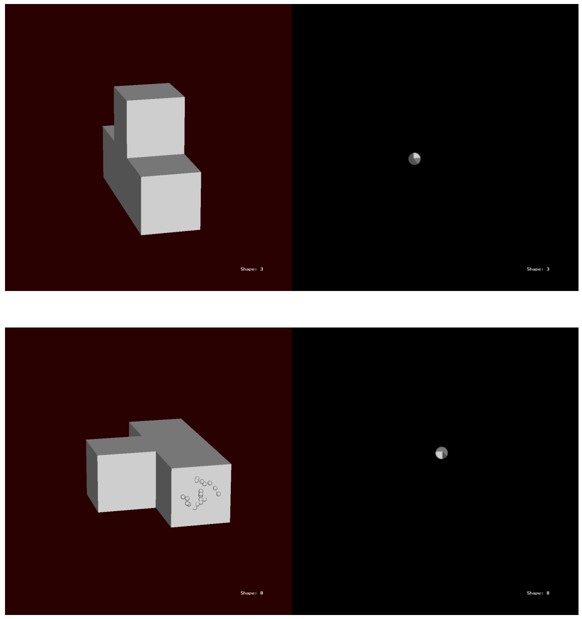

Figure 1. Visual objects seen in full view and reduced-aperture view. The aperture was 50 pixels during trials, corresponding to a visual angle of approximately 2 degrees.

The visual plus haptic group received both visual and haptic feedback from the PHANTOM. As they moved the PHANTOM stylus around, they could simultaneously see a portion of the shape through the same size aperture as that used with the visual group, and they could feel the portion of the virtual object that they saw through the aperture in the same manner as the haptic group. Similarly, in a study of visual and haptic recognition of line drawings, Loomis, Klatzky, and Lederman (1991) used a variable aperture to narrow the visual field to match the visual acuity to tactile acuity of the fingertip.

At Session 1, participants were told they would explore 10 different three-dimensional geometric shapes (Figure 2) and would be asked to sketch those shapes as accurately as possible, to provide a written description of the shape on the back side of the sheet of paper, and would be asked to give the paper to the researcher and verbally describe the shape to the researcher. Participants were instructed to thoroughly explore the shape until they believed they understood it. There was no time limit placed on exploration, however once the participants stopped exploration and started to sketch, they were not allowed to explore the current shape again. Participants were given instruction on how to hold and use the PHANTOM, and an opportunity to experiment with the PHANTOM to experience its multi-dimensional freedom of motion without a shape present and with a cube as a training shape until they were comfortable with the technology.

During Session 2, participants were first asked to recall as many of the shapes as possible from the week before. After describing all the shapes they could remember, they were then asked what helped them remember those shapes from the week before. Participants were instructed that Session 2 would be similar to Session 1, with the exception of the addition of a patch of texture added to one side of each shape.

Texture was added to investigate the impact on patterns of exploration of shapes. Participants were asked to indicate the location of this texture patch by circling the appropriate spot on their sketch. For those with visual feedback, the texture looked like small bumps; for those with haptic feedback, the texture felt bumpy or rough. Figure 1 shows an example of a shape with the texture patch. The 10 test shapes used in Session 2 were rotated or mirror images of the shapes from the first session, presented in a different order (Figure 3). Upon completion of exploring and describing these 10 shapes, participants were asked to explore three additional shapes. These were a cube rotated and twisted 45° about the z and y-axes, a sphere, and a torus. The curved objects were added to allow us to compare how participants explored sharp edged objects to smooth objects. These different objects were added to explore the stimulus-specific object effects to guide further research.

The assessments included a measurement of the exploration time, time spent touching the shape surface, time spent on the back half of shapes, accuracy of the shape recall (description and drawing of the object), and descriptive words used to describe the shapes. The multiple assessments allowed us to examine both the acquisition of information (time of exploration, time spent on the surface) with different modalities and the results of acquiring information (accuracy of identification). The time spent exploring the surface (rather than exploring the space around the outside of the object) was examined to see if there were differences in the perception of the object sides. The accuracy of recall was examined to see if one modality enabled the participant to more accurately detect the object. In addition to drawings, the descriptions were used to determine accuracy and to control for some participants' inability to draw accurately. The descriptive words used were examined for evidence that participants mentally encoded the objects differently depending on the treatment condition.

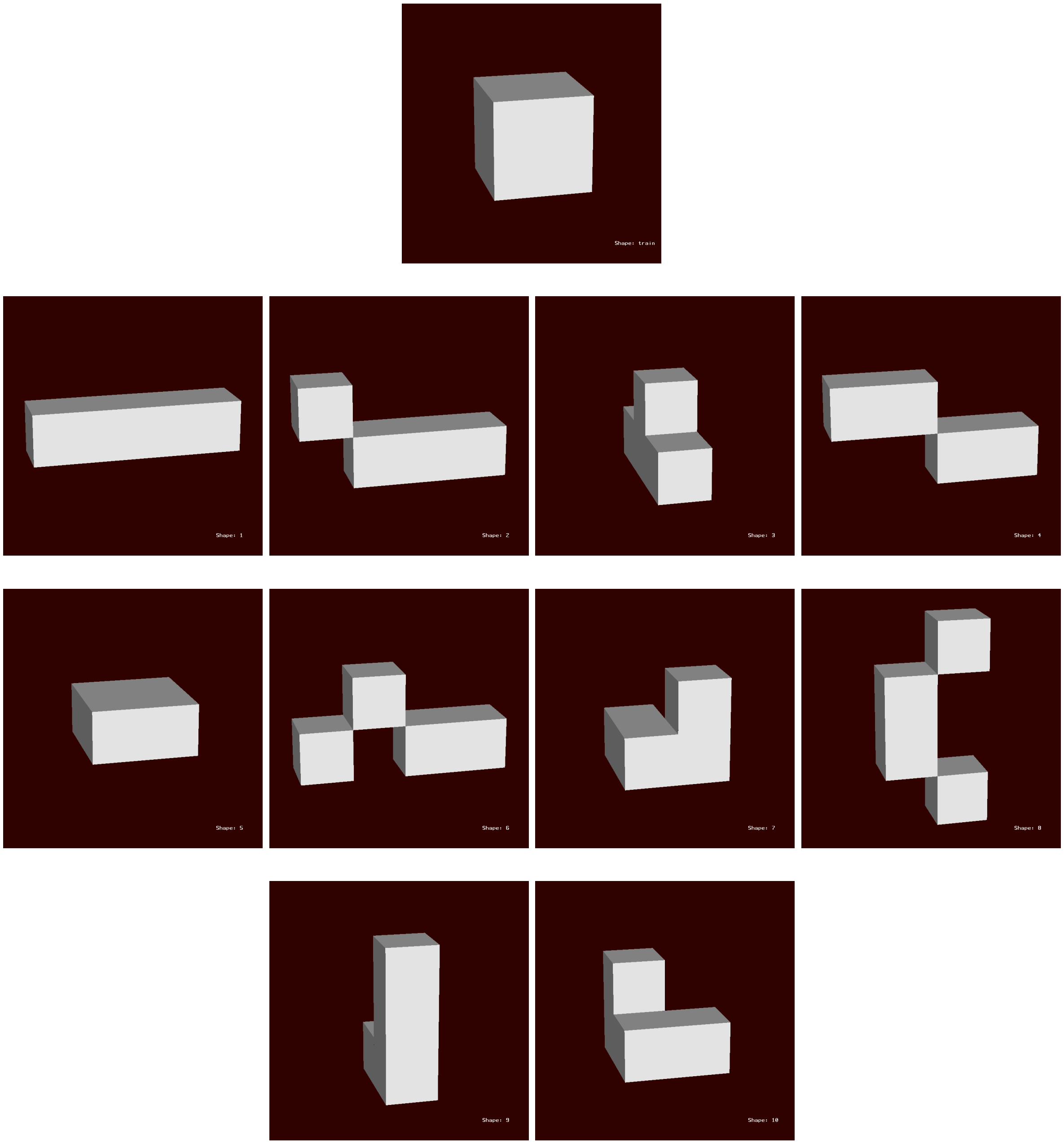

Figure 2. Sequence of virtual shapes from session one. The shapes are shown in the order they were presented to the participants, with the training shape shown first.

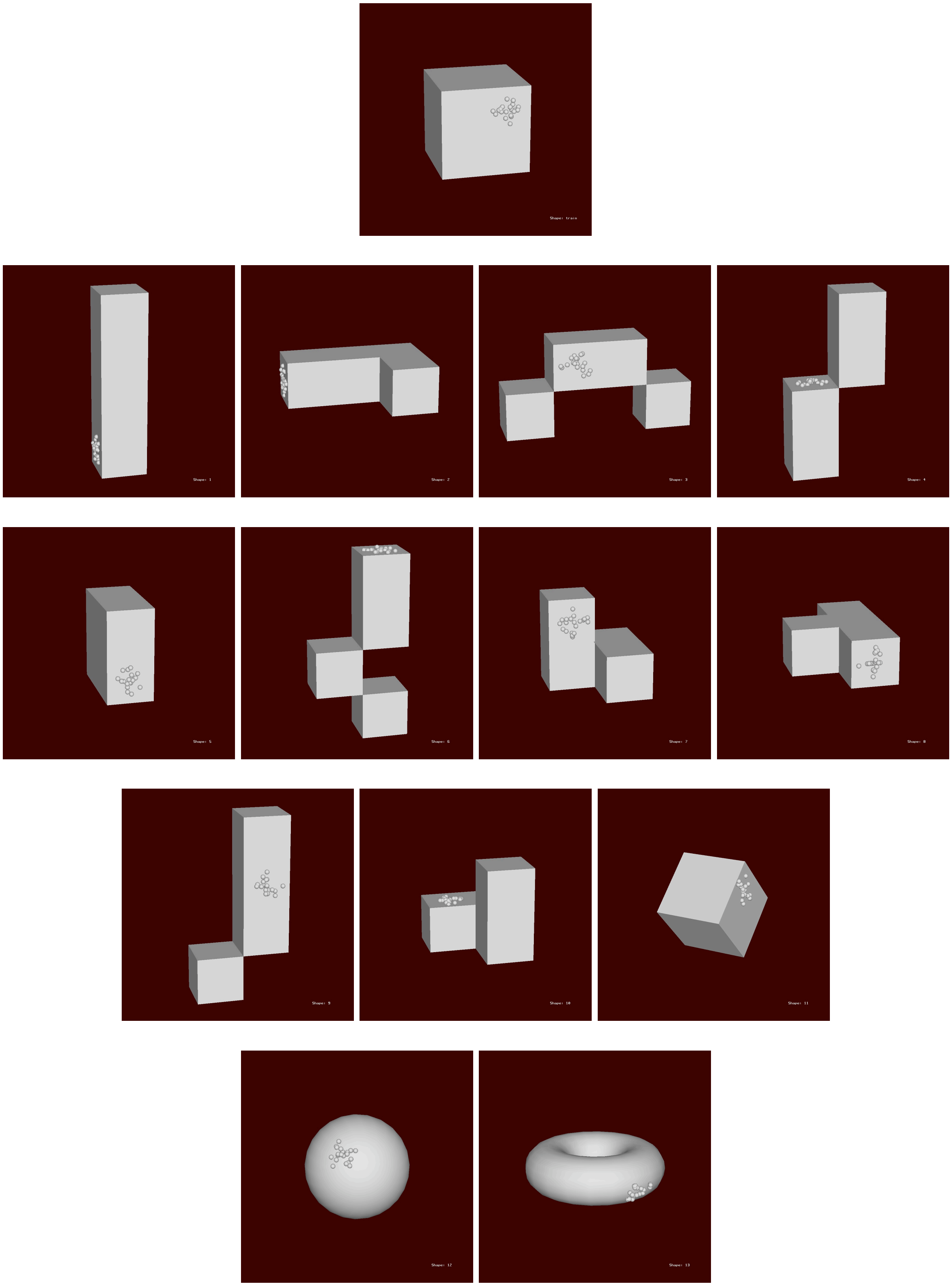

Figure 3. Virtual sharp-edged shapes and soft-edged shapes from session two, shown in the order the shapes were presented to the participants. The first shape, a cube, was used as a training shape. Shapes in this session all had small patches of texture.

3. RESULTS

3.1 Exploration Time

The ANOVA for exploration time showed that there were significant differences between groups (Session 1, F (2) = 16.25, p< .001; Session 2, F (2) = 26.30, p < .001) for exploration time (Table 1). A Least Significant Difference post hoc test showed that in both sessions the haptic group took significantly longer to explore than the visual group and longer than the visual plus haptic group. There were no significant differences between the visual and visual plus haptic group for exploration time in either session.

Table 1

Exploration Time for Shapes 1-10 (seconds)

	Mean (SD)		
	Haptic	Visual	Visual & Haptic
Session 1***	194 (72)	93 (30)	134 (64)
Session 2***	173 (57)	83 (30)	84 (19)

Note 1. Session 1, F (2) = 16.25, p< .001.
Note 2. Session 2, F (2) = 26.30, p < .001

To test for the possibility that the groups would experience a differential practice effect in their exploration time as each session progressed, mean exploration times for the first half of the shape set (shapes 1-5) and the second half (shapes 6-10) were separately computed for each participant, and then group means were compared using an ANOVA (see Table 2).

The ANOVA showed that there were significant differences between groups for each half of the shape set (First Half Session 1, F (2) = 13.26, p< .001; Second Half Session 1, F (2) = 13.54, p < .001; First Half Session 2, F (2) = 16.82, p < .001; Second Half Session 2, F (2) = 28.16, p < .001). A Least Significant Difference post hoc test showed that in both halves of both sessions the haptic group took significantly longer to explore than the visual group and longer than the visual plus haptic group. The visual group and the visual plus haptic group did not show any significant differences in exploration time in any session except for the first half of Session 1, where the visual plus haptic group took significantly longer than the visual group. An ANOVA comparing the exploration time of the two smoothly curving shapes in Session 2 showed no significant differences between the three groups.

Table 2
Exploration Time for Each Half of the Shape Set (seconds)

	Mean (SD)		
	Haptic	Visual	Visual & Haptic
First Half Session 1***	178 (63)	87 (27)	123 (49)
Second Half Session 1***	210 (89)	101 (40)	114 (45)
First Half Session 2***	148 (52)	78 (28)	84 (19)
Second Half Session 2***	199 (71)	87 (34)	84 (24)

Note 1. First Half Session 1, F (2) = 13.26, p< .001.
Note 2. Second Half Session 1, F (2) = 13.54, p < .001
Note 3. First Half Session 2, F (2) = 16.82, p < .001
Note 4. Second Half Session 2, F (2) = 28.16, p < .001

Time exploring shape surface. As one measure to compare exploration strategies between the three groups, the ratio of the exploration time spent touching the surface of each shape to total exploration time was computed. A mean ratio of time on the surface was computed over the 10 shapes in Session 1 and for the first 10 shapes in Session 2 for each participant.

In Session 1, the haptic group spent on average 73% (*SD* = 7%) of their time touching the shapes, whereas the visual and haptic group spent 44% (*SD* = 26%) and the visual group spent 6% (SD = 7%). An ANOVA showed that there were significant differences between these groups in ratio of time spent on shape surfaces (F(2) = 61.88, p < .001.) A Least Significant Difference post hoc test showed that the haptic group spent a significantly (p < .001) larger percentage of their time on the surface compared to the visual plus haptic group, and in turn that the visual plus haptic group spent a significantly (p < .001) larger percentage of their time on the surface compared to the visual group. This suggests that the group with both sensory inputs used the haptic capability of the instrument to some degree, but not as much as the exclusively haptic group.

Session 2 ratios of time spent on the surfaces of the shapes were similar to that of Session 1 [Haptic = 77% (7%); Visual = 7% (8%); V & H = 49% (25%)]. As with Session 1, an ANOVA showed significant differences (F(2) = 72.59, p < .001) between groups, and a Least Significant Difference post hoc test again showed that haptic spent a significantly (p < .001) larger percentage on surface than visual plus haptic, while the group with both sensory inputs spent a significantly (p < .001) larger percentage of time on the shapes' surfaces than did the visual group. The similarity of these results with those from Session 1 suggests a consistency of use of explorations of each object's surface by participants in all three treatment groups. Analysis of the time spent on the objects' surfaces for the first half and second half of each session by all groups show similar ratios within groups for each half, suggesting no differences in ratio of time spent on objects' surfaces throughout the duration of each session.

Time exploring the back half of objects. To investigate the participants' explorations of the back half of each shape, the percentage of the exploration time spent on the back half of each shape was computed. A mean of these percentages was computed for shapes 1-10 for each participant, and group means were compared (see Table 3 and the path of exploration in Figure 4).

Table 3
Percentage of Time Spent on Back Half of Shapes 1-10

	Mean (SD)		
	Haptic	Visual	Visual & Haptic
Session 1***	49 (5)	22 (29)	31 (12)
Session 2***	54 (5)	16 (20)	37 (13)

Note *1*. Session 1, *F* (2) = 7.67, p< .001.
Note 2. Session 2, *F* (2) = 26.82, p< .001.

The ANOVA showed that there were significant differences between groups (Session 1, $F(2) = 7.67$, $p < .001$; Session 2, $F(2) = 26.82$, $p < .001$), and a Least Significant Difference post hoc test showed that in both sessions the haptic group spent a significantly larger proportion of their exploration time on the back half of shapes than the visual group ($p<.001$ in each session) and longer than the visual plus haptic group ($p<.05$ in Session 1 and $p<.002$ in Session 2). The visual group and the visual plus haptic group did not show any significant differences in proportion of time spent on the back half in Session 1, whereas in Session 2 the visual plus haptic group spent a significantly greater proportion of time on the back half than did the visual group ($p<.001$).

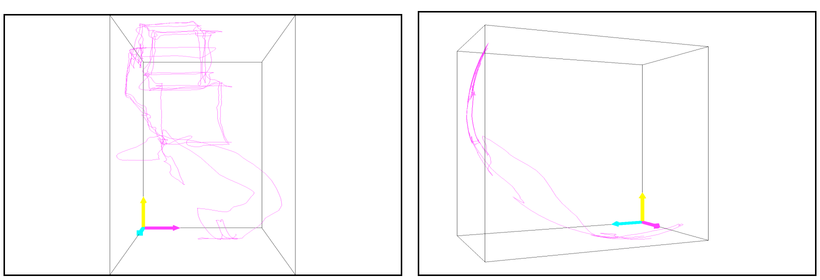

Figure 4. Vision participant movement tracing, front and side view.

3.2 Accuracy

Session 1, shapes 1-10. After coding each participant's drawing and description of each shape, the total number of shapes falling in four accuracy categories was computed by treatment group for Session 1 (see Table 4). Some shapes were far from accurate, with at least two of the four basic component cubes of each object (see Figure 2 for the objects explored) being incorrect, either missing or misplaced and these shapes were coded as 0 accuracy. Some shapes were closer to accurate, but were still missing or had misplaced one of the basic component cubes—these were coded as an accuracy of 1. Other drawings and descriptions had the basic components of the actual shape correct, except that one or more dimensions was distorted or a component cube was shifted from its actual position—such shapes were coded as an accuracy of 2. Those shapes that completely described the target shape accurately with both the number and placement of the basic component cubes as well as the correct proportions were coded with an accuracy of 3. These four categories of accuracy captured all attempts by participants to represent the objects they were exploring.

Using this four-point scale, two raters independently coded 30% of all object representations. The interrater reliability between the researchers was 90%. One researcher then coded all the remaining objects.

Table 4
Accuracy of Shape Identification, Shapes 1-10

	Accuracy Category			
Group	0	1	2	3
Session 1				
Haptic	6	23	38	87
Visual	0	14	74	77
V & H	0	10	50	105
Session 2				
Haptic	3	10	27	114
Visual	0	3	44	118
V & H	0	2	32	131

Note 1. Data represent total number of shapes in each category.
Note 2. Accuracy was coded on a scale of 0= not accurate to 3= completely accurate.

A chi-square test for each pair of treatment groups showed that all three groups were significantly different from each other in accuracy of shapes in Session 1. The haptic group was significantly different from the visual group [χ^2 (3, *N*=319) = 20.015, *p*<.001]; the visual group was significantly different from the V & H group [χ^2 (3, *N*=330) = 9.620, *p*<.01]; and the haptic group was significantly different from the V & H group [χ^2 (3, *N*=319) = 14.083, *p*<.01] in accuracy in Session 1.

<u>Session 2, shapes 1-10 with texture patch</u>. The total numbers of shapes in each accuracy category for Session 2, shapes 1-10, for each treatment group for Session 2 are shown in Table 4. A chi-square test for each treatment group from Session 1 accuracy to Session 2 accuracy showed that each group improved on accuracy in Session 2 (haptic χ^2 (3, *N*=308) = 11.610, *p*<.01; visual χ^2 (2, *N*=330) = 23.365, *p*<.001; V & H χ^2 (2, *N*=330) = 12.149, *p*<.01.)

A pairwise chi-square test was used to determine which treatment group was more accurate than another. The haptic group was significantly different from the visual group [χ^2 (3, N=319) = 10.542, p<.05] in accuracy in Session 2. A chi-square to compare Session 2 accuracy for the visual group and the V & H group showed no statistical difference between these two groups. The haptic group was significantly different from the V & H group in Session 2 accuracy [χ^2 (3, N=319) = 9.569, p<.05]. In general, for the first ten shapes in Session 2 (with texture patches), all groups improved in accuracy. However, the haptic group was least accurate, and the visual and V & H groups had similar accuracy ratings for these shapes.

Session 2, shapes 12-13. The accuracy codings for the shapes with smoothly curving surfaces, shape 12 (the sphere) and shape 13 (the torus) are shown in Table 5. Because one of the participants in the haptic group did not explore these shapes due to time constraints, there are 13 participants in the haptic group for this analysis.

Table 5
Accuracy of Shape Identification for Session 2 Curving Shapes (12-13)

	Accuracy Category			
Group	0	1	2	3
Haptic	0	0	1	25
Visual	12	7	1	10
V & H	4	3	4	19

Note 1. Data represent total number of shapes in each category.
Note 2. Accuracy was coded on a scale of 0= not accurate to 3= completely accurate.

The haptic group was significantly different from the visual group [χ^2 (3, N=56) = 25.272, p<.001] in accuracy for shapes 12-13 in Session 2. The influential cells accounting for this difference are the greater numbers of accuracy category 3 for the haptic group and the correspondingly lower number of categories 0 and 1 accuracies. The visual group was significantly different from the V & H group [χ^2 (3, N=60) = 10.193, p<.05] for these two shapes. The influential cells accounting for this difference are the lower number of category 3 classifications for the visual group and the correspondingly higher number of 0 classifications. The haptic group is significantly different [χ^2 (3, N=56) = 9.380, p<.05] from the V & H group in accuracy ratings for these shapes; the most influential cells were the relatively lower number of category 0 and 1 accuracy ratings for the haptic group.

In contrast to the accuracy results for the straight-edge shapes, the haptic group outperformed both other treatment groups in accurately identifying these two smoothly curving shapes, and the V & H group likewise outperformed the visual group. This suggests that the haptic sensory data was most effective at identifying these smoothly curving shapes. The V & H group may have benefited from the availability of the haptic sensory mode to improve their performance over the group which only had visual input. The differences in performance for the haptic group for cubed and curved shapes may be due to greater ease that participants have in keeping the probe on the curve. When the probe leaves the edge of a cubed shape the participant has to search to locate a surface within the exploratory space. Curved shapes could be explored continuously without loss of probe contact.

3.3 Descriptive Words

The language used in the descriptions of the drawings was examined for evidence that participants mentally encoded the information differently based on different modes of learning about the shape (haptic, visual, or visual plus haptic). Descriptive words were identified and then categorized as Box (terms noting any combination of box or block), Geometric (terms representing cube, prism, rectangle, or other geometric term), Letter (a letter shape such as T or L), or Everyday (object terms such as stair, tetris piece, or pencil).

Session 1, shapes 1-10. A chi-square test was used to compare types of descriptive terms from Table 6 for each pair of treatment groups. The haptic group was significantly different from the visual group [χ^2 (3, N=318) = 34.773, p<.001] and from the V & H group [χ^2 (3, N=317) = 39.531, p<.001] in their use of descriptive words. The chi-square test residuals indicate that the haptic group's higher number of words in Everyday objects and lower number of words in Geometric terms was primarily responsible for group differences. The visual and V & H groups were not significantly different in their use of descriptive words in Session 1.

Table 6
Descriptive Words used for Shapes 1-10

	Descriptive Word Category			
Group	Box/Block	Geometric	Letter	Everyday
Session 1				
Haptic	25	59	20	49
Visual	29	108	14	14
V & H	32	107	14	11
Session 2				
Haptic	30	73	24	27
Visual	36	98	20	10
V & H	33	112	19	1

Note 1. Data represent total number of shapes in each category.
Note 2. Descriptions were coded as Box/ block, Geometric terms, Letter shapes, or Everyday/ familiar 3-d object.

Session 2, shapes 1-10. Session 2 use of descriptive words was similar to Session 1, with the haptic group again significantly different from the visual group [χ^2 (3, N=318) = 12.072, p<.01] and from the V & H group [χ^2 (3, N=319) = 32.748, p<.001] in their use of descriptive words. The primary difference was again due to the haptic group's higher number of words in Everyday objects and the lower number of words in Geometric terms.

Session 2, shapes 12-13. The descriptive words used with the smoothly curving shapes, shape 12 (sphere) and shape 13 (torus) are shown in Table 7.

Table 7
Descriptive Words used for Shapes 12-13 in Session 2

	Descriptive Word Category			
Group	Box/Block	Geometric	Letter	Everyday
Haptic	0	10	0	16
Visual	0	24	0	5
V & H	0	20	0	10

Note 1. Data represent total number of shapes in each category.
Note 2. Descriptions were coded as Box/ block, Geometric terms, Letter shapes, or Everyday/ familiar 3-d object.

Table 7 shows that no participant in any treatment group used a Box/Block term or a Letter in describing these shapes, most likely due to the nature of these particular shapes. The chi-square test showed that the haptic group was significantly different in use of descriptive words compared to the visual group [χ^2 (1, *N*=55) = 11.397, *p*<.001] and compared to the V & H group [χ^2 (1, *N*=56) = 4.455, *p*<.05]. In both cases, this difference is due to the haptic group's greater use of everyday objects to describe the shape compared to the visual and V & H groups. The visual and V & H groups did not show any statistically significant difference between groups for the use of descriptive words for shapes 12 and 13 in Session 2.

Across the different shapes and in both Sessions 1 and 2 the haptic group used more everyday objects to describe the shapes. This suggests that the haptic group tended to encode the objects differently in memory. It is plausible that the different sensory modalities evoke different connections with prior experiences. For example a haptic-only participant may think while exploring the object, "this is like a set of stairs" for a cubed object, whereas a participant in the visual condition may think "this is a cube with another cube at the bottom right."

3.4 Shape Recall

Comparisons of the number of shapes from Session 1 recalled (maximum of 10) one week later during Session 2 using a one-way ANOVA showed no statistically significant differences between treatment groups (haptic *M* = 4.86, *SD* = 1.96; visual *M* = 5.00, *SD* = 1.13; V & H *M* = 5.47, *SD* = 1.51.) This result suggests that all treatment groups were able to equally effectively retain memory of the shapes explored regardless of the sensory mode of input in learning the shapes.

3.5 Blind vs. Sighted Participants

The small group of blind students was compared to the haptic group of sighted students on the various measures used above. There were no statistically significant differences between the haptic group and the blind group on any of these measures of time spent exploring objects. This suggests that the use of the haptic capability of the instrument is as easily learned by sighted students as it is by blind students.

There were no statistically significant differences in accuracy for the blind group and the sighted haptic group. In the use of descriptive words, the blind students tended to use significantly more geometric terms and fewer Box/Block and Everyday object terms than the haptic group of students. A comparison of the two groups' recall of shapes from Session 1 a week after having done the exploration showed no difference [$t(16) = 0.625$, $p = .541$] between the haptic group (M = 4.86, SD = 1.96) and the blind group (M = 5.50, SD = 1.00).

4. SUMMARY OF RESULTS

Sharp-edged shapes. As might be expected, the haptic group was slower in their explorations than either the visual group or the V & H group. The V & H group overall spent approximately the same amount of exploration time as the visual group. Although the V & H group started out in the beginning of Session 1 being slower than the visual group, they made improvement in their speed over the two sessions to be equally as fast as the visual group by the end of Session 2. It is important to note that it is not possible to partition out the whether or not changes from Session 1 to Session 2 are due to the addition of the texture patch or due to the additional experience that the participants had exploring the objects. The V & H group did not seem to rely exclusively on the visual mode of input, showing evidence of using the haptic input capability of the instrument by falling between the haptic and visual group in percent of time spent on the surface of the shapes and spending more time on the back half of the shapes than the visual group by Session 2. Klatzky, Lederman and Matula (1993) examined visual and haptic exploration and found providing a visual preview of an object before touch increased the speed of initiation of touch and their work suggested that vision serves a role in visual guidance of haptic exploration.

All three groups improved in accuracy of identifying the shapes from Session 1 to 2, suggesting a learning curve where performance improves with practice for all treatment conditions. In Session 1, the haptic group had more completely accurate shapes than the visual group, but also more highly inaccurately identified shapes; the visual group had more almost accurately identified shapes. These mixed results make it difficult to interpret whether the haptic or the visual group outperformed the other in Session 1 accuracy. However, it is clear that the V & H group outperformed both the haptic and the visual group in Session 1, suggesting a benefit was to be gained from having both modes of sensory input. In Session 2 a texture patch was added and the V & H group again outperformed or at least equally performed with the haptic group and the visual group in spite of the accuracy improvements made by these groups in Session 2. This suggests that the advantage of having both sensory modes of input was retained even after all participants improved by Session 2 due to a practice effect.

The haptic group tended to use different categories of words, using more everyday objects as opposed to abstract geometrical terms, when describing the shapes than either the visual group or the V & H group, which suggests a different mode of processing the information obtained about the shapes during exploration. The visual and V & H groups were very similar to each other on their use of descriptive words, suggesting a closer cognitive processing match between these two data gathering treatments as opposed to one relying exclusively on haptics. However, all three groups were able to recall about the same number of shapes one week later, suggesting that the different modes of processing the shapes being explored were equally effective for long-term memory retention.

Smoothly curving shapes. In contrast to the sharp-edged shapes, there was no significant exploration time difference for any of the three treatment groups with the smoothly curving shapes, suggesting that having only haptic input is not contributing to a speed disadvantage for these shapes. The haptic group was more accurate than any other group in identifying and describing the smoothly curving shapes, and the V & H group was more accurate than the visual group. This suggests that haptic data may be superior to visual data for identifying smoothly curving shapes, and that the V & H group was able to take advantage of haptic capability in order to outperform the visual group on accuracy for these shapes.

In science, most of the microscopic shapes that would be explored by students would fall under the category of smoothly curving, suggesting that the addition of haptics to such explorations could add significantly to students' understandings of the morphology of the objects of exploration. As was found with the sharp-edged shapes, the haptic group used more everyday objects than either other group to describe these smoothly curving shapes, suggesting a consistency of cognitive processing procedures as they learn different shapes whether they are sharp-edged or not.

Blind vs. sighted. The blind and sighted participants who used only haptic input to explore the shapes did not show large differences in the data. Both groups spent approximately equal time exploring shapes, both sharp-edged and smoothly curving, and spent approximately the same percentage of time touching the surface of objects as well as exploring the back half of the object.

These two groups had very similar accuracy ratings for both sharp-edged and smoothly curving shapes, and they also had about the same number of shapes they could recall one week after exploring them. A difference between these two groups was found in the use of descriptive words for the shapes, with the blind students tending to use more geometric terms than the sighted students and correspondingly fewer either generic or everyday object terms.

5. DISCUSSION

Although this research was designed to carefully control for random selection and placement of participants and the creation of equivalent treatment conditions, these results are limited by the small number of blind participants that were available for study and the limited number of curved objects. Results should be considered preliminary until other studies can confirm these findings.

The results showed that the haptic group spent more time exploring the back half of the objects than the other treatment groups. This supports our previous findings that students who use the PHANTOM tend to develop more 3-dimensional understandings of objects than those students who just have visual feedback. The opportunity to explore all the dimensions of objects may prove valuable for the development of complex scientific visualizations.

The addition of texture in Session 2 seemed to have little impact on the paths that the participants used to explore the objects as seen on the movement tracings. Participants were able to identify the location of the texture patches on the virtual objects but did not appear to use the patches as anchoring points for exploration. Klatzky and Lederman (1999) showed that rigid probes can be effective in roughness discrimination. They maintain that remote probes should be fit to the geometric properties of the probed surface in order to be most effective. Furthermore, Klatzky and Lederman suggest that in virtual environments texture cues provide a greater sense of "presence."

The curved shapes proved to be significantly more challenging for the visual and V & H groups and the finding that the haptic group was significantly more accurate in the perception of the curved objects was an unexpected finding. Further research can provide insight into why curved figures are more difficult to detect with the limited visual or haptic plus visual feedback. Perhaps there is something about the visual representation of edges that made these objects more difficult to identify. These results clearly suggest that any study that compares visual and haptic feedback may vary by object form and context.

The significant differences in the haptic group compared to the visual and visual plus haptic group for the descriptive words suggests that participants are conceptualizing and encoding these objects in different ways. One possible explanation is that because haptics involves kinesthetics and tactile properties, then objects perceived with haptics are conceptualized similar to other real life objects that are experienced with a fuller range of modalities such as stairs or dice.

The lack of differences in the different treatment groups for recall a week later suggests that none of the three treatments was more effective in creating long term memory. We hypothesized that having multimodal feedback could lead to stronger (more connected) knowledge of the objects. This hypothesis was not supported by the data.

As educators we are interested in how haptics can address the needs of a wide variety of students. Teachers are constantly challenged by the need to find effective strategies that can be used for students with special needs such as dyslexics and those with visual impairments. The results of this study for the blind participants and sighted haptic participants for exploration time, time on the surface of the object, time spent exploring the back of the object, and accuracy support the results of other researchers. Grant, Thiagarajh, and Sathian (2000) conducted a study of blind and sighted individuals' tactile perception with Braille. These researchers found that initially the blind outperformed the sighted but with practice both groups performed equally well. Although it has been suggested that the blind develop supernormal perceptual abilities with auditory and somatosensory systems, there is evidence that with practice, haptic discrimination is perceived equally well by congentially blind, adventitiously blind, and normally sighted participants (Heller, 1989).

In order to determine the best educational applications for haptics there is a need to understand if haptics is more effective at particular ages or stages of development. There is initial evidence that haptic perception is influenced by development. In a study of haptics and vision in size-conflict experiments with different ages of children, Misceo, Hershberger, and Mancini (1999) found differences in haptic dominance depending on the age of the participant. Haptics dominated over vision with the older children. Additional research with a wider range of participants can provide insight into whether or not the age and experience of the participant is a significant factor in tasks involving haptic perception.

Another area that warrants further research is the use of haptic tools such as the PHANTOM with participants with perceptual difficulties such as dyslexics. Dyslexic students struggle with spatial orientation and many science topics found in chemistry and microbiology build on spatial skills. Understanding how students with dyslexia use a haptic point probe to explore software applications is needed. Grant, Zangaladze, Thiagarajah, and Sathian (1999) found that dyslexics had significantly poorer performance on haptic tasks involving grating orientation perception. Given the motor and perceptual challenges of the PHANTOM accompanied with graphics in normal applications, it is likely that dyslexics and others with perceptual disabilities may experience difficulty using the PHANTOM. In our application where students use the PHANTOM to experiment with viruses under an Atomic Force Microscope, the problem is exacerbated by the fact that the microscope scans across the microscope sample in a left to right orientation which is subsequently shown on the computer screen as a visual image.

This study supports the use of a point probe haptic interface as a tool to explore 3 dimensional objects, particularly when visual feedback is limited. In this study the haptic feedback made available the back side of objects for students' exploration and conceptualization. For complicated shapes, participants with haptic feedback were more accurate. As a learning tool, haptic feedback shows promise as a tool to conceptualize complex virtual worlds.

REFERENCES

[1] Ernst, M.O.,and Banks, M.S., "Humans integrate visual and haptic information in a statistically optimal fashion." *Nature*, 415, pp. 482-433, 2002.

[2] Grant, A., Thiagarajah, M. and Sathian, K., "Tactile perception in blind Braille readers: A psychophysical study of acuity and hyperacuity using gratings and dot patterns," *Perception and Psychophysics*, 62, pp.301-312, 2000.

[3] Grant AC, Zangaladze A, Thiagarajah MC, Sathian K., "Tactile perception in developmental dyslexia: a psychophysical study using gratings," *Neuropsychologia*, 37, pp.1201-1211, 1999.

[4] Heller, M., "Texture perception in sighted and blind observers," *Perception and Psychophysics*, 45, pp. 49-54, 1989.

[5] Heller, M., Calcaterra, J., Green, S. and Brown, L., "Intersensory conflict between vision and touch: The response modality dominates with precise, attention-riveting judgments are required," *Perception and Psychology*, 61, pp. 1384-1398, 1999.

[6] Jansson, G., The Haptic Sense Interacting With a Haptic Display," Paper presented to the Swedish Symposium on Multimodal Communication, Stockholm, October 26-27, 2000.

[7] Jones, G., Andre, T., Negishi, A., Tretter, T., Kubasko, D., Bokinsky, A. , Taylor, R. and Superfine, R. "Hands-on Science: The Impact of Haptic Experiences on Attitudes and Concepts," Paper presented at the National Association of Research in Science Teaching Annual Meeting, Philadelphia, PA., March, 2003.

[8] Jones, M. G., Bokinsky, A., Tretter, T., Negishi, A., Kubasko, D., Superfine, R., Taylor, R. (2003). Atomic force microscopy with touch: Educational applications. *Science, technology and education of microscopy: An overview*, vol. II, (pp. 776-686). A. Mendez-Vilas, (Ed.). Madrid, Spain: Formatex.

[9] Klatzky, R., and Lederman, S., "Tactile roughness perception with a rigid link interposed between skin and surface," *Perception and Psychophysics*, 61, pp. 591-607, 1999.

[10] Klatzky, R., Lederman, S., and Matula, D. , "Haptic exploration in the presence of vision," *Journal of Experimental Psychology*, 19 (4), pp. 726-743, 1993.

[11] Lederman, S. "Tactile roughness perception: Spatial and temporal determinants," *Canadian Journal of Psychology*, 37, (4), pp. 498-511, 1983.

[12] Lederman, S., and Klatsky, R., "Haptic identification of common objects: Effects of constraining the manual exploration process," *Perception & Psychophysics*, 66(4), pp. 618-628, 2004.

[13] Locher, P. "Influence of vision on haptic encoding process," *Perceptual and Motor Skills*, 55, pp. 59-74, 1982.

[14] Loomis, J., Klatzky, R., and Lederman, S., "Similarity of tactile and visual picture recognition with limited field of view," *Perception*, 20, pp. 167-177, 1991.
[15] Newell, F.N., Ernst, M. O., Tjan, B. S., and Bülthoff, H. H., "Viewpoint Dependence in Visual and Haptic Object Recognition," *Psychological Science*, 12 (1), pp. 37-42, 2001.
[16] Misceo, G., Hershberger, W. and Mancini, R., "Haptic Estimates of Discordant Visual-Haptic Size Vary Developmentally," *Perception and Psychophysics*, 61, pp. 608-614, 1999.
[17] Sathian, K. and Zangladze, A., "Tactile learning is task specific but transfers between fingers," *Perception and Psychophysics*, 59, pp.119-128, 1997.
[18] Taylor II, R.M., Robinett, W., Chi, V.L., Frederic J., Brooks, P., Wright, W.V., Williams, R.S. and Snyder E.J. *The Nanomanipulator: A Virtual-Reality Interface for a Scanning Tunneling Microscope*. *SIGGRAPH 93*, Anaheim, California: ACM SIGGRAPH. pp. 127-134, 1993.
[19] Verry, R. "Don't Take Touch for Granted: An interview with Susan Lederman," *Teaching Psychology*, 25, pp. 64-67, 1998.

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