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Abstract

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Keywords

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EFFECTIVENESS OF HAPTIC SENSATION FOR THE EVALUATION OF VIRTUAL PROTOTYPES

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ABSTRACT

Virtual Reality techniques provide a unique new way to interact with three-dimensional digital objects. Virtual prototyping refers to the use of virtual reality to obtain evaluations of designs while they are still in digital form before physical prototypes are built. While the current state-of-the-art in virtual reality relies mainly on the use of stereo viewing and auditory feedback, commercial haptic devices have recently become available that can be integrated into the virtual environment to provide force feedback to the user. This paper outlines a study that was performed to determine whether the addition of force feedback to the virtual prototyping task improved the ability of the participants to make design decisions. The specific task involved comparing the location and movement of two virtual parking brakes located in the virtual cockpit of an automobile. The paper describes the purpose, methods and results of the study.

INTRODUCTION

Virtual reality (VR) devices enable users to experience virtual environments where interaction with three-dimensional digital models becomes similar to interaction with real objects. Because of this feature, VR devices are increasingly being used for virtual prototyping. This could potentially have a major impact on the efficiency of the engineering design process. Engineers, designers and customers can all use VR to evaluate designs before costly physical prototypes are built. This will facilitate design decision making early in the design process resulting in reduced product development costs.

While VR relies mainly on head tracked stereo viewing and audio feedback, there have been several impressive inventions and developments in the field of haptic computer devices and their integration with virtual environments in recent years which have fostered the use of force feedback in virtual environments. Haptic devices provide users with a sense of force that improves their sense of immersion in the virtual environment. This is believed to increase the user's ability to evaluate virtual models, designs and environments. Repperger, et al. (1995) explains that although the visual system capacity to process information is on the order of 10^6 bits per second whereas the fingertip can process information at only 10^2 bits per second, haptic senses still provide a very efficient method of information gathering for humans. Hasser and Massie (1999) assert that haptic devices can be effectively used in industry, science, medicine, education and entertainment to reduce training time, reduce errors and completion time, and increase the sense of immersion in virtual environments.

Several studies have evaluated the effect of haptic sensation on the interaction between humans and the surrounding world. Human haptic perception of real objects is distorted and affected by characteristic illusions (Hogan et al. 1990). People consistently misperceive the shape of real objects that they touch (Fasse et al. 1994). Lederman and Klatzky (1987) investigated the importance of haptic information in relation to shape recognition and evaluation of shape dimensions. Simple shapes could be quickly recognized by simple grasp, but dimension evaluation required a much longer time. This study focuses on the ability of a user to determine changes in position and orientation of a mechanism in the interior of a car, not necessarily the shape of an object.

In 1991, Hannaford et al. investigated the potential of force feedback for improving teleoperation performance. In the study, force feedback did not improve the accuracy and precision of the positioning task, but force feedback allowed the user to avoid placing damaging forces on the experiment object, which was not possible without the haptic device. The study also emphasized the necessity of multiple measures for performance.

We were also interested in whether people preferred the haptic interface. Klatzky, et al. (1993) addressed issues of how people select the option of haptic exploration. They found that haptic information was mostly desired when the object's material properties were questioned. People tend to rely on visual information when they need to encode the geometric properties of an object. Haptic exploration was invoked only when visual efforts were exhausted or to increase confidence about visually based decisions.

The goal of this study was to evaluate how a haptic device affects the ability of a person to make design decisions based on virtual prototypes. The study evaluated how the haptic device affected participant design evaluation time, accuracy and precision. The study also evaluated participants' preference for a haptic or nonhaptic treatment for the tasks presented. The specific task involved evaluation of position and range of motion of a virtual hand brake in a virtual automotive cockpit.

METHODS AND PROCEDURES

Two separate groups of participants performed similar mechanism design evaluation tasks under two different treatments. Both groups used the PHANToM™ device as an interface with the virtual geometry. One group performed the tasks with the force feedback activated (the haptic treatment group) and the other group performed the tasks with the force feedback turned off (the nonhaptic treatment group). This provided for the same physical interface to interacting with the virtual models and the only difference was the presence or absence of the force feedback to the user. The data from the two groups were analyzed in order to determine if haptic and nonhaptic treatments affected participants' performance.

Task Overview

Each participant went through a training session, four trials, and an alternative treatment experience. In each trial, a participant was asked to detect and estimate differences between two alternative designs of a parking brake mechanism (Figure 1). Each trial had a unique set of differences between the alternative mechanism designs in terms of location and motion. Table 1 shows the type of design differences that existed between the alternative designs of the parking brake for each trial. The first design in each trial was identified as the base design. Participants were asked to evaluate changes in the second design as compared to the base design.

Following four trials, participants were able to experience the other treatment to ascertain their preference for either the haptic or nonhaptic treatments. This exercise was not timed or recorded, but treated as an exploratory trial session with no specific task assignment.

Before the experiment began, participants filled out a survey form concerning general background information. During the study, participants completed a questionnaire form immediately after each trial. The researcher kept track of the amount of time that each participant required for a single design evaluation on a separate form.

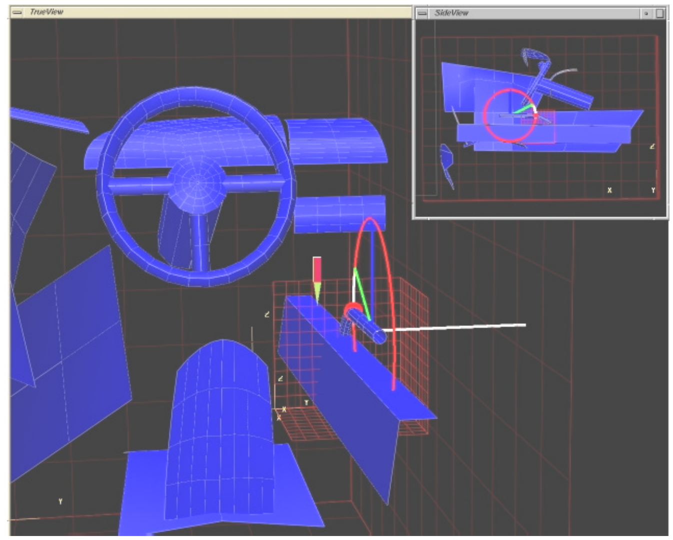

Figure 1: Virtual environment generated by software used for the study

Participants

Ninety-two students and employees of Iowa State University (ISU) volunteered to participate in the study. Data from 16 participants were disregarded due to incomplete reports or incomplete pilot study sessions. Therefore, study conclusions were based on a total of 76 surveys. There were 38 participants in each group. To ensure that each group had a similar representation of participants, groups were compared in terms of age representation, gender representation, quality of vision, level of education, experience with computers, and how comfortable a participant was with learning new applications. The ANOVA showed that each group had a similar representation of participants based on these criteria. The diversity in age amongst all participants ranged from 16 to 43 years old with an average age of 24.2 years (stdev = 5.3). Twenty-two percent of all participants were female and eighty percent of the participants were students.

Question	Trial 1 *Direction* *Value*	Trial 2 *Direction* *Value*	Trial 3 *Direction* *Value*	Trial 4 *Direction* *Value*
1) Left-right location	left -0.875	right 0.875	same 0	same 0
2) Up-down location	up 0.875	up 0.875	same 0	same 0
3) Forward-rearward location	rearward 0.875	forward -0.875	same 0	same 0
4) Arm length	same 0	same 0	longer 0.875	longer 0.875
5) Angle of motion	same 0	same 0	smaller -8.59	larger 8.59

Table 1: Design differences between the second and the first virtual mechanisms in each trial (linear values are in inches; angular values are in degrees)

Hardware and Software

This study was arranged in a computer laboratory in the Virtual Reality Applications Center at Iowa State University. A Silicon Graphics (SGI) Octane computer with two R10000 processors and 256 MB memory provided computational power for the study. Two SGI color display monitors model CM2187ME were used for mono visual display of the 3D virtual environment. One monitor was used by the study participants. The other monitor was used by the researcher to manage study trials. The head position of the participant was not tracked. The PHANToM™ (Model 1.5) three degree-of-freedom haptic device, which is a product of SensAble Technologies, was used to provide haptic feedback with the virtual environment. Participants sat in front of a monitor and used the PHANToM™ to investigate the virtual mechanism designs (Figure 2). In the nonhaptic trials the PHANToM™ controlled a virtual 3D cursor on the screen with no haptic feedback to the user. In the haptic trials, the PHANToM™ provided haptic feedback to the user whenever the virtual 3D cursor moved the parking brake.

The software used in the study was the proprietary product of the Ford Motor Company. The software allowed presentation of a simplified 3D car interior design and pre-defined interaction with digital images. CAD models of the car interior were initially loaded into the software. Different parts of the car interior design could be modified, relocated, and tested for motion functionality. The software and the haptic device allowed us to simulate the motion of a parking brake that was restricted to a defined path. While holding onto the PHANToM pen, the user moved the virtual cursor in the vicinity of the end of the parking brake. When the virtual cursor intersected with the end of the parking brake, the color of the end of the parking brake would change to indicate collision of the cursor and the digital parking brake. The user could then click and hold a button on the PHANToM input device to select the parking brake. As the user moved his/her hand, the visual display of the parking brake rotated around one end to simulate the motion of a real parking brake. The difference between the two treatments was in what each group felt as they moved the parking brake. Participants in the nonhaptic group could move their hand without restriction and as long as they moved "up", the visual display of the parking brake would rotate around its end. The haptic group was confined to moving their hand along the path that defined the rotation of the virtual hand brake because the motors of the PHANToM restricted their hand motion to a specific pre-defined path. This is the real key to the study. Without haptics, the physical motion is not restricted and therefore does not match the visual display. With haptics, the physical motion is restricted and therefore matches the visual display.

Figure 1 shows a picture of the computer screen that each participant saw during the study trials. The view of the main window simulated the point of view of a driver for each participant. The small window in the upper right corner of the screen showed a side view of the car interior design, which was provided to help the participant judge depth.

Figure 2: Computer display and haptic device arrangement used for the study

Data Collection

Four sets of data were collected during the experiment to address a variety of research questions.

The first set of data collected was the percentage of correctly detected differences between the two alternative mechanism designs. The information gathered allowed an evaluation of which treatment resulted in the greatest number of successful detection of differences between the alternative designs.

The second set of data collected concerned the precision of estimations for differences between alternative mechanism designs. If a participant detected a difference between alternative designs, then he/she was asked to estimate the amount of the detected difference. Later, the estimated values were compared with actual values and the error of each estimation was obtained. This information allowed evaluation of which treatment group had estimations that deviated least from the actual values.

The third set of data collected was the time that each participant required to evaluate a mechanism design. Participants were not restricted in the amount of time that they could spend for a design evaluation. This information allowed analysis of how alternative treatments affected the time required for design evaluation.

The fourth set of data collected evaluated the participants' treatment preference. After completion of the four trials, each participant was given the opportunity to try the alternative treatment. Participants were asked to record their treatment preference for performing a variety of design evaluation tasks. This information allowed evaluation of participants' preference for each treatment. These data explored the subjectivity of human preference.

RESULTS

The data were analyzed using ANOVA and F-tests. The data were defined to be significantly different if $p < 0.05$. The results are presented in the next four sections.

Percentage Correctly Detected Differences Between Two Alternative Mechanism Designs

No significant differences in the percentage correct answers were found between the two treatments in all groupings considered. The average percentage correct answers and the standard errors (SE) for the treatment groups are shown in Table 2.

Question combinations	Haptic group		Nonhaptic group		
	Average	*SE*	*Average*	*SE*	*p-value*
a) all questions	56.1	1.88	54.2	1.97	0.502
b) questions with length units	53.5	2.29	53.1	2.28	0.919
c) all questions about location	60.3	3.02	57.7	2.78	0.524
d) all questions about motion	49.7	2.51	49.1	2.42	0.851
e) four trials combined:					
• left-right location	65.8	4.15	55.3	3.54	0.058
• up-down location	53.3	4.53	62.5	4.29	0.144
• forward-rearward location	61.9	4.19	55.3	3.67	0.241
• arm length	32.9	3.54	39.5	3.48	0.189
• angle of motion	66.5	3.43	58.6	3.31	0.102

Table 2: Percentage correct answers for combination of questions

Accuracy and Precision of Estimations for Differences Between Alternative Designs

Accuracy refers to how close measured values are to the true value.

Table 3 shows that accuracy of the nonhaptic group was significantly better for estimation of location differences in the up direction (question 2, trial 1). Accuracy of the haptic group was significantly better for estimation of location differences in forward – rearward directions (question 3) using data from four trials combined. Other analyses did not show significant differences in accuracy between the treatments.

Precision is a reflection of the variance among the estimated data. Table 4 shows that out of 25 comparisons, the haptic group estimated values with more precision in nine cases, whereas the nonhaptic group showed more precision in only three cases.

Trial	Question	Haptic group *Average*	Haptic group *SE*	Nonhaptic group *Average*	Nonhaptic group *SE*	ANOVA *p-value*
1	1	0.684	0.134	0.564	0.258	0.6813
	2	-0.504	0.146	0.224	0.137	0.0005
	3	-0.346	0.219	-0.813	0.254	0.1682
	4	-0.099	0.322	0.001	0.213	0.7948
	5	-0.342	0.941	-0.473	1.571	0.9429
2	1	0.427	0.218	0.364	0.254	0.8531
	2	-0.162	0.169	0.102	0.168	0.8029
	3	0.146	0.161	-0.293	0.171	0.0643
	4	0.261	0.228	0.205	0.149	0.8378
	5	0.211	1.682	1.974	1.341	0.4151
3	1	0.001	0.076	0.204	0.152	0.2347
	2	0.101	0.168	-0.124	0.128	0.2899
	3	-0.225	0.136	-0.302	0.182	0.7352
	4	-0.594	0.209	-0.783	0.217	0.5332
	5	4.672	1.186	3.725	1.292	0.5906
4	1	0.138	0.067	0.076	0.126	0.6663
	2	-0.089	0.114	-0.114	0.226	0.9199
	3	0.053	0.154	-0.024	0.201	0.7614
	4	-0.003	0.226	-0.204	0.239	0.5434
	5	3.591	0.946	4.998	1.353	0.3968
Four trials combined:						
1) left-right location		0.312	0.072	0.302	0.103	0.9366
2) up-down location		-0.163	0.077	-0.029	0.085	0.2408
3) forward-rear-ward location		-0.093	0.086	-0.358	0.104	0.0498
4) arm length		-0.108	0.127	-0.195	0.107	0.6028
5) angle of motion		2.032	0.632	2.556	0.709	0.5824

Table 3: Estimation errors (Accuracy)

Trial	Question	Haptic group *Average*	Haptic group *SD*	Nonhaptic group *Average*	Nonhaptic group *SD*	F-Test *p-value*
1	1	0.684	0.829	0.564	1.591	0.00007
	2	-0.504	0.903	0.224	0.845	0.34485
	3	-0.346	1.349	-0.813	1.565	0.18579
	4	-0.099	1.986	0.001	1.311	0.00662
	5	-0.342	5.795	-0.473	9.686	0.00118
2	1	0.427	1.345	0.364	1.571	0.17599
	2	-0.162	1.042	0.102	1.037	0.49021
	3	0.146	0.994	-0.293	1.048	0.37287
	4	0.261	1.408	0.205	0.921	0.00566
	5	0.211	10.375	1.974	8.264	0.08562
3	1	0.001	0.474	0.204	0.938	0.00003
	2	0.101	1.036	-0.124	0.789	0.05061
	3	-0.225	0.838	-0.302	1.121	0.04041
	4	-0.594	1.293	-0.783	1.337	0.41953
	5	4.672	7.309	3.725	7.962	0.30264
4	1	0.138	0.414	0.076	0.777	0.00011
	2	-0.089	0.701	-0.114	1.393	0.00003
	3	0.053	0.951	-0.024	1.237	0.05652
	4	-0.003	1.394	-0.204	1.477	0.36321
	5	3.591	5.835	4.998	8.345	0.01618
Four trials combined:						
1) left-right location		0.312	0.883	0.302	1.274	0.00001
2) up-down location		-0.163	0.947	-0.029	1.043	0.11932
3) forward-rear-ward location		-0.093	1.059	-0.358	1.278	0.01068
4) arm length		-0.108	1.561	-0.195	1.318	0.01956
5) angle of motion		2.032	7.788	2.556	8.751	0.07674

Table 4: Estimation errors (Precision)

Time Required by Participants to Evaluate a Mechanism Design

Table 5 presents the time required for design evaluation for each treatment group. Figures 3 and 4 show the data distribution for the design evaluation times of each treatment group. The analyses showed that in all cases the design evaluation time of the haptic group was significantly less than the time required by the nonhaptic group.

		Haptic group		Nonhaptic group		
Trial	Design	*Average*	*SE*	*Average*	*SE*	*p-value*
1	1	41.9	2.399	76.1	6.151	0.00001
	2	37.8	2.593	65	6.415	0.00012
	combined	39.9	2.111	70	5.542	0.00001
2	1	32.2	2.553	50.1	3.621	0.00014
	2	32.7	2.515	49.6	5.113	0.00408
	combined	32.4	2.106	49.8	3.791	0.00015
3	1	32.8	3.288	42.1	2.448	0.02765
	2	30.6	3.192	44.5	4.182	0.00994
	combined	31.7	2.897	43.3	2.851	0.00573
4	1	29.7	2.881	40.5	3.341	0.01684
	2	32.1	2.295	47.3	3.862	0.00076
	combined	30.9	2.293	43.9	2.996	0.00093
Four trials	1	34.2	1.437	52.1	2.348	0.00001
	2	33.3	1.339	51.9	2.547	0.00001
	combined	33.7	1.211	52	2.156	0.00001

Table 5: Time required for design evaluation

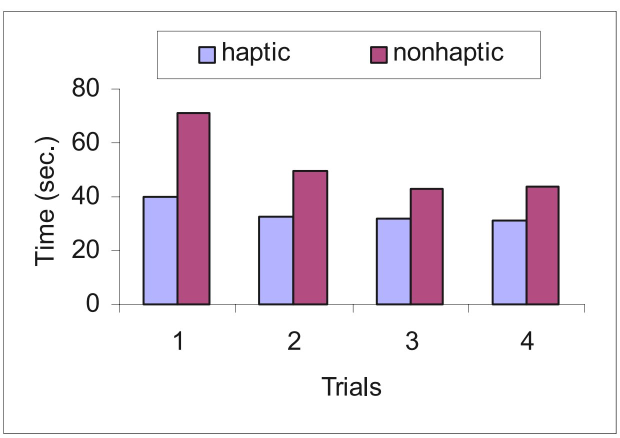

Figure 3: Average time required for design evaluation (sequence of four trials)

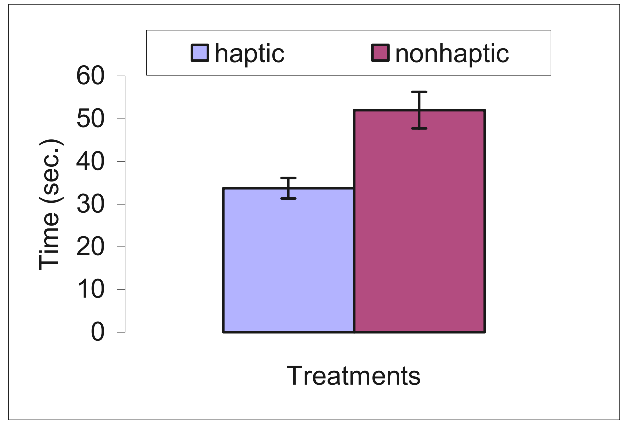

Figure 4: Average time required for design evaluation (four trials combined) (range bars indicate standard error)

Participants' Treatment Preference

Figures 5 and 6 show the distribution of the data related to the treatment preferences of all participants combined. The majority of the haptic group participants preferred the haptic treatment for design evaluation tasks. Also, the majority of the nonhaptic group preferred the haptic treatment as well.

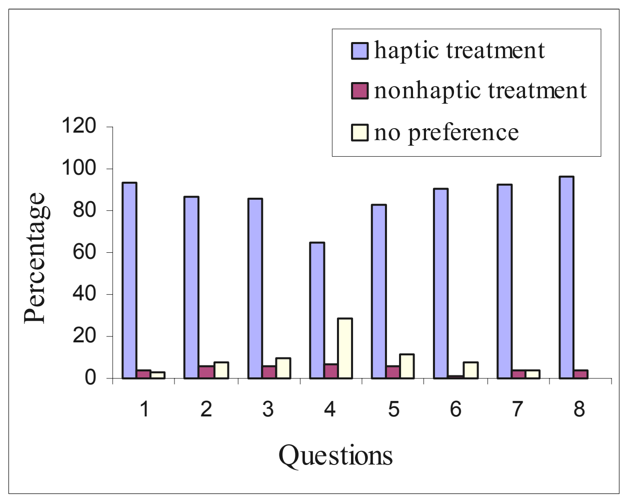

Figure 5: Response of all participants to the treatment preference questions

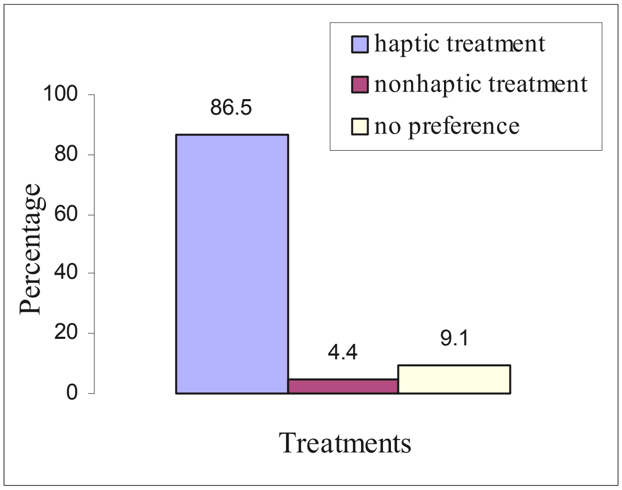

Figure 6: Combined participants' preference for each treatment

Effect of Learning

Data presented in Figure 3 suggest that there was an effect of learning amongst participants in both groups. However, the learning effect could not be evaluated in this experiment because each trial had a unique combination of differences between designs, and the sequence of trials was consistent for each participant. It is possible that some combinations of design differences were more challenging to distinguish and estimate than other combinations.

Future human factor studies could randomize the sequence of trials in order to counterbalance for learning so it would be possible to consider learning as a factor with other variables in a study.

DISCUSSION

The following discussion highlights observations that may have affected the variance in the data samples, which was critical in defining differences between alternative treatments.

Variation in participants

The time required to examine each mechanism was one of the variables investigated in the study. Each person progressed through the trials with a different pattern in how much time they required for design evaluation and these patterns did not depend on the treatment. There were four major types of participants in terms of time that they required for design evaluation.

The first type of participant started slow and required less time from trial to trial. The second type of participant required a very short amount of time in the first trials and was willing to spend more time during the last trials. The third type of participant had consistent time across all trials. The fourth type of participant had inconsistent time across all trials. The differences observed here highlight the need for this study to record data from a large number of participants in order to produce reliable results.

The participant group was weighted heavily by students and also by males. This could be a contributing factor to the overwhelming acceptance of the haptic interface. Male college students might be more acceptable of new technology than the general public. This should be taken into account in further studies.

Hand motion base

The variation in participant's responses related to detection and estimation of the linear and angular differences may be attributed to the study setup and the mechanics of the human body. When people write, they often rest their wrist on a desk. The wrist, in this case, is the base for the writing motion. Because of the short distance from the base to the final motion point of the hand and the simplicity of the human linkage mechanism (palm with solidly fixed fingers), a person can produce a very precise motion while writing.

In this study, the participant's chair was supposed to simulate a car seat without armrests. This prevented the participants from resting his/her hand on anything in the car interior. In the study, the base for the motion was established at the person's hipbone where he/she was connected with chair. There is a big difference between the wrist base for hand motion and the hipbone base for hand motion. The short distance and linkage simplicity of the wrist base was replaced in this study by the long distance of a person's hand and body, which made it even more complex by the joints in the elbow, shoulder, collarbone, and spine. This could account for some of the variance in the responses.

Many participants naturally attempted to simplify the linkage mechanism of their bodies and to shorten the distance between their hand motion base and the motion point. Some people attempted to push their hands towards their bodies, so that the elbow joint was firmly established next to the hipbone. Several other participants attempted to perform the simplification for their position of the hand motion base by moving their right leg to the side and resting their right hand on this leg. Some participants tried to stiffen their bodies and hands using muscles.

These attempts to simplify the task by improving the location of the hand motion base and simplifying the linkage of body mechanism were difficult to regulate or restrict because people claimed that these positions felt the most natural. The variety of locations for the base of motion could have affected the participant's performance and led to increased variation for both groups.

Magnitude of differences

The design of the study assumed that a person in a real situation (not computer generated) could detect differences in location as small as 0.875 inches and 8.59 º in the setting established for the study. It is unclear if 0.875 inch for linear values and 8.59 º for angular values were large enough for the setting. The fact that participants were asked to detect and estimate small challenging differences may have affected the variance in participants' estimations. It is possible that using larger linear and angular values for differences between virtual mechanisms could reduce variation in responses for one or both of the treatments.

However, very large differences could be so obvious that any treatment would not make any difference. A future study on haptic perception of linear and angular values under different treatments could be designed so that it would determine whether there is a range of values where a particular treatment makes a significant difference in a particular setup.

Combination of differences between designs

The large variance in participants' responses in both treatment groups could be attributed to participant difficulty in distinguishing multiple component differences. In evaluating the two designs, a participant could sense only the absolute distance between different locations of the virtual mechanisms and feel the difference in the arc of motion of each mechanism. There was an additional challenge for the participant to divide these absolute sensations about the differences in location into X, Y, Z components in order to answer the questionnaire. Also, it appeared that for many participants it was difficult to describe the difference between the two arcs of motion in terms of angle and radius simultaneously. This additional complexity could have affected the variance in participants' performance in both treatment groups.

Time required to switch between alternative designs

Several participants acknowledged that the switching time between alternative designs affected their performance. It could be one more factor that affected variance in both groups. Due to software design, the activation of a new mechanism design required closure of the previous file and opening of a new file, and establishing the appropriate position of the new virtual mechanism. The researcher was able to switch files very quickly (switching time varied somewhere between 10 ~ 15 seconds). However, sometimes this was long enough for participants to start doubting if they could remember the original design properties and whether they were ready to make a comparison.

It is likely that different people have slightly different abilities to remember mechanical and physical sensations. If a participant barely remembered the sensation about the original design and was asked to answer the questionnaire about differences between the two alternative designs, it is possible that he/she wrote down very rough guesses.

Head position tracking and stereo visualization

The visual display of the mechanism was provided for participants during the study to help them find the location of the virtual mechanism with the PHANToM™'s pen. The head position tracking was not provided for the participants, nor did they have a stereo display. The study was specifically designed without stereo viewing and head tracking in order to investigate how the PHANToM could be used in a desktop, non-immersive environment. The study setup and application were similar to the most common arrangements for haptic devices being investigated by industry and development companies today. Most of the applications that currently explore haptic device utilization assume the user is in a sitting position without any additional support for the operating hand. The visual display is assumed to be located in front of the user and the interface to the haptic device is a pen-like device. Thus, the general setup for the experiment was designed to correspond to the most common practices. The participants' confusion between the mechanical sensation of the virtual mechanism and the visual perception of the same virtual mechanism may have caused the increase in the variation in participants' responses in both groups.

The range of the mechanism's motion on the display may have appeared to a participant to be smaller than the actual range of motion provided by the PHANToM™ interface. It depended on the location of the virtual point of view and the location of the virtual mechanism that were established by the researcher and had nothing to do with the head position of the participant.

The head tracking would provide a person with a user centered point of view and additional visual information about the size and range of motion of the virtual mechanism to be evaluated. The 3D stereo sensation would help a person to clarify the location of the virtual mechanism in 3D, which is essential information if a person is asked to answer questions related to distances.

CONCLUSIONS

The results of this study were designed to evaluate how a haptic device affects the ability of a person to make design decisions based on virtual prototypes. Ninety-two people participated in the study and were asked to determine location and motion differences between pairs of parking brake designs presented in a virtual environment.

The major findings from this study are:

- The group that used the haptic treatment took significantly less time to evaluate the virtual prototypes than the group with the nonhaptic treatment.

- A significant majority of participants preferred the haptic interface for tasks related to design evaluation.
- There were no significant differences in the percentage correct answers found between the haptic and nonhaptic groups.

Other findings include:

- The nonhaptic group estimated differences in design changes in the up direction significantly better (more accurately) than the haptic group.
- The haptic group estimated differences in design changes in the forward – rearward direction significantly better (more accurately) than the nonhaptic group.
- In more cases there was a significantly smaller variance (better precision) in the estimations of the haptic group than the nonhaptic group.

The time measurements revealed the clearest difference between the two treatments. Data about time from all four trials, combined and separate, as well as data about the time required for individual design evaluations showed that participants using the haptic treatment required significantly less time for design evaluation than participants using the nonhaptic treatment. In addition, participants from the haptic group required significantly less time to produce similar or often more precise results than participants from the nonhaptic group.

Another distinct finding of the study was the comparison of participants' treatment preference. People responded to eight questions about design evaluation by selecting their preferred treatment. The result of the survey showed that a significant majority of participants preferred the haptic treatment.

The contrast between participants' preference for the use of a haptic device and their actual performance reflected in the percentage correct answers, accuracy of estimations, and precision of estimation, indicates that participants were willing to support the new technology even though, in many cases, their performance was not improved by the haptic treatment. This contrast between preference and performance, as well as side observations of the study, suggest that future investigation in the area of haptic sensation and virtual prototyping is needed.

RECOMMENDATIONS FOR FUTURE WORK

The results of this research defined several significant differences between haptic and nonhaptic treatments which lead to new areas for future investigation. Potential areas of future work include:

- Investigate the addition of head tracked stereo viewing to the virtual environment.
- Investigate the sensitivity ranges for various human arm joints (motion pivots) where haptic sensation may play significant role as an information source in evaluation of linear parameters of virtual geometry.
- Use a six degree of freedom haptic device in order to evaluate how the addition of restrictions in rotations around each axis affects acquisition of information about virtual geometry.
- Reduce or eliminate the time required to switch between alternative designs. If possible, both designs should be displayed, so participants can work with either design at any time.
- Randomize the sequence of trials to allow consideration of the learning effect.

Future studies should incorporate the findings of this research and further investigate the use of haptic devices for virtual prototype evaluations.

Overall, the study showed that haptic sensation is a natural feeling that is well liked by the users when it is integrated with computer applications. Even though the haptic group's percentage correct answers in detecting design differences, and accuracy in estimation of design differences was not better than the nonhaptic group's performance, the haptic group completed the tasks in significantly less time, and often with better precision.

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REFERENCES

Fasse, E. D., and Neville H. (1994). Quantitative Measurement of Haptic Perception *IEEE Transactions on Robotics and Automation*, Vol. 4, 3199 – 3204.

Hannaford, B., Wood, L., McAffee, D., and Zak, H. (1991) Performance Evaluation of a Six-axis Generalized Force-reflecting Tele-operator *IEEE Transactions on Systems, Man, and Cybernetics,* Vol. 21(3), 620-633.

Hasser, C. J., and Massie, T. H. (1999). The Haptic Illusion *in Digital Illusion, Entertaining the Future with High Technology,* edited by Dodsworth Jr., C., ACM Press, SIGGRAPH Series, New York, New York, 287 - 310.

Hogan N., Kay B. A., Fasse E. D. (1990). Haptic Illusions: Experiments on Human Manipulation and Perception of Virtual Objects *Gold Spring Harbor Symposia on Quantitative Biology*, Cold Spring Harbor Laboratory Press, Vol. LV, 925 – 931.

Klatzky, R. L., Lederman, S. J., and Matula, D. E. (1993). Haptic Exploration in the Presence of Vision *Journal of Experimental Psychology: Human Perception and Performance*, Vol. 19, No. 4, 726 – 743.

Lederman, S. J., and Klatzky, R. L. (1987). Hand Movements: a Window into Haptic Object Recognition *Cognitive Psychology*, No.19, 342 - 368.

Repperger, D. W., Phillips, C. A., and Chelette, T. L. (1995). A Study on Spatially Induced Virtual Force with an Information Theoretic Investigation of Human Performance *IEEE Transactions on Systems, Man, and Cybernetics,* Vol. 25(10), 1392-1404.

