Paper: Rb18-4-2617; 2006/5/22

A Study of Perceptual Performance in Haptic Virtual Environments

Marcia K. O'Malley, and Gina Upperman

Mechanical Engineering and Materials Science, Rice University
6100 Main Street, MEMS - MS 321, Houston, TX 77005-1892, USA
E-mail: omalleym@rice.edu

[Received January 9, 2006; accepted March 23, 2006]

The performance levels of human subjects in size identification and size discrimination experiments in both real and virtual environments are presented. The virtual environments are displayed with a PHANToM desktop three degree-of-freedom haptic interface. Results indicate that performance of the size identification and size discrimination tasks in the virtual environment is comparable to that in the real environment, implying that the haptic device does a good job of simulating reality for these tasks. Additionally, performance in the virtual environment was measured at below maximum machine performance levels for two machine parameters. The tabulated scores for the perception tasks in a sub-optimal virtual environment were found to be comparable to that in the real environment, supporting previous claims that haptic interface hardware may be able to convey, for these perceptual tasks, sufficient perceptual information to the user with relatively low levels of machine quality in terms of the following parameters: maximum endpoint force and maximum virtual surface stiffness. Results are comparable to those found for similar experiments conducted with other haptic interface hardware, further supporting this claim. Finally, it was found that varying maximum output force and virtual surface stiffness simultaneously does not have a compounding effect that significantly affects performance for size discrimination tasks.

Keywords: haptic interface, perception, virtual environments, performance

1. Introduction

The primary purpose of a haptic interface is to present an effective simulated mechanical environment to a human user. Though several published studies exist that compare the quality or effectiveness of various haptic simulation techniques relative to other simulation techniques, relatively few experimental comparisons exist that directly compares human performance in a haptically simulated environment relative to their performance in a real environment.

There is a vast amount of literature on human haptic recognition (identification) and discrimination of size in real environments. Several of these studies focus specifically on perception via a hand-held probe [1, 2]; however they do not address perceptual performance in simulated environments. Another body of literature presents studies that compare performance of tasks in simulated and real environments, including [3–7]. The studies by Buttolo et al., Richard et al., and Unger et al. all compare task completion times for both real and simulated tasks [4, 5]. The experiments of Buttolo et al. indicated that the completion times for the real and simulated tasks were nearly the same [3]. For a different set of experimental conditions, however, Richard et al. and Unger et al. reported significant increases in task completion times for the simulated versus the real tasks [4, 5]. Unlike these prior works, West and Cutkosky compared the ability of human subjects to identify spatial frequency in real and simulated sinusoidally varying textured surfaces [6]. Their experiments indicated that the ability of a human to identify spatial frequency was impaired in the simulated versus the real cases. Finally, Shimojo et al. performed comparisons in shape recognition between simulated and real objects for a pin-matrix type tactile display [7]. Their experiments also indicated that the ability of human subjects to identify shapes was impaired by the tactile interface.

This paper characterizes the ability of humans to identify and discriminate shape primitives simulated with a haptic interface as compared to their performance of the same identification and discrimination tasks for real shape primitives. Shape primitives are defined as simple three-dimensional shapes that can be combined to form more complex three-dimensional objects. In this case, square cross-section and semi-circular cross-section objects constitute the shape primitives. This study further investigates the performance of humans in identification and discrimination tasks in a virtual environment for the cases of limited force and stiffness output. Unlike prior work by the first author [8], this paper utilizes a commercial haptic interface (PHANToM Desktop) rather than a custom research-quality haptic device, to determine if results from the prior work are generalized across hardware platforms. In the paper describing experiments with a custom haptic device, results indicated that performance of size identification tasks with haptic interface hardware capa-

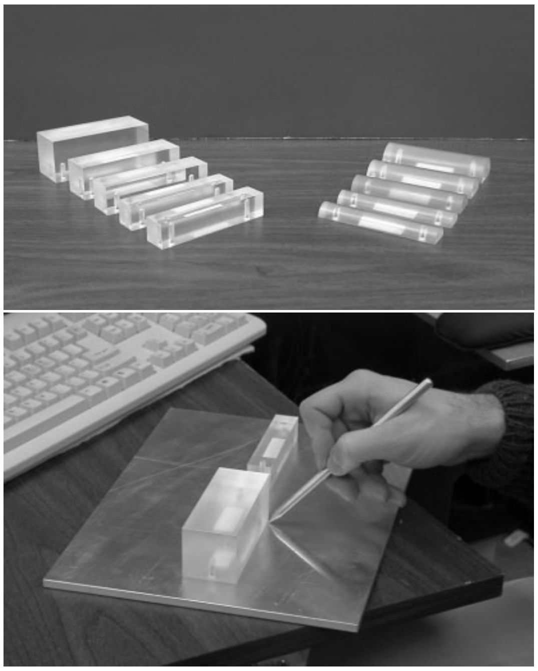


Fig. 1. Photograph of the real blocks and the environment for a square object size discrimination task.

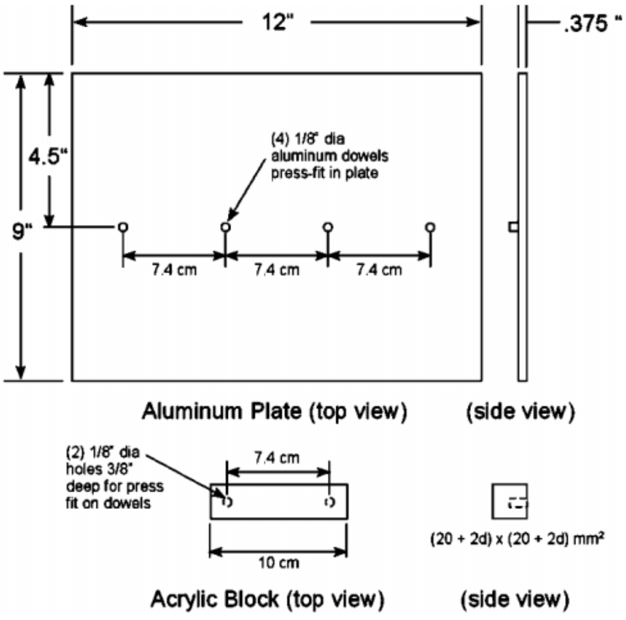


Fig. 2. Dimensions of aluminum plate, acrylic blocks used in real environment experiments.

Fig. 3. Test subject seated at testing station for simulated environment experiments with Sensable’s PHANToM Desktop. The haptic device and subject’s hand were shielded from view during actual experimental sessions.

ble of a minimum of 3N of maximum force output can approach performance in real environments, but falls short when virtual surface stiffness is limited. For size discrimination tasks, performance in simulated environments was consistently lower than performance in a comparable real environment. Interestingly, significant variations in the fidelity of the haptic simulation did not appear to significantly alter the ability of a subject to identify or discriminate between the types of simulated objects described herein. Here similar experiments are carried out with a commercial grade haptic device (PHANToM Desktop from Sensable Technologies), and potential compounding effects of limiting maximum force output and virtual surface stiffness are studied.

2. Methods

2.1. Perceptual Environments

The real environment used for the perception tests incorporated round and square cross-section shape primitives fabricated from acrylic, as shown in **Fig.1**. These objects were presented on an aluminum base plate, which was fitted with four dowels that were used to secure the shape primitives to the base plate. The dowels were arranged such that one block could be placed on the center of the base plate (as was the procedure for size identification experiments), or two blocks could be placed side by side for discrimination tasks. **Fig.2** indicates the dimensions of the aluminum plate and the nominal dimensions of one of the acrylic shape primitives. A smooth-tipped aluminum stylus with diameter of 5/16” and length of approximately 6” was fabricated to probe the shapes. The surfaces of all blocks were smooth to minimize friction (which was not modeled in the simulated environments). Contact paper on the surface of the blocks ensured that any machining irregularities could not be used as cues in the identification or discrimination tasks. Audio cues that arose during the experiments were masked by the sound of fans for the haptic device’s motor amplifiers.

The simulated environment was constructed to emulate the experimental setup shown in **Fig.1**. As such, the simulation included a “base plate,” along with variable sized round and square cross-section shape primitives of the same dimensions shown in **Fig.2**. The simulations were performed with a three degree-of-freedom point-contact force-reflecting haptic interface shown in **Fig.3**, with a

Table 1. Experiment details – Factors and levels for all experiments.

<table>
<tr><th rowspan="2">Experiment</th><th rowspan="2">No.</th><th colspan="4">Experiment Factors</th></tr>
<tr><th>Shape primitive</th><th>Size Difference (mm)</th><th colspan="2">Environment type</th></tr>
<tr><td rowspan="4">Size Identification</td><td rowspan="4">1A</td><td rowspan="4">Square</td><td rowspan="4">1.25, 2.5 and 5</td><td colspan="2">Real</td></tr>
<tr><td colspan="2">High fidelity simulated</td></tr>
<tr><td colspan="2">Low fidelity simulated (force)</td></tr>
<tr><td colspan="2">Low fidelity simulated (stiffness)</td></tr>
<tr><td rowspan="4">Size Identification</td><td rowspan="4">1B</td><td rowspan="4">Round</td><td rowspan="4">1.25, 2.5 and 5</td><td colspan="2">Real</td></tr>
<tr><td colspan="2">High fidelity simulated</td></tr>
<tr><td colspan="2">Low fidelity simulated (force)</td></tr>
<tr><td colspan="2">Low fidelity simulated (stiffness)</td></tr>
<tr><td rowspan="4">Size Discrimination</td><td rowspan="4">2A</td><td rowspan="4">Square</td><td rowspan="4">1.25, 2.5 and 5</td><td colspan="2">Real</td></tr>
<tr><td colspan="2">High fidelity simulated</td></tr>
<tr><td colspan="2">Low fidelity simulated (force)</td></tr>
<tr><td colspan="2">Low fidelity simulated (stiffness)</td></tr>
<tr><td rowspan="4">Size Discrimination</td><td rowspan="4">2B</td><td rowspan="4">Round</td><td rowspan="4">1.25, 2.5 and 5</td><td colspan="2">Real</td></tr>
<tr><td colspan="2">High fidelity simulated</td></tr>
<tr><td colspan="2">Low fidelity simulated (force)</td></tr>
<tr><td colspan="2">Low fidelity simulated (stiffness)</td></tr>
<tr><td rowspan="5">Size Discrimination</td><td rowspan="5">3</td><td rowspan="5">Square</td><td rowspan="5">2.5, 5, and 10</td><th>Force values</th><th>Stiffness values</th></tr>
<tr><td>1 N</td><td>100 N/m</td></tr>
<tr><td>2.2 N</td><td>220 N/m</td></tr>
<tr><td>4.6 N</td><td>460 N/m</td></tr>
<tr><td>10 N</td><td>1000 N/m</td></tr>
</table>

Note: Object sizes correspond to half of object edge length for square cross-section shape primitives and to object radius for round cross-section shape primitives.

stylus diameter of approximately 1/2”.

In order to test the real and simulated environments under what were considered like circumstances, the real environment interactions were constrained via a probe, rather than allowing the subjects to use a more natural configuration of the hand. Recent findings of Lederman and Klatzky [9] show that constrained manipulation involves a loss of information transfer to the subject by eliminating spatially distributed information and relaying it in a sequential manner. This ultimately results in significantly lower performance in tasks performed with a probe as compared to those with the real hand. Based on these findings, the subjects were constrained to interact with both the real and simulated environments via a probe.

It is expected that performance in the real environment will not differ much from that in the high or low fidelity simulated environments rendered with the PHANToM Desktop, as was seen with the custom haptic device employed in [8]. This hypothesis is based on prior work that showed limited improvements in task performance in the virtual environments for forces and stiffnesses greater than 3N and 470N/m respectively. Further, it is hypothesized that force has less of an effect on performance than stiffness, since relatively low values of force were sufficient whereas higher values of stiffness (relative to the achievable limit of the device) were necessary to reach the same level of performance. Finally, it is expected that simultaneously limiting force and virtual surface stiffness should not compound performance degradation, since limited force output does not significantly hamper performance.

2.2. Experimental Design and Procedures

Size identification and size discrimination experiments were performed in both real and simulated environments. For Experiments 1 and 2 (identification or discrimination), the within-subjects factors were the size difference between objects, for which there were three levels (1.25mm, 2.5mm and 5mm), the object shape (two levels: square and round), and the environment type (four levels: real, high fidelity simulated, low fidelity simulated (force), and low fidelity simulated (stiffness)). For Experiment 3 (discrimination with varying force and stiffness), the within-subjects factors were the size difference between objects, for which there were three levels (2.5mm, 5mm, and 10mm), the maximum output force for which there were four levels (1N, 2.2N, 4.6N, and 10N) and the virtual surface stiffness, for which there were four levels (100N/m, 220N/m, 460N/m, and 1000N/m). A total of ten subjects performed experiments in each of the simulated environments and in the real environment. The factors and levels are summarized in **Table 1**.

2.2.1. Size Identification

Size identification tasks determine the ability of a test subject to classify similarly shaped objects, presented one at a time, by size alone. The identification of square cross-section shape primitives (Experiment 1A) and semicircular cross-section shape primitives (Experiment 1B) were

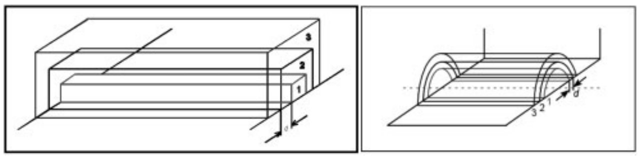


Fig. 4. Representation of square (left, Experiment 1A) and round (right, Experiment 1B) cross-section objects in three rendered sizes showing object size difference, *d*.

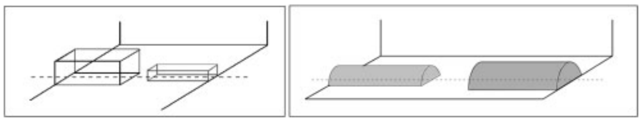


Fig. 5. Model of the simulated environment for the square and round object size discrimination task.

conducted separately using three sizes for each size difference set, as described by **Fig.4** and **Table 1**. The radius of the smallest shape primitive was always 1cm. The medium and large sizes were generated by adding a value *d*, the size difference (1.25mm, 2.5mm or 5mm), to this radius. Note that for square shape primitives, the “radius” corresponds to half the edge length.

2.2.2. Size Discrimination

Size discrimination experiments test the ability of a human subject to notice size differences between objects placed side by side. The discrimination of square cross-section shape primitives (Experiment 2A) and semi-circular cross-section shape primitives (Experiment 2B) were conducted separately using three size differences (1.25mm, 2.5mm and 5mm) for each shape primitive, as described by **Fig.5** and **Table 1**. The discrimination of square cross-section shape primitives (Experiment 3) was conducted to determine compounding effects of limiting both maximum force output and virtual surface stiffness.

2.3. Quality of Haptic Simulation

In order to vary the fidelity of the virtual environments, two machine parameters were selected to describe haptic interface machine performance, namely maximum force output and virtual surface stiffness. Force output correlates to torque output limits of motors, and increased torque output requirements are typically proportional to motor cost and size. When time delays are present in a system, the virtual surface stiffness can be decreased to maintain stability. These two quantifiable machine parameters are easily understood by designers and are typical measures of system quality.

During experimentation, the maximum output force and the virtual surface stiffness were varied in the achievable range for the PHANToM Desktop device. For Experiments 1 and 2, the high fidelity performance capability of the haptic interface corresponds to a maximum continuous endpoint force of 10N, and a maximum simulated surface stiffness of 1000N/m. Since the PHANToM Desktop is not capable of outputting a continuous force greater than 10N, the 10N trials correspond to the highest achievable force output of the PHANToM haptic device. For Experiments 1 and 2, the two lower fidelity performance conditions correspond to limiting the maximum continuous endpoint force to 4N and limiting the maximum simulated surface stiffness to 450N/m, respectively. The damping coefficients used for the high and low fidelity stiffnesses were 100Ns/m and 45Ns/m, respectively. For Experiment 3, the output command force was saturated at four different values: 1, 2.2, 4.6, and 10N, which were chosen because they give an approximately logarithmic distribution across the achievable range. The stiffness was varied by setting virtual surface stiffness (k) to one of four values: 100, 220, 460, and 1000N/m, which again gives an approximate logarithmic distribution across the achievable range of stiffness.

The saturation was accomplished by creating new classes in GhostSDK, the software application through which the PHANToM is programmed. These classes, called WeakCube and WeakCylinder, take the maximum output force as an input and are based upon the GstCube and GstCylinder classes in GhostSDK. To vary the stiffness of the virtual surfaces, functions within GhostSDK allowed the user to set the desired stiffness and damping ratios. The ratio of damping to stiffness was maintained at 0.1, as this was found by the authors to give good virtual wall properties.

The values of maximum endpoint force and maximum virtual surface stiffness were chosen based on previous findings of the first author. Prior work has characterized the effect of maximum force output and varying virtual surface stiffness on the ability of human subjects to perform perceptual tasks including size identification and size discrimination in a simulated environment [10, 11]. For the force output experiments, results showed that 3 to 4N of maximum force feedback to the user was sufficient to achieve good performance in the perception tasks, while the hardware was capable of up to 10N of continuous force feedback. Higher levels of force feedback did not produce better human performance in the tasks. In the virtual surface stiffness experiments, test results indicated that performance, measured as a percent correct score in the perception experiments, improves in a nonlinear fashion as the maximum level of virtual surface stiffness in the simulation increases. Further, test subjects appeared to reach a limit in their perception capabilities at maximum stiffness levels of 470N/m, while the hardware was capable of 1000N/m of maximum virtual surface stiffness. These results indicate that haptic interface hardware may be able to convey sufficient perceptual information to the user with relatively low levels of maximum force output and virtual surface stiffness.

Performance of these perceptual tasks in simulated and real environments was directly compared and presented in [8]. Results indicated that performance of size identification tasks with haptic interface hardware capable of a minimum of 3N of maximum force output approached performance in real environments, but fell short when virtual surface stiffness is limited. For size discrimination tasks, performance in simulated environments was consistently lower than performance in a comparable real environment. Interestingly, significant variations in the fidelity of the haptic simulation did not appear to significantly alter the ability of a subject to identify or discriminate between the types of simulated objects described herein. Here similar experiments (Experiments 1 and 2) are carried out with a commercial grade haptic device (PHANToM Desktop from Sensable Technologies), and potential compounding effects of limiting maximum force output and virtual surface stiffness are studied for a size discrimination task (Experiment 3).

2.4. Experimental Protocol

2.4.1. Experiment 1: Size Identification

Objects were placed, one at a time, in front of the subject. Each subject was asked to identify, via haptic interaction with the stylus-type probe, whether the object was the small, medium, or large object. The subject's view of their hand and the environments both simulated and real, were shielded from view by a curtain. A single test session consisted of one size difference, one shape primitive, and one of the four environments. A training session prior to each test session was used to familiarize the subjects with the three sizes of objects they would be classifying, and provided the subjects with correct-answer feedback. Each subject completed two test sessions. During the testing, subjects were presented each of the three sizes 15 times in a random order, for a total of 45 stimuli. Ten subjects separately completed the experiment in the real and virtual environments. Within a given environment, the order of testing was randomized in terms of fidelity.

2.4.2. Experiment 2: Size Discrimination

For each shape primitive (square or round cross-section), two objects were placed side by side in front of each subject. Each subject was asked to determine, via haptic interaction with the stylus-type probe, which of the two objects was larger. The subject's view of their hand and the environments, both simulated and real, were shielded from view by a curtain. A single test session consisted of all size differences, one shape primitive, and one of the four environments. A training session was allowed prior to each test session that mimicked the actual experiment, yet gave feedback after each user response. Training sessions occurred in the same environment type that was to be tested, and subjects were allowed to determine the amount of training they underwent prior to each test session. Twenty trials of each stimulus pair were presented for each test, for a total of 80 trials per test session. Ten subjects were tested in each of the simulated environments and in the real environment.

2.4.3. Experiment 3: Compounding Effects

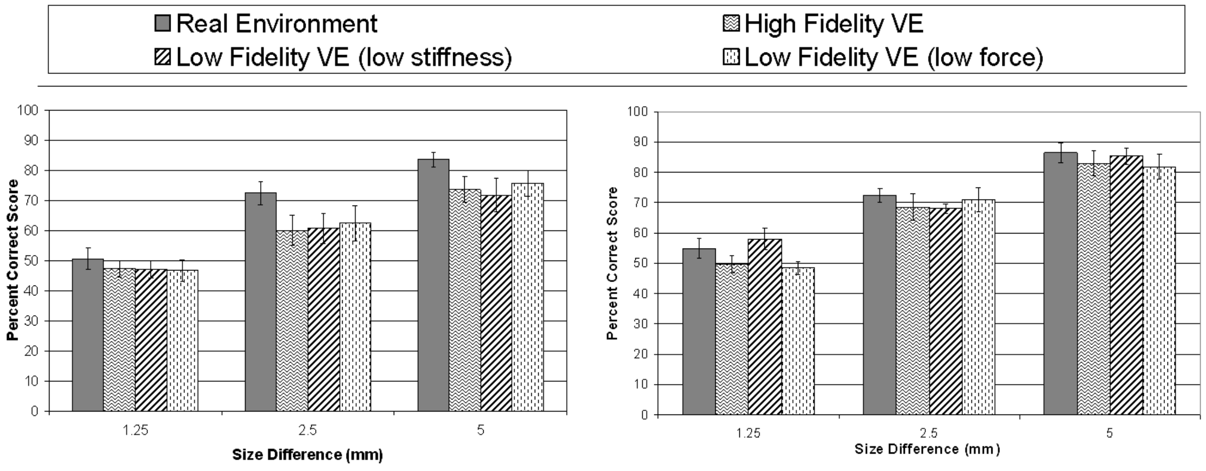
Ten test subjects were used for the compounding effects size discrimination experiment with square cross-section shape primitives. In each experiment, the subject was asked to feel the surfaces of the two virtual objects and determine which was larger, entering their response on the keyboard ('1' if the left object is larger and '3' if the right objects is larger). Three size differences were tested: 2.5, 5, and 10mm. The size difference refers to the difference in edge length between the two ridges placed side-by-side: one of the two ridges was always the base size, with an edge length of 20mm, and the second ridge had an edge length of 22.5, 25, or 30mm. The edge length corresponds to the height and width of the ridge; all of the ridges were 100mm in length. The location of the base-size ridge, either left or right, was chosen randomly for each trial. In each environment, 15 repetitions of the stimulus pair for each size difference were presented to the subject, for a total of 45 trials per combination of force and stiffness. In all, subjects sat for one practice session and then sixteen test sessions of 45 trials.

3. Results

Table 1 reviews the factors and levels that were implemented in the experiments. The dependent variable for all test sessions was the mean accuracy achieved by a subject for a given experiment-shape-size-environment combination. Size identification and size discrimination results were analyzed separately for statistical significance. For each experiment, size difference, shape primitive, and environment type are within-subjects factors.

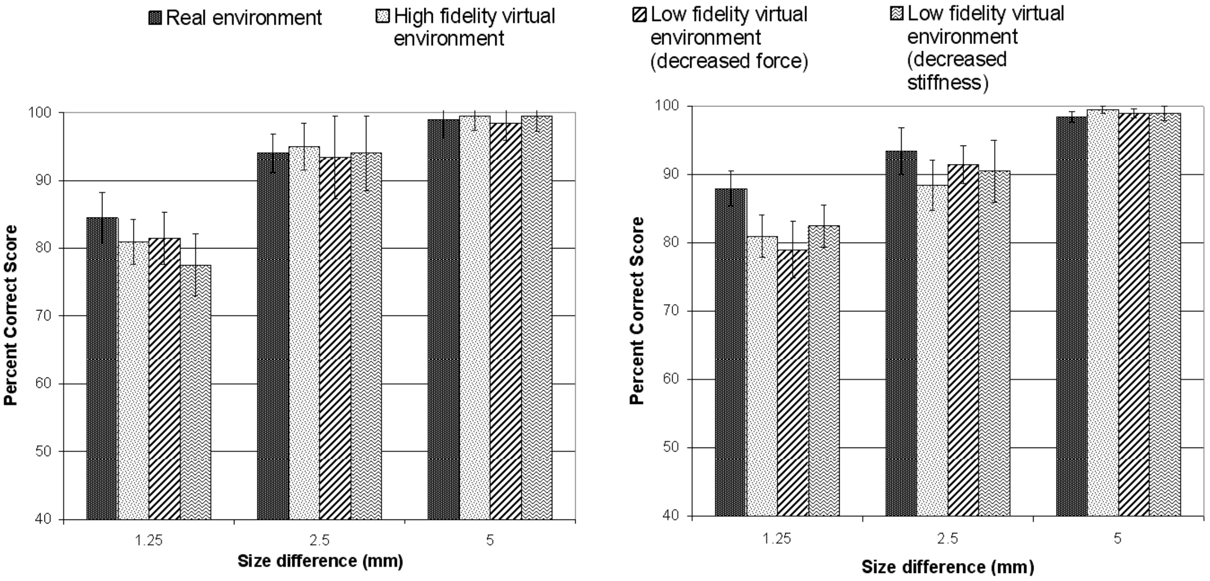
3.1. Experiment 1 – Size Identification

Figure 6 shows averaged results across subjects for Experiments 1A and 1B for the four environment cases (real, simulated high fidelity, simulated limited stiffness, and simulated limited force). Standard errors are shown with error bars. As seen in the figures, the size identification for the maximum quality simulation falls within ten percent of the real environment, followed closely by the limited force and stiffness cases. The differences between the real and simulated environments are significant at the alpha=0.05 level according to a 4-factor analysis of variance (ANOVA) and Tukey Studentized Range test for response, and could be due to the varying levels of performance of the small set of subjects (10) tested in the real environment or differences in audio and friction cues in the real environment as compared to the simulated environment. As such, for this particular task, although it appears that the simulation approximates fairly well the real environment, maximum force and stiffness play important roles in the effectiveness of the simulation. The differences between the high and low fidelity simulated environments were not significant at the alpha=0.05 level according to the Tukey Studentized Range test, further strengthening the conclusions of prior work by our group.



(a) (b)

Fig. 6. (a) Results for all size identification experiments with square cross-section ridges (1A), (b) Results for all size identification experiments with round cross-section ridges (1B).



(a) (b)

Fig. 7. (a) Results for all size discrimination experiments with square cross-section ridges (2A), (b) Results for all size discrimination experiments with round cross-section ridges (2B).

All other effects (size, shape, and subject) were significant at the alpha=0.05 level, as would be expected.

3.2. Experiment 2 – Size Discrimination

Figure 7 shows averaged results across subjects for Experiments 2A and 2B for the four environment cases (real, simulated high fidelity, simulated limited stiffness, and simulated limited force). Standard errors are shown with error bars. As seen in the figure, the size discrimination for the simulated environments approaches that of the real environment more than was seen in the size identification experiments. Differences in performance between the real and simulated environments were not significant at the alpha=0.05 level, and differences between the high and low quality virtual environments were also not statistically significant. The effect of shape was not significant, however the size and subject effects were significant at the alpha=0.05 level.

3.3. Experiment 3 – Compounding Effects

Results for Experiment 3 are presented in **Fig.8**. Each graph shows the percent correct scores (the average results across all test subjects), broken down by size difference and stiffness, for one value of force. Standard errors are

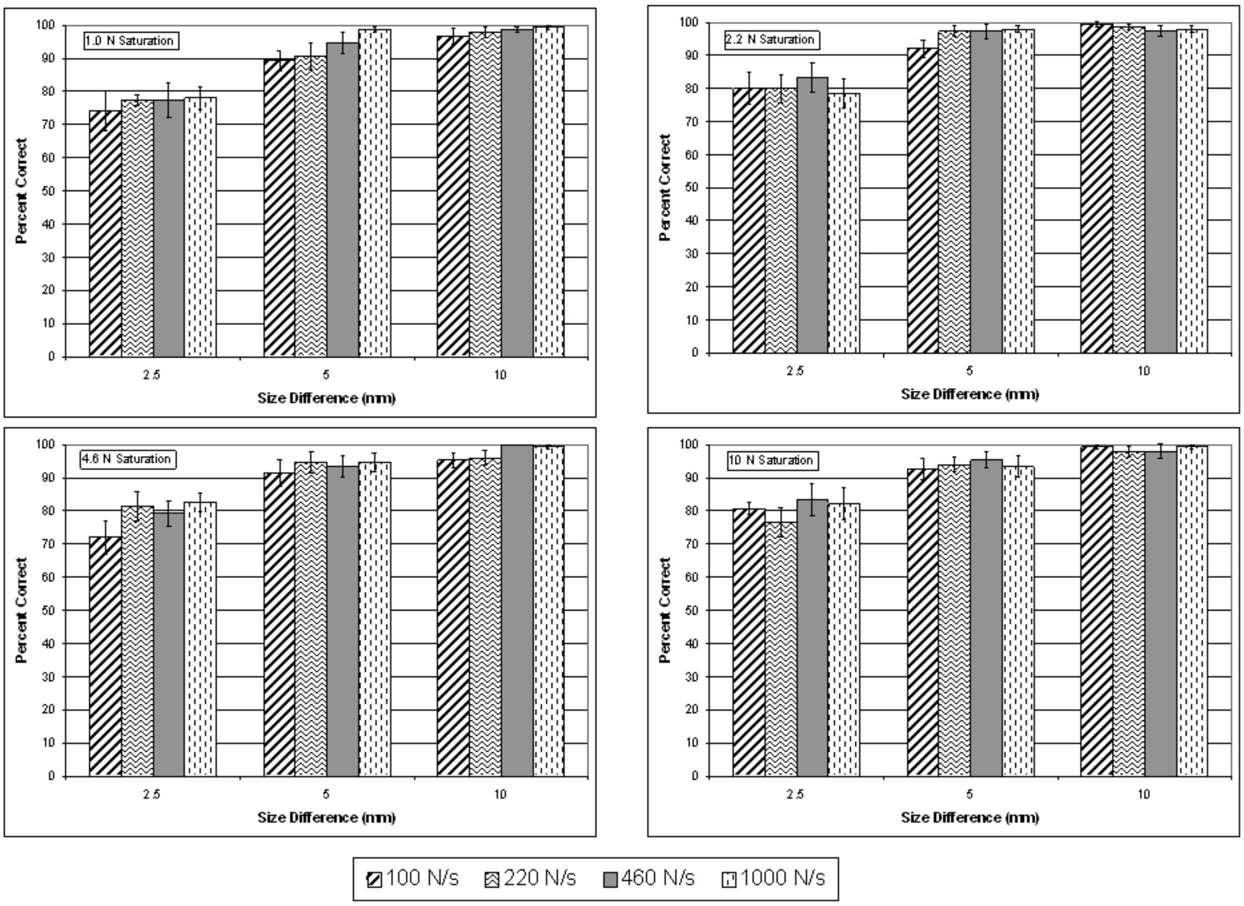


Fig. 8. Results for size discrimination experiments for all force saturation values tested: 1N (upper left), 2.2N (upper right), 4.6N (lower left), 10N (lower right).

shown with error bars.

The differences in performance for varying force were significant [$F(3,17) = 2.39$, $P = 0.0681$]. Further investigation of the pair wise comparisons shows that only comparisons of performance at 1N and 2.2N of maximum force feedback were significant at the 90% confidence level. This leads to the conclusion that the maximum force feedback has little effect on performance of the size discrimination task, although it recommended that 2.2N be used as a rough approximation of the minimum force needed for good performance, since the level of performance at 1N was significantly different than that at 2.2N.

Varying stiffness resulted in significant variations in performance [$F(3, 17) = 5.03$, $P = 0.0019$]. Upon investigation of the pair wise combinations, only 100N/m versus 460N/m and 100N/m versus 1000N/m were significant with 95% confidence. When comparing performance in environments with maximum virtual surface stiffness of 100N/m and 220N/m, significant differences were not noted. However, when comparing 100N/m to higher levels of virtual surface stiffness, performance is significantly improved. This leads to the conclusion that stiffnesses in virtual environments should be at least 220N/m and possibly above 460N/m to assure good performance of such size discrimination tasks. Further investigation is necessary to determine the minimum recommended level of virtual surface stiffness for this task.

It is interesting to note that simultaneously varying stiffness and maximum force output does not have a compounding effect on performance. The recommended minimum levels of force and stiffness from this experiment are comparable to those recommended levels from prior work by the first author [10, 11]. It was hypothesized that such compounded degradation of the environment fidelity should not have a detrimental effect on performance since force saturation does not adversely affect performance, and this was validated by the experiment.

As a final note, varying size and subject were found to be significant according to the Tukey Studentized Range test [$F(2, 15) = 194.88$, $P < .0001$ and $F(9, 15) = 10.38$, $P < .0001$, respectively].

For comparison to human haptic size discrimination ability in natural environments, Durlach et al. found that the just noticeable difference in length measured in discrimination experiments was roughly 1mm for reference lengths of 10 to 20mm [21]. This correlates to results from prior work by the first author [10, 11] and the results presented here. Size differences of 1.25mm were tested in prior work, but performance was no better than guessing. Indeed, the same phenomenon is realized in these experiments.

4. Discussion

When comparing virtual environments, performance is not significantly affected by fidelity, as long as some minimal level is met. Low fidelity levels for this work are based on previous work by the first author. Once maximum force output reached 4N, and once the virtual surface stiffness reached 450N/m, significant improvements in performance were not seen.

The findings of the experiments presented in this paper, in which performance in a real environment was compared to performance in a simulated environment for two perception tasks, indicate that the PHANToM Desktop haptic interface can approach the real environments described here for the size discrimination task, but falls short for the size identification experiments. It is possible that, since the discrimination task is inherently less difficult than the size identification task, the fidelity of the environment is less of a factor when determining the level of user performance. In both experiments, significant variations in the fidelity of the haptic simulation do not appear to significantly alter the ability of a subject to identify or discriminate between the types of simulated objects described herein.

It is important to note that these experiments did not consider the perceived quality or fidelity of the environment. Subjects were not asked if they preferred real over high fidelity or high fidelity over low fidelity. The primary goal was to determine if fidelity affected their performance in the size identification and discrimination tasks. Anecdotally, subjects noted that they could tell a difference between the environments, as would be expected. While they may have preferred interacting in the higher fidelity environments, this preference did not correlate with improved performance. The conclusion then is that, if constraints such as cost limit the available resources when designing and fabricating haptic devices, as long as some lower limit of fidelity is achieved, performance, in terms of these perceptual tasks, is not significantly affected.

5. Conclusions

Experiments 1 and 2 compare human perceptual performance in a real environment to performance in a simulated environment for two perception tasks, size identification and size discrimination. Findings indicate that performance of size identification tasks with commercial haptic interface hardware with reasonable maximum force output can approach performance in real environments, but falls short when virtual surface stiffness is limited. For size discrimination tasks, performance in simulated environments was consistently lower than performance in a comparable real environment. Interestingly, significant variations in the fidelity of the haptic simulation do not appear to significantly alter the ability of a subject to identify or discriminate between the types of simulated objects described herein.

To insure good performance of size identification tasks, designers of haptic interfaces should

- First, aim to create simulated environments with high virtual surface stiffness.
- Treat maximum force output of the haptic device as a secondary design goal, since limited force output had an insignificant effect on performance when compared to performance in a real environment.

For size discrimination tasks, designers of haptic devices should

- Aim to reach recommended minimum levels of maximum force output and virtual surface stiffness (4N and 450N/m, respectively) to insure acceptable performance.
- Note that this performance will never reach the level that can be attained in a comparable real environment.

In Experiment 3, size discrimination tests were performed to characterize the effect of simultaneously lowering the maximum endpoint force and the maximum virtual surface stiffness on the ability to perform a simple perceptual task, size discrimination. For haptic simulation in a stylus-type interface, the following relationships were observed:

- Varying maximum output force and virtual surface stiffness simultaneously does not have a compounding effect that significantly affects performance.
- Varying maximum output force had no significant effect on performance of the size discrimination task.
- Varying virtual surface stiffness between 220N/m and 1000N/m did not significantly affect performance of the size discrimination task.

These observations indicate that commercial haptic interface hardware such as the PHANToM may be capable of conveying significant perceptual information to the user at fairly low levels of stiffness and force feedback. While higher levels of stiffness force output in a haptic simulation may improve the simulation in terms of perceived realism, the results of these experiments indicate that high levels are not required to reach maximum performance for the size discrimination task in virtual environments.

Acknowledgements

Many thanks go to Scott Baggett of the Statistical Consulting Lab at Rice for his assistance with the statistical analysis of results. The authors also wish to thank the perception test volunteers for their participation. Finally, thanks to Susan Lederman for her suggestions and comments for improving this paper.

References:

[1] T. C. Chan, and M.T. Turvey, "Perceiving the vertical distances of surfaces by means of a hand-held probe," J. Exp. Psychol. Hum. Percept. Perform., Vol.17, No.2, pp. 347-358, May, 1991.

[2] D. Barac-Cikoja, and M. T. Turvey, "Does perceived size depend on perceived distance? An argument from extended haptic perception," Percept. Psychophys., Vol.57, No.2, pp. 216-224, Feb., 1995.

[3] P. Buttolo, D. Kung, and B. Hannaford, "Manipulation in Real, Simulated, and Remote Environments," Intelligent Systems for the 21st Century. Systems, Man, and Cybernetics, Vol.5, pp. 4656-4661, 1995.

[4] P. Richard, Ph. Coiffet, A. Kheddar, and R. England, "Human Performance Evaluation of Two Handle Haptic Devices in a Dextrous Virtual Telemanipulation Task," Proceedings of the IEEE International Conference on Intelligent Robots and Systems, pp. 1543-1548, 1999.

[5] B. J. Unger, A. Nicolaidis, P. J. Berkelman, A. Thompson, R. L. Klatzky, and R. L. Hollis, "Comparison of 3-D Haptic Peg-in-Hole Tasks in Real and Virtual Environments," IEEE International Conference on Intelligent Robots and Systems, Vol.3, pp. 1751-1756, 2001.

[6] A. M. West, and M. R. Cutkosky, "Detection of Real and Virtual Fine Surface Features with a Haptic Interface and Stylus," Proceedings of the ASME IMECE, DSC-Vol.61, pp. 159-166, 1997.

[7] M. Shimojo, M. Shinohara, and Y. Fukui, "Human Shape Recognition Performance for 3D Tactile Display," Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, Vol.4, pp. 3192-3197, 1997.

[8] M. O'Malley, and M. Goldfarb, "On the Ability of Humans to Haptically Identify and Discriminate Real and Simulated Objects," Presence: Teleoperators and Virtual Environments, Vol.14, No.3, pp. 366-376, 2005.

[9] S. L. Lederman, and R. L. Klatzky, "Haptic identification of common objects: Effects of constraining the manual exploration process," Perception and Psychophysics, Vol.66, No.4, pp. 618-628, 2004.

[10] M. K. O'Malley, and M. Goldfarb, "The effect of force saturation on the haptic perception of detail," IEEE/ASME Transactions on Mechatronics, Vol.7, No.3, pp. 280-288, 2002.

[11] M. O'Malley, and M. Goldfarb, "The Effect of Virtual Surface Stiffness on the Haptic Perception of Detail," IEEE/ASME Transactions on Mechatronics, Vol.9, No.2, pp. 448-454, 2004.

Name:
Marcia K. O'Malley

Affiliation:
Mechanical Engineering and Materials Science, Rice University, Houston, Texas

Address:
6100 Main Street, MEMS MS 321, Houston, TX 77005, USA

Brief Biographical History:
2001- Assistant Professor, Mechanical Engineering, Rice University
2005- Assistant Professor, Computer Science, Rice University
2005- Adjunct Assistant Professor, Physical Medicine and Rehabilitation, Baylor College of Medicine

Main Works:

- A. Gupta, and M. O'Malley, "Design of a Haptic Arm Exoskeleton for Training and Rehabilitation," ASME/IEEE Transactions Mechatronics (to appear, accepted 10/05).
- M. K. O'Malley, A. Gupta, M. Gen, and Y. Li, "Shared Control in Haptic Systems for Performance Enhancement and Training," ASME Journal of Dynamic Systems, Measurement and Control (JDSMC) Special Issue on Novel Robotics and Control, Vol.128, No.1, pp. 75-85, March, 2006.
- M. O'Malley, and M. Goldfarb, "On the Ability of Humans to Haptically Identify and Discriminate Real and Simulated Objects," Presence: Teleoperators and Virtual Environments, Vol.14, No.3, pp. 366-376, June, 2005.
- M. O'Malley, and M. Goldfarb, "The Effect of Virtual Surface Stiffness on the Haptic Perception of Detail," IEEE/ASME Transactions on Mechatronics, Vol.9, No.2, pp. 448-454, June, 2004.
- M. O'Malley, and R. Ambrose, "Haptic Feedback Applications for Robonaut," Industrial Robot: An International Journal, Vol.30, No.6, pp. 531-542, November, 2003.
- M. O'Malley, and M. Goldfarb, "The Effect of Force Saturation on the Haptic Perception of Detail," IEEE/ASME Transactions on Mechatronics, Vol.7, No.3, pp. 280-288, September, 2002.

Membership in Learned Societies:

- American Society of Mechanical Engineers
- Institute of Electrical and Electronics Engineers

Name:
Gina Upperman

Affiliation:
Student, Rice University, Houston, Texas

Address:
6100 Main Street, Houston, TX 77005, USA

Brief Biographical History:
2002- Student, Electrical Engineering, Rice University

Main Works:

- G. Upperman, A. Suzuki, and M. O'Malley, "Comparison of Human Haptic Size Discrimination Performance in Simulated Environments with Varying Levels of Force and Stiffness," 12th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Chicago, IL, March 27-28, 2004.

Membership in Learned Societies:

- Institute of Electrical and Electronics Engineers