Comparison of human haptic size identification and discrimination performance in real and simulated environments

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Marcia Kilchenman O'Malley
Rice University

Comparison of Human Haptic Size Identification and Discrimination Performance in Real and Simulated Environments

Marcia Kilchenman O'Malley
Mechanical Engineering and Materials Science
Rice University
omalleym@rice.edu

Michael Goldfarb
Mechanical Engineering
Vanderbilt University
goldfarb@vuse.vanderbilt.edu

Abstract

The performance levels of human subjects in size identification and discrimination experiments in both real and virtual environments are presented. The virtual environments are displayed with a three degree-of-freedom haptic interface, developed at Vanderbilt University. Results indicate that performance of the size identification and 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 three 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 [1] 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, system bandwidth, and time delay.

1 Introduction

This paper presents a comparison of human haptic performance in real and virtual environments. Results support the case that haptic interfaces are good at simulating real objects, and indicate that they can do so without excessive machine performance demands for the tasks described here. Comparisons of performance in real and virtual environments have been made in the past. Typically these comparisons are made with the virtual environment display operating such that the best achievable representation of reality is presented to the user. For example, completion times for a pick and place task performed in a real-world control environment and in three virtual conditions were presented by Richard et al. [2]. Their findings showed that for the pick and place task, completion times, a measure of task performance, were lower for the real-world control environment than for each of the three virtual environments tested. However, accuracy for depth and lateral placement were comparable for one haptic display and the real-world control. Similarly, Buttolo et al. [3] used comparative methods to study the differences in performance of simple manipulation tasks with real objects, with a virtual reality simulation containing force feedback, and remotely with a master and slave system, also with force feedback. Their findings also showed that performance with the virtual environment was similar to that with real objects. This paper takes a similar comparative approach to verify the quality of a haptic device in simulating realistic virtual environments for simple perceptual tasks. These tasks included a size identification task, where users are asked to classify objects by size when presented one at a time, and a size discrimination tasks, where subjects determine which of two objects placed side by side is larger. Additionally, the quality of the haptic device, in terms of three parameters, is degraded and another performance comparison is made.

2 Methods

Size identification and size discrimination experiments were performed in both real and virtual environments. In the following sections the haptic interface, used to display the virtual environment, will be introduced. Then the real and virtual testing environments will be described. Additionally, the experimental procedures will be outlined.

2.1 Virtual Environment Apparatus

A three degree-of-freedom manipulator, shown in Figure 1, was designed to exhibit minimal rotational inertia, minimal friction forces, zero backlash, and maximum link stiffness [4], which are physical characteristics generally known to facilitate high fidelity haptic simulations [5]. The manipulator is a point-contact force-reflecting device that senses the three-dimensional motion of the stylus endpoint and displays a three-dimensional force vector corresponding to the rendered haptic environment.

All simulations ran at a sampling frequency of 3000 Hz. System bandwidth is approximately 100 Hz, limited by first-order low pass filters placed on each of the motor torque command signals. This particular apparatus is capable of displaying constant forces of over 10 N in the spatial region of the haptically displayed ridges, and peak forces of roughly 40 N.

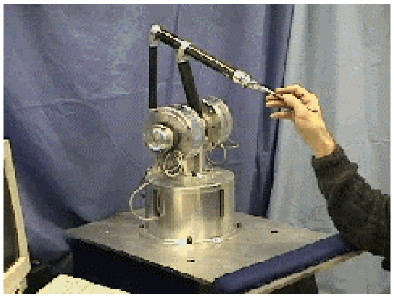

Figure 1. Test subject seated at testing station for virtual environment experiments.

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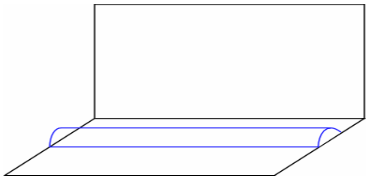

Figure 2. Round ridge in virtual environment.

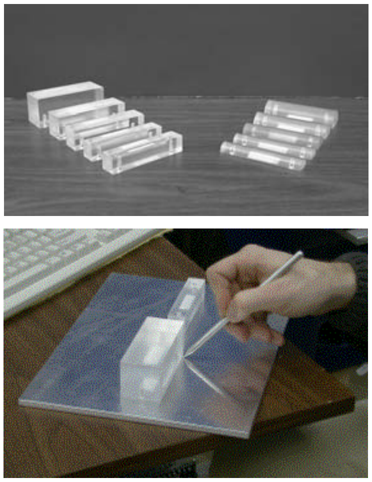

Figure 3. Photograph of the real blocks and the environment for a square ridge size identification task (Experiment 1A).

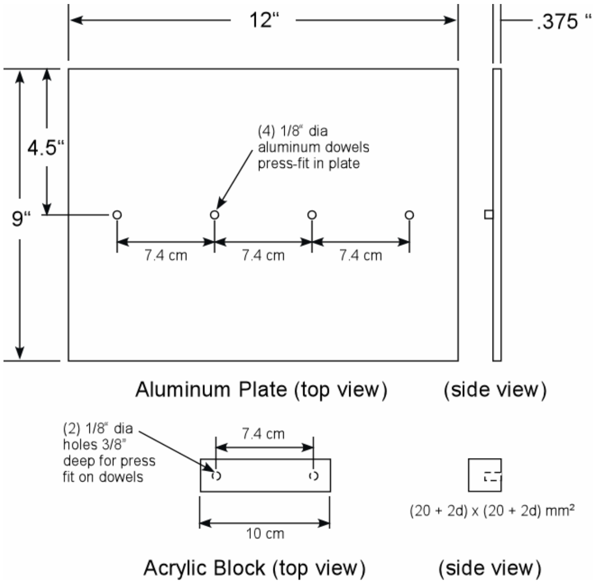

Figure 4. Dimensions of aluminum plate and acrylic blocks used in real environment experiments.

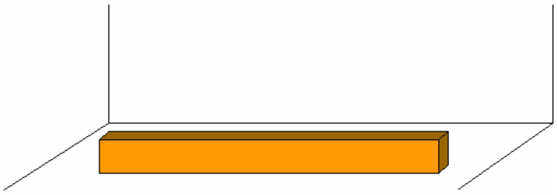

Figure 5. Square cross-section ridge in virtual environment.

2.2 Testing Environments

2.2.1 Virtual Environment

The virtual environment consisted of a floor and an enclosed workspace approximately the size of a soccer ball. On the floor, blocks (ridges) were displayed either one at a time for size identification experiments or side by side for size discrimination experiments. In each experiment, the stimuli extended to both the left and right limits of the workspace. When two stimuli were displayed side by side, a gap of 2 cm existed between them. Figure 2 shows a round cross-section ridge in the virtual environment.

2.2.2 Real Environment

Blocks were constructed out of acrylic and a base plate and stylus were machined from aluminum to create a real block environment that matched the simulated environments used in the perception experiments. The base plate was fitted with four dowels that fit inside blocks of square and round cross-sections. 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. Figure 3 shows a photograph of the real block environment for one experiment. Figure 4 shows a basic sketch of the aluminum plate and acrylic blocks. The surfaces of all blocks were smooth.

2.3 Experimental Paradigms

Perception experiments were conducted for ridges of square and hemicylindrical cross-sections, since both shapes can be characterized with a single parameter, namely the diameter (or radius) for the rounded ridges and the edge length for square ridges. These two shapes were chosen because of the similarities in their cross-sectional area for ridges of the same base width. Additionally, any differences between sharp-edged and smooth features would presumably appear in test results. These basic geometries can be easily combined to form more complex geometries. A round cross-section ridge is shown in Figure 2, and a square cross-section ridge is shown in Figure 5.

For interactions with the virtual environment, each subject sat in front of the haptic interface with the dominant hand holding the stylus and the non-dominant hand typing responses on a keyboard. There were no measures taken to obstruct the subject's views of the haptic interface during testing. Subjects reported that the tasks relied heavily on their sense of touch and little on their sense of sight, despite the ability to see the motion of their hands. Procedures for the virtual environment experiments are described in detail in [1]. For the real-world experiments, subjects were instructed to close their eyes and turn their heads so that visual cues were not a factor in the real environment experiments.

2.4 Subjects

Six test subjects were used for each virtual environment experiment. Because of the time involved in virtual environment experiments (several hours total per subject), the subject sets varied for each machine parameter and perception task being studied. A cross-section of subject types (gender, dominant handedness, and experience with haptic devices) was chosen for each of these experiments. A subset of three subjects from each group was used for each real environment experience so that their

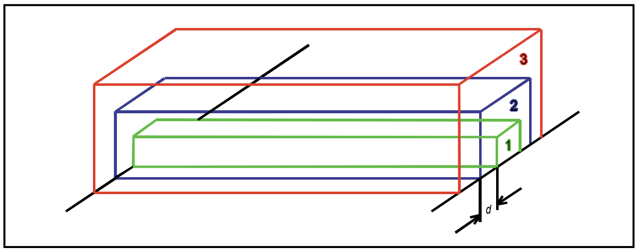

Figure 6. Representation of square cross-section ridges in three rendered sizes showing ridge size difference, *d*

Table 1. Ridge sizes (mm) for each test session.

Session Number	Small (1)	Medium (2)	Large (3)	Difference in Ridge Size (mm) -- *d*
1	10.00	12.50	15.00	2.50
2	10.00	15.00	20.00	5.00

Note: Ridge sizes correspond to half of ridge edge length for square cross-section stimuli and to ridge radius for round cross-section stimuli.

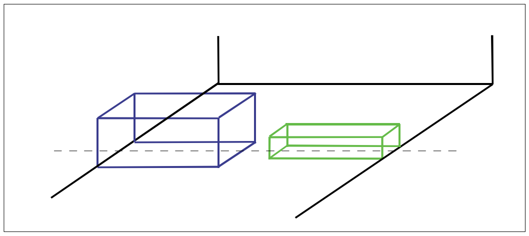

Figure 7. 3-D model of the simulated environment for the square ridge size discrimination task (Experiment 2A).

performance could be directly compared. Again, the number of subjects was limited due to the length of experiments. Additionally, several subjects that participated in the virtual environment experiments were not available to be tested in the real environment.

2.5 Procedures

Size identification and size discrimination experiments were performed in both real-world and virtual environments. During the virtual environment experiments, three machine parameters were varied individually in order to determine the effect of each parameter on human performance of the perception tasks. In one set of experiments, maximum endpoint force was varied between 0.5 N and 10 N by saturating the output command force prior to sending the command signal to the actuators. In a second set of experiments, system bandwidth was varied between 5 Hz and 100 Hz by applying a digital filter with varying cut-off frequency to the output force commands. The final set of experiments with the haptic interface studied performance for varying maximum surface stiffness in the range of 50 N/m to 1000 N/m. Stiffness experiments were utilized to indirectly characterize time delay effects, as subsequently described. The upper limits of each machine parameter test range were limited by the hardware used in experimentation.

After completion of the virtual environment experiments, a real model of the test environment was constructed and a subset of test subjects performed the same size identification and discrimination tasks in the real environment. Their percent correct scores were tallied and compared to their scores from the virtual environment experiments. It was hypothesized that scores in the real environment should be comparable to scores in a high quality virtual environment (machine parameters at maximum achievable levels for this hardware).

2.5.2 Experiment 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 objects in this case were acrylic blocks in a real environment, or synthetic ridges, or blocks, displayed on a virtual floor. Both square (Experiment 1A) and semicircular (Experiment 1B) cross-section ridges were used in testing. Three sizes of ridges were used in each experiment, and subjects were asked to classify a ridge by its corresponding number. Figure 6 illustrates the three sizes for square cross-section ridges. A training session prior to testing was used to familiarize the subjects with the three sizes of ridges they would be classifying. During virtual environment testing, subjects were presented with 45 virtual stimuli (15 of each size) for each level of machine parameter being tested. For example, when maximum force output was varied, six settings of maximum force output levels were used and 15 trials of each size-force combination were presented. The stimuli sizes for the size identification testing sessions are shown in Table 1. In each session, subjects were presented with 45 times the number of machine parameter levels trials per session. From one session to the next, the size difference between stimuli was varied. In the real environment, 45 trials were presented to each subject for each size difference.

2.5.2 Experiment 2 – Size Discrimination

The second perception experiment was size discrimination. These discrimination experiments test the ability of a human subject to notice size differences between objects placed side by side. For this set of tests, square and round ridges were presented in separate groups, Experiments 2A and 2B, respectively. For either test, ridges were displayed side-by-side along a common centerline in the workspace, as shown in Figure 7. The gap between ridges in the real environment was 4.8 cm, chosen so that the same aluminum plate could be used for either identification or discrimination tests. The gap between the ridges in the virtual environment was 2 cm, so that haptic distortion was avoided towards the right and left extents of the virtual workspace. The subject was asked to feel the exterior of the two ridges and determine which was larger, entering a response of ‘l’ for left, ‘r’ for right, or ‘n’ for neither ridge. One of the two ridges was always the base size, with an edge length of 20 mm. The second ridge had an edge length of 20, 25, 30, or 40 mm. Again, a training session was allowed prior to each test session that mimicked the actual experiment, yet gave feedback after each user response. Test subjects were allowed to determine the amount of training they underwent. In the virtual environment experiments, fourteen trials of each stimulus pair were presented for each level of the machine parameter being varied. Similarly, in the real environment, fourteen trials of each stimulus pair were presented to the subject.

2.5.3 Machine Parameters

Three machine parameters were selected to describe haptic interface machine performance, namely maximum force output, system bandwidth, and time delay. Force output correlates to torque output limits of motors, and increased torque output requirements are typically proportional to motor cost and size. System bandwidth in a sense defines the speed of response of a given electromechanical system, and increased bandwidth implies increased cost. Time delays are unfavorable in a real-time system, and reduction of time delay usually requires faster computing speed and higher quality electronics, each coupled to an increase in price. These three quantifiable machine parameters are easily understood by designers and are typical measures of system quality. During experimentation in the virtual environment, these machine parameters were varied and performance was measured

The motors on this manipulator are capable of 10 N continuous force output and 40 N peak force output in the region of the ridges that are simulated. To control force output of the manipulator as a variable machine parameter, a saturation was imposed on the command force in the simulation code. For each iteration of the program loop, the force outputs that the user should feel corresponding to the environment are calculated. Saturation values were selected so that the entire range of achievable force output levels for this hardware were tested.

System bandwidth was the second machine parameter selected for investigation in this work. This parameter corresponds to the speed of response of the electromechanical system. High bandwidth is typically favorable, but at an increased cost. In order to vary system bandwidth real-time with the haptic interface, a bilinear approximation of a low-pass filter was designed. The bilinear approximation is derived with the following equations:

$$\omega_n = 2\pi f_c \tag{1}$$

$$G(s) = \frac{\omega_n^{\,2}}{s^2 + 2\zeta\omega_n s + \omega_n^{\,2}} \tag{2}$$

$$\frac{2}{T}\left(\frac{z-1}{z+1}\right) \rightarrow s \tag{3}$$

Varying the cut-off frequency of the filter, which is applied to the force output commands just before they are sent to the motor amps, varies system bandwidth. Cut-off frequencies are varied in the range of achievable system bandwidths for this system, between 5 and 100 Hz. Filters on the output command signals limited the range of cut-off frequencies used in simulations to below 100 Hz.

When time delays are present in a haptic interface system, the designer can decrease the virtual wall stiffness, in effect the gain of the system, to assure stability. In order to avoid the unpleasant situation of a user interacting with an unstable haptic interface, time delay was examined indirectly. Wall stiffnesses were varied in the range achievable by this haptic interface hardware (50 N/m to 1000 N/m). The ratio of wall damping to wall stiffness was maintained at a constant value of 0.1.

3 Results

3.1 Results: Experiment 1 – Size Identification

Size identification tasks were conducted in both the real block environment and a virtual environment. Eleven subjects performed the experiments in a virtual environment with square cross-section stimuli and thirteen subjects performed experiments with round cross-section stimuli. A subset of six subjects was tested for each machine parameter that was varied. Three subjects performed the experiments in a real environment for each shape of ridge and percent correct scores were recorded. Two values of *d*, the ridge size difference, were tested (2.5 and 5 mm).

3.1.1 Experiment 1A – Virtual Environment Results

Eleven subjects participated in the size identification experiments with square cross-section ridges in a virtual environment. Subsets of six subjects from this pool of eleven performed the experiments while a single machine parameter was varied in the achievable range for this hardware. For each machine parameter that was varied, the maximum value of that parameter was considered to be a high-quality simulation, while lower values corresponded to lower grades of simulation quality. In terms of the first machine parameter, maximum force output, the range 0.5 N to 10 N was tested. Results indicated that performance improvements (in terms of a percent correct score) were not significant for maximum endpoint forces above 3 N. For the experiments in which system bandwidth was varied (between 5 Hz and 100 Hz), significant improvements in performance were not achieved for levels greater than 40 Hz. Finally, for the experiments in which maximum virtual surface stiffness was varied between 50 N/m and 1000 N/m, significant performance gains were not noticed for the size identification task for stiffnesses greater than 470 N/m. Details of these experimental results can be found in [1, 6]. These results indicate that haptic interface hardware may be capable of conveying significant perceptual information to the user at fairly low levels of force feedback, system bandwidth, and virtual surface stiffness for this stylus-based size identification task.

3.1.2 Experiment 1A – Real Environment Results

Three subjects performed Experiment 1A in the real block environment in order to provide a basis for comparison between real-environment size identification performance and human haptic size identification performance in a high-quality haptic environment, described in the previous section. Subject A had comparable performance for both size differences regardless of whether the task was performed in a real or simulated environment. The most notable differences occurred at *d* = 5 mm, where performance in the simulated environment was slightly better than that in the real environment. Subject B showed slightly better performance in the simulated environment for *d* = 2.5 mm, but slightly poorer performance in the same environments as compared to the real environment at *d* = 5 mm. Finally, Subject C performed at a much higher level for both size differences in the real environment.

Figure 8 shows average results across subjects for Experiment 1A with real and simulated blocks. The first two columns show the average scores of the three subjects who performed the size identification task with square ridges in a real environment compared to the average results of the same three subjects for Experiment 1A at the maximum setting for each machine parameter tested. Virtual environment results for only those subjects that also performed the experiments in the real environment are shown for the purpose of direct comparison and ANOVA calculations. Average scores for the machine parameter tests are also shown individually (i.e., averages of the subjects' percent correct scores for maximum force output at 10 N, system bandwidth at 100 Hz, and virtual surface stiffness at 1000 N/m). Standard errors are shown with error bars. All ANOVA results are included in Table 2 at the end of this paper.

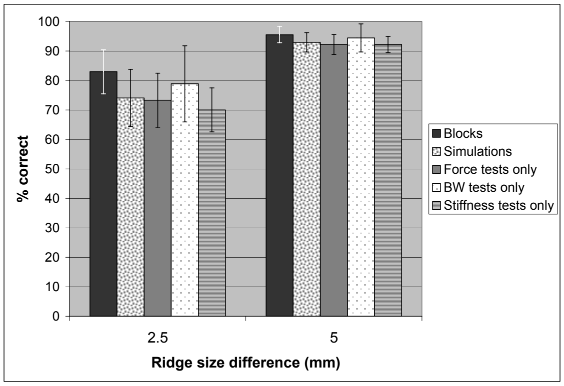

Figure 8. Percent correct scores for Experiment 1A with real blocks compared to simulated blocks (average results for all subjects)

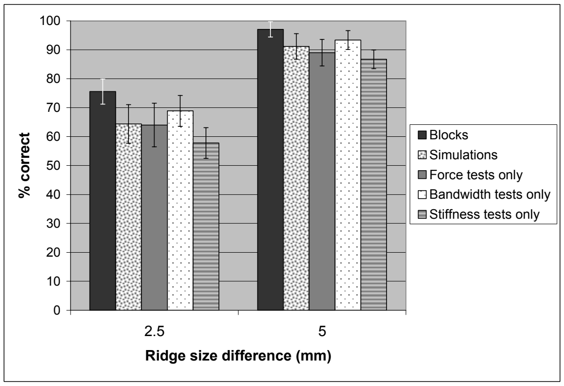

Figure 9. Percent correct scores for Experiment 1B with real blocks compared to simulated blocks (average results for all subjects)

3.1.3 Experiment 1B – Virtual Environment Results

Thirteen subjects participated in the size identification experiments with round cross-section ridges in a virtual environment. Subsets of six subjects from this pool of thirteen performed the experiments while a single machine parameter was varied in the achievable range for this hardware. Percent correct scores were recorded for a high-quality simulation (maximum value of each parameter that was varied) and for lower levels of each machine parameter, relating to lower-quality haptic simulations. In terms of the first machine parameter, maximum force output, the range of 0.5 N to 10 N was tested. Results indicated that performance improvements (in terms of a percent correct score) were not significant for maximum endpoint forces above 3 N. For the experiments in which system bandwidth was varied (between 5 Hz and 100 Hz), significant improvements in performance were not achieved for levels greater than 40 Hz, however an analysis of variance of the data could not verify that variations in scores were attributable to varying system bandwidth. Finally, for the experiments in which maximum virtual surface stiffness was varied between 50 N/m and 1000 N/m, significant performance gains were not noticed for the size identification task for stiffnesses greater than 470 N/m. These results indicate that haptic interface hardware may be capable of conveying significant perceptual information to the user at fairly low levels of force feedback and virtual surface stiffness for this stylus-based size identification task, while the effects of lower levels of system bandwidth are unclear from these experiments.

3.1.4 Experiment 1B – Real Environment Results

Three subjects performed Experiment 1B in the real block environment in order to provide a basis for comparison between real-environment size identification performance and human haptic size identification performance. Subject D had comparable performance for *d* = 5 mm size differences regardless of whether the task was performed in a real or simulated environment. However, performance in the real environment was higher for *d* = 2.5 mm. Subject E showed somewhat better performance in the real environments for both size differences. This was also seen in the results for size identification experiments by Subject F.

Figure 9 shows average results across subjects for Experiment 1B with real and simulated ridges. The first two columns show the average scores of the three subjects who performed the size identification task with round ridges in a real environment compared to the average results of the same subjects for Experiment 1B at the maximum setting for each machine parameter tested. Average scores for the machine parameter tests are also shown individually.

3.2 Experiment 2 – Size Discrimination

Size discrimination tasks were also conducted in the real block environment and the virtual environment. Fifteen subjects performed experiments in virtual environments with square cross-section ridges and thirteen subjects performed experiments with round cross-section ridges. A subset of six subjects was tested for each of the three machine parameters and stimulus shapes. For the real block experiments, three subjects for each ridge shape were tested and percent correct scores were recorded. Scores for the virtual and real block size identification experiment for square (2A) and round (2B) ridges are presented in this section. For the experiments, each subject was presented with 56 trials for each machine parameter level. The discrimination tests contained 14 presentations of each discrimination size (0 mm, 2.5 mm, 5 mm and 10 mm), and square and round ridges were tested separately.

3.2.1 Experiment 2A – Virtual Environment Results

Fifteen subjects participated in the size discrimination experiments with square cross-section ridges in a virtual environment. Subsets of six subjects from this pool of fifteen performed the experiments while a single machine parameter was varied in the achievable range for this hardware. Percent correct scores were recorded for a high-quality simulation (maximum value of each parameter that was varied) and for lower levels of each machine parameter, relating to lower-quality haptic simulations. In terms of the first machine parameter, maximum force output, the range of 0.5 N to 10 N was tested. Results indicated that performance improvements (in terms of a percent correct score) were not significant for maximum endpoint forces above 3 N. For the experiments in which system bandwidth was varied (between 5 Hz and 100 Hz), significant improvements in performance were not achieved for levels greater than 40 Hz, however an analysis of variance of the data could not verify that variations in scores were attributable to varying system bandwidth. Finally, for the experiments in which maximum virtual surface stiffness was varied between 50 N/m and 1000 N/m, significant performance gains were not noticed for the size

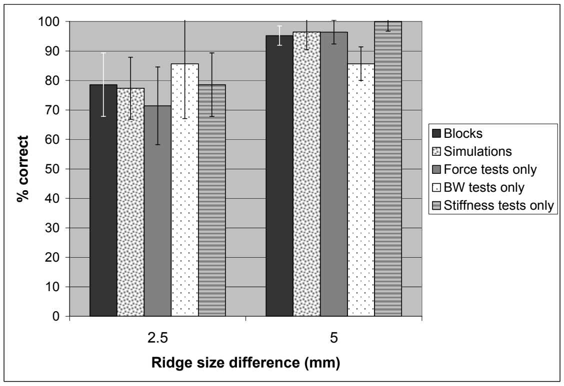

Figure 10. Percent correct scores for Experiment 2A with real blocks compared to simulated blocks (average results for all subjects)

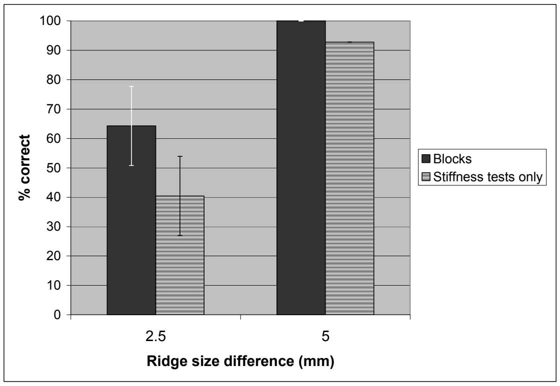

Figure 11. Percent correct scores for Experiment 2B with real blocks compared to simulated blocks (average results for all subjects)

identification task for stiffnesses greater than 470 N/m. These results indicate that haptic interface hardware may be capable of conveying significant perceptual information to the user at fairly low levels of force feedback and virtual surface stiffness for this stylus-based size discrimination task, while the effects of lower levels of system bandwidth are unclear from these experiments.

3.2.2 Experiment 2A – Real Environment Results

A set of three subjects performed Experiment 2A in the real block environment. Subject G had lower performance for *d* = 2.5 mm size differences when the task was performed in a real environment rather than a simulated one. However, performance in the real environment was the same as that for the simulated environment for the stiffness test at *d* = 5 mm. This performance was slightly above that for the bandwidth test. Subject H showed somewhat better performance in the real environment for *d* = 2.5 mm size differences, but scored 100% correct for both simulated environment tests and the real environment test at *d* = 5mm. Subject I had identical performance for Experiment 2A in the real environment and the simulated environment for the bandwidth test at both size differences. For the stiffness test, performance in the real environment was slightly lower at *d* = 2.5 mm and somewhat higher at *d* = 5 mm than in the simulated environment.

Figure 10 shows average results across all subjects for Experiment 2A with real and simulated blocks. The first two columns show the average scores of the three subjects who performed the size discrimination task with square ridges in a real environment compared to the average results of the three subjects for Experiment 2A at the maximum setting for each machine parameter tested. Average scores for the machine parameter tests are also shown individually.

3.2.3 Experiment 2B – Virtual Environment Results

Thirteen subjects participated in the size discrimination experiments with round cross-section ridges in a virtual environment. Subsets of six subjects from this pool of thirteen performed the experiments while a single machine parameter was varied in the achievable range for this hardware. Percent correct scores were recorded as before. Results indicated that performance improvements (in terms of a percent correct score) were not significant for maximum endpoint forces above 3 N. Experiments for varying values of bandwidth were not conducted for round ridges due to large standard deviations and inconclusive results for square ridge experiments. Finally, for the experiments in which maximum virtual surface stiffness was varied between 50 N/m and 1000 N/m, significant performance gains were not noticed for the size identification task for stiffnesses greater than 470 N/m. These results indicate that haptic interface hardware may be capable of conveying significant perceptual information to the user at fairly low levels of force feedback and virtual surface stiffness for this stylus-based size discrimination task, while the effects of lower levels of system bandwidth are unclear from these experiments.

3.2.4 Experiment 2B – Real Environment Results

A set of three subjects performed Experiment 2B in the real block environment. Subject J and Subject K scored much higher in the real environment than in the simulated environment at *d* = 2.5 mm for Experiment 2B. Both also showed higher performance in the real environment at *d* = 5 mm, but the difference in scores at this size difference was much smaller. Subject L also scored higher in the real environment at *d* = 5 mm, but that was not the case for *d* = 2.5 mm.

Figure 11 shows average results across all subjects for Experiment 2B with real and simulated ridges. The first two columns show the average scores of the three subjects who performed the size discrimination task with round ridges in a real environment compared to the average results of the three subjects for Experiment 2B at the maximum setting for the virtual environment experiment with varying stiffness. Subjects who had performed virtual environment experiments for other machine parameters were not available for real environment testing, therefore only a comparison to the stiffness variation experiments can be made.

4 Discussion

Figure 8 shows average results across all subjects for Experiment 1A with real and simulated blocks. The first two columns show the average scores of the three subjects who performed the size identification task with square ridges in a real environment compared to the average results of all subjects for Experiment 1A at the maximum setting for each machine parameter tested. Average scores for the machine parameter tests are also shown individually. Analysis of the average percent correct scores shows that performance in the real environment is slightly better than that for the simulated environment. However, these differences are not significant according to an analysis of variance (ANOVA), and could be due only to the varying levels of performance of the three subjects tested in the real environment or differences in audio and friction cues in the real environment as compared to the virtual environment.

Figure 9 shows average results across all subjects for Experiment 1B with real and simulated ridges. The first two columns show the average scores of the three subjects who performed the size identification task with round ridges in a real environment compared to the average results of all subjects for Experiment 1B at the maximum setting for each machine parameter tested. Average scores for the machine parameter tests are also shown individually. For Experiment 1B, performance in the real environment is slightly better than that for the simulated environment at both size differences, but the difference are not significant according to an ANOVA of the data.

Figure 10 shows average results across subjects for Experiment 2A with real and simulated blocks. The first two columns show the average scores of the three subjects who performed the size discrimination task with square ridges in a real environment compared to the average results of the three subjects for Experiment 2A at the maximum setting for each machine parameter tested. Average scores for the machine parameter tests are also shown individually. For Experiment 2A, performance in the real environment is not significantly better than that for the simulated environment at either size difference according to the ANOVA.

Figure 11 shows average results across all subjects for Experiment 2B with real and simulated ridges. The first two columns show the average scores of the three subjects who performed the size discrimination task with round ridges in a real environment compared to the average results of the subjects for Experiment 2B at the maximum setting for each machine parameter tested. As observed from Experiment 1 and Experiment 2A results, performance in the real environment is slightly better than that for the simulated environment at d = 2.5 mm. However, performance at d = 5 mm was higher for the real environment compared to simulated environment test results for the round ridge size discrimination task. The differences in performance were significant at the 5 mm size difference only.

The results for comparison of human haptic performance in a real environment to that in a high-quality virtual environment suggest that differences are slight. Additional subject testing is necessary, however, in order to perform a more complete statistical analysis. Also, a set of follow-up experiments should be conducted in which the same set of subjects is tested in the real environment and in each sub-optimal virtual environment so that direct comparisons of their performance can be made.

Scores from the virtual environment experiments indicated that performance levels reached a maximum level before the hardware limits of the device were reached. This finding implies that lower quality haptic devices may be capable of conveying sufficient perceptual information to a user for some tasks. Minimum values for maximum force output, system bandwidth, and time delay via virtual surface stiffness were derived for 90% accuracy in the perception tasks. These values corresponded to the machine parameter levels above which significant gains in performance were no longer noticeable (e.g., 3N for maximum force output, 40 Hz for system bandwidth, and 470 N/m for virtual surface stiffness). In a second set of comparisons, scores in the real environment are presented along with scores in the virtual environment with each machine parameter set at its minimum recommended value for 90% accuracy in the described perception tasks. Results support the previous findings, showing that performance in a degraded environment is comparable to performance in the real environment for the size identification and discrimination tasks presented here.

In Figure 12, results for Experiment 1A are shown. It should be noted that all subjects reported that they were able to note the difference in feel between the sub-optimal and optimal simulations. Specifically, at the smaller size difference, performance in the real environment is better than that for the virtual environment with lower levels of maximum force output, system bandwidth, and virtual surface stiffness than are achievable by this hardware. Differences in performance are not significant however, according to the ANOVA. At the larger size difference however, performance in the real environment is comparable to that in the virtual environment at degraded quality levels.

Figure 13 shows the same comparison for the round ridge size identification task. Performance is again better in the real environment than that in the degraded virtual environments, but not significantly so at the 2.5 mm size difference. Lower levels of bandwidth do not seem to have as great an effect on performance as lower levels of force output and surface stiffness. This is most likely due to the fact that bandwidth is a time-related parameter,

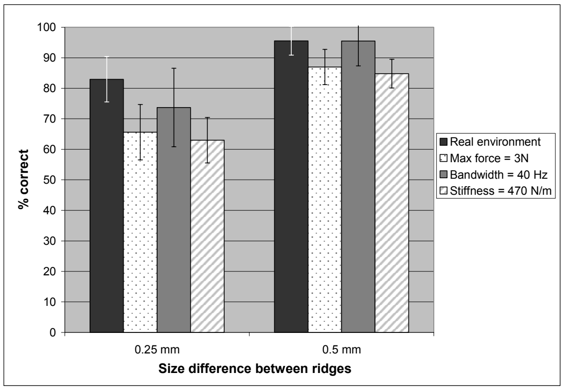

Figure 12. Experiment 1A - Square ridge size identification performance in a real haptic environment compared to that in sub-optimal virtual environments.

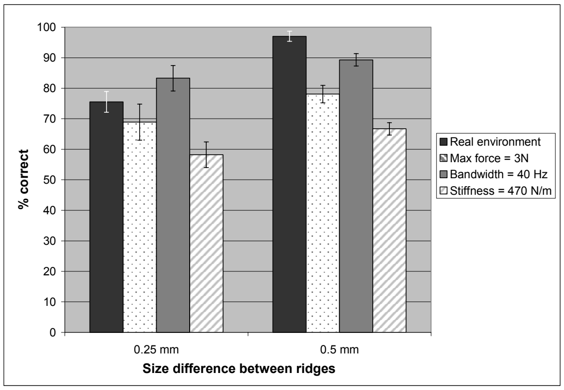

Figure 13. Experiment 1B - Round ridge size identification performance in a real haptic environment compared to that in sub-optimal virtual environments.

while the size identification and discrimination tasks are not time-dependent. Subjects were able to compensate for reduced system quality in terms of lower system bandwidth by slowing their exploration speeds in the virtual environment. This adjustment negated the effects of lower system bandwidth, which was most noticeable as a phase lag in the simulation. Slow interaction with the virtual environment for 40 Hz bandwidth was then similar in feel to slow interaction with the environment at higher levels of system bandwidth. In order to better understand the effects of varying system bandwidth on human haptic perception, time-dependent tasks should be used in future experiments. The fact that the ANOVA for the size identification and discrimination tasks in the virtual environment for varying bandwidth did not verify that variations in results could be attributed to variations in system bandwidth, could also be due to the fact that the tasks were not time-related, while the system bandwidth was time-related.

Results for the size discrimination tasks with square and round ridges are shown in Figures 14 and 15. An ANOVA verified that performance in the real environment was not significantly different from that in the virtual environment at less than maximum machine parameter settings for the size discrimination tasks, except for round ridge size discrimination at 5 mm size differences. With this exception, the findings support the claim that haptic simulations can convey sufficient perceptual information to complete a size discrimination task with maximum performance (same as real-world performance) at lower levels of machine parameters than are achievable by current hardware. Additional subject testing should be conducted in order to have additional data for statistical analysis.

5 Conclusions

The findings of these experiments, in which performance in a real environment was compared to performance in a simulated environment for two perception tasks, indicate that the haptic interface hardware used in these experiments does a fairly good job of approximating reality for the block environments described here. Not only do these results support the case that haptic interfaces are good at simulating real environments for these perceptual tasks, but they also show that they can do so without excessive machine performance demands.

6 Acknowledgements

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7 References

[1] M. Kilchenman and M. Goldfarb, “Implications of haptic interface force saturation on the haptic display of detail.” Proceedings of the ASME International Mechanical Engineering Congress and Exposition, DSC-Vol. 69-2, pp. 1125-1131, 2000.

[2] P. Richard and Ph. Coiffet, “Dextrous Haptic Interaction in Virtual Environments: Human Performance Evaluations,” Proceedings of the IEEE International Workshop on Robot and Human Interaction, pp. 315-320, 1999.

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

[4] C. M. Perry, “Design of a High Performance Robot for Use in Haptic Interface and Force Feedback Research.” Master’s Thesis, Dept. of Mechanical Engineering, Vanderbilt University, 1997.

[5] R. Ellis, O. Ismaeil, and M. Lipsett, “Design and evaluation of a high-performance prototype planar haptic interface.” Advances in Robotics, Mechatronics, and Haptic Interfaces, DSC-Vol. 49, pp. 55-64, 1993.

[6] M. Kilchenman and M. Goldfarb, “Force Saturation, System Bandwidth, Information Transfer, and Surface Quality in Haptic Interfaces.” Proceedings of the IEEE International Conference on Robotics and Automation, pp. 1382-1387, 2001.

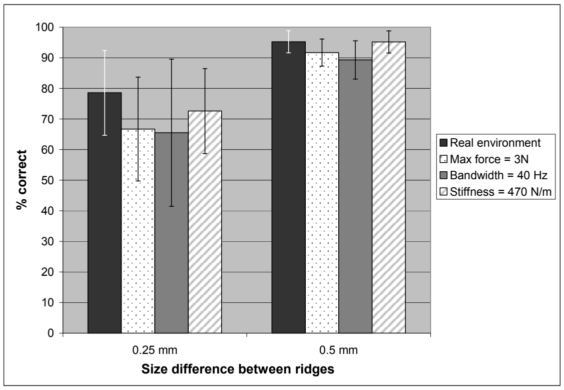

Figure 14. Experiment 2A - Square ridge size discrimination performance in a real haptic environment compared to that in sub-optimal virtual environments.

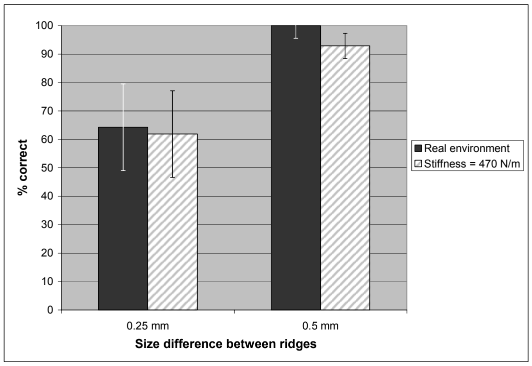

Figure 15. Experiment 2B - Round ridge size discrimination performance in a real haptic environment compared to that in sub-optimal virtual environments.

Table 2. ANOVA confidence intervals (% confidence that differences in scores are significant) for all real environment vs. simulated environment experiments.

Exp. #	Environment Comparison		Confidence Interval	
			2.5 mm	5 mm
1A	Real	High-quality virtual	20%	19%
1A	Real	Low-quality virtual	45%	6%
1B	Real	High-quality virtual	72%	61%
1B	Real	Low-quality virtual	52%	94%
2A	Real	High-quality virtual	17%	70%
2A	Real	Low-quality virtual	10%	9%
2B	Real	High-quality virtual	72%	100%
2B	Real	Low-quality virtual	39%	87%