Comparison of Human Haptic Size Discrimination Performance in Simulated Environments with Varying Levels of Force and Stiffness

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Abstract

The performance levels of human subjects in size discrimination experiments in virtual environments with varying levels of stiffness and force saturation are presented. The virtual environments are displayed with a Phantom desktop three degree-of-freedom haptic interface. Performance was measured at below maximum machine performance levels for two machine parameters: maximum endpoint force and maximum virtual surface stiffness. The tabulated scores for the size discrimination in the sub-optimal virtual environments, except for those of the lowest stiffness, 100 N/m, were found to be comparable to that in the highest-quality virtual environment. This supports previous claims that haptic interface hardware may be able to convey, for this perceptual task, sufficient perceptual information to the user with relatively low levels of machine quality in terms of these parameters, as long as certain minimum levels, 1.0 N force and 220 N/m stiffness, are met.

1. Introduction

The proper design of any machine requires a well-defined set of performance specifications. Although much work has been accomplished in the field in general [see, for example, the surveys 1, 2], hardware specifications for haptic interfaces that relate machine parameters to human perceptual performance are notably absent. The absence of such specifications is most likely because haptic interface performance specifications must consider issues of human perception, which is complex in nature and difficult to assess quantitatively. With the recent introduction of several commercially oriented haptic devices and applications, the need for a set of specifications to guide the cost-optimal design of haptic devices is that much more pronounced.

Prior work published by the third author 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 [3, 4]. For the force output experiments, results showed that 3 to 4 N 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 10 N 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 300 to 400 N/m, while the hardware was capable of 1000 N/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.

This paper serves as a continuation of that prior work, and investigates the effects of simultaneously varying maximum force output and virtual surface stiffness on human perception in simulated environments. Along with similar characterizations of other performance specifications, this work should help form a set of specifications from which a designer can effectively design a stylus-type haptic interface for a given application. This study in particular should highlight any coupling between these machine parameters when it comes to human performance in virtual environments.

The vast majority of the research literature related to this topic has generally either focused on quantitative measures of human factors, measures of machine performance independent of human perception, or the effects of software on the haptic perception of virtual environments. Regarding the first area, psychophysical experiments conducted by several research groups have quantified several haptic perception characteristics, such as pressure perception, position resolution, stiffness, force output range, and force output resolution [for example, 5-9]. Since these experiments did not involve haptic interface equipment, however, they were not able to create a direct link between machine performance and human perception during haptic task performance.

Within the second area of research, optimal machine performance has been characterized in the literature, yet these measures are typically disparate from human perceptual measures. When designing high-performance equipment, designers seek to build a device with characteristics such as high force bandwidth, high force dynamic range, and low apparent mass [10, 11, 12]. These are typically qualitative specifications, however, since the designers have little reference information regarding the quantitative effects of these machine parameters on the performance of humans with regard to perception in a haptically simulated environment. Several researchers have incorporated human sensory and motor capability as a prescription for design specifications of a haptic interface [13, 14]. Such measures are logical, though indirectly related to haptic perception and most likely quite conservative for common haptic tasks. Colgate and Brown offer qualitative suggestions for haptic machine design that are conducive to the stable simulation of high impedances [15]. Though simulation of a high impedance is a useful and logical performance objective for a haptic device, the objective is not directly based upon measurements of human perception.

Finally, researchers have studied the effects of software on the haptic perception of virtual environments [for example, 16-18], yet these experiments did not address the relationships between haptic interface hardware design and haptic perception. This paper addresses the relationship between haptic interface hardware and human perception, and in particular measures the effects of varying virtual surface stiffness in a simulated environment on human perceptual capabilities in a haptic environment. Virtual surface stiffness is of interest as a machine parameter because hardware selections, including position sensors and computers, can limit achievable virtual surface stiffnesses. A good discussion of the relationship between hardware and achievable surface stiffness is given in [15].

Other than the third author's prior work [3, 4], the only prior attempt (of which the authors are aware) to elucidate the relationship between haptic device design and human perception was the doctoral work of MacLean, which investigated the effects of machine sampling frequency and mechanical damping on human perception, and suggested "preliminary" design guidelines regarding these traits [19]. Additionally, there is prior work on the effect of machine parameters on human perception in teleoperated peg-in-hole tasks, where completion times and errors decreased in increasing bandwidth and decreasing delay [20].

Unlike these prior works, this paper presents quantitative data on the effects of varying both maximum force output and virtual surface stiffness on the ability of human subjects to correctly discriminate sizes of virtual objects. In addition, this work is conducted on a commercial haptic device, rather than with a laboratory haptic interface.

2. Methods

2.1 Virtual Environment Apparatus

The Phantom Desktop was used to simulate the virtual environments. Hardware specifications for the Phantom Desktop are listed in Table 1.

Table 1. Phantom Desktop hardware specifications

Workspace	16x13x13 cm
Maximum force	6.4 N
Maximum continuous force	1.7 N
Force feedback	3 DOF
Position sensing	6 DOF

2.2 Testing Environments

During the experiment, the subjects held a stylus with the dominant hand and entered responses on a computer keyboard with the non-dominant hand. The dominant hand was shielded from view with a curtain.

Square cross-section shape primitives were displayed haptically with the Phantom Desktop. The ridges were displayed side-by-side along a common centerline in the haptic interface workspace. The stimuli were oriented horizontally and perpendicular to the subject's midline. Figure 1 shows a visual representation of the virtual environment. Subjects explored the environment with the Phantom stylus as shown in Figure 2.

2.3 Experimental Paradigms

Perception experiments were conducted for ridges of square cross-sections in 16 different virtual environments, each with a different combination of a value for maximum surface stiffness and a value for maximum endpoint force. The stiffness values used were 100, 220, 460, and 1000 N/m, and the force values used were 1, 2.2, 4.6, and 10 N.

The order that these environments were presented was varied for each subject to ensure that learning effects were not a factor in the averages. A training session preceded the experiment where the subject performed the size-discrimination tasks without force or stiffness saturation. The practice session was conducted in the same way as the real session, except the subject was given immediate feedback on whether their choice was correct. They were instructed to continue until they felt comfortable with the task and were allowed to train before each session if they wished.

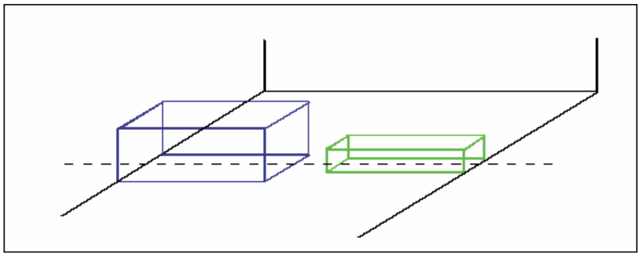

Figure 1. 3-D model of the simulated environment for the size discrimination tasks

Figure 2. Test subject seated at testing station for virtual environment experiments. (The curtain used to obstruct the subject's view are removed in this picture)

2.4 Subjects

Ten test subjects were used for the size discrimination experiment. Subjects varied by gender, dominant handedness, and experience with haptic devices.

2.5 Procedures

In each experiment, the subject was asked to feel the exterior of the two virtual ridges 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). The experiment was forced-choice, so that "same" was not a valid response.

Three size differences were tested: 2.5, 5, and 10 mm. 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 20 mm, and the second ridge had an edge length of 22.5, 25, or 30 mm. The edge length corresponds to the height and width of the ridge; all of the ridges were 100 mm in length. The location of the base-size ridge, either left or right, was chosen randomly for each trial.

In each environment, fifteen repetitions of the stimulus pair for each size difference were presented to the subject, for a total of forty-five trials per combination of force and stiffness. In all, subjects sat for one practice session and then sixteen test sessions of forty-five trials.

2.6 Machine Parameters

In order to create low-fidelity 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. The output command force was saturated at four different values: 1 2.2, 4.6, and 10 N, which were chosen because they give an approximately logarithmic distribution across the achievable range. In this case, since the Phantom Desktop is not capable of outputting a continuous force greater than 10 N, the 10 N trials correspond to the highest achievable force output of the Phantom haptic device.

The saturation was accomplished by creating new classes in GhostSDK, the software application through which the Phantom is programmed, called WeakCube and WeakCylinder that take the maximum output force as an input. These classes were based upon the GstCube and GstCylinder classes in GhostSDK. The stiffness was varied by setting k to one of four values: 100, 220, 460, and 1000 N/m, which again gives an approximate logarithmic distribution across the achievable range of stiffness. 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.

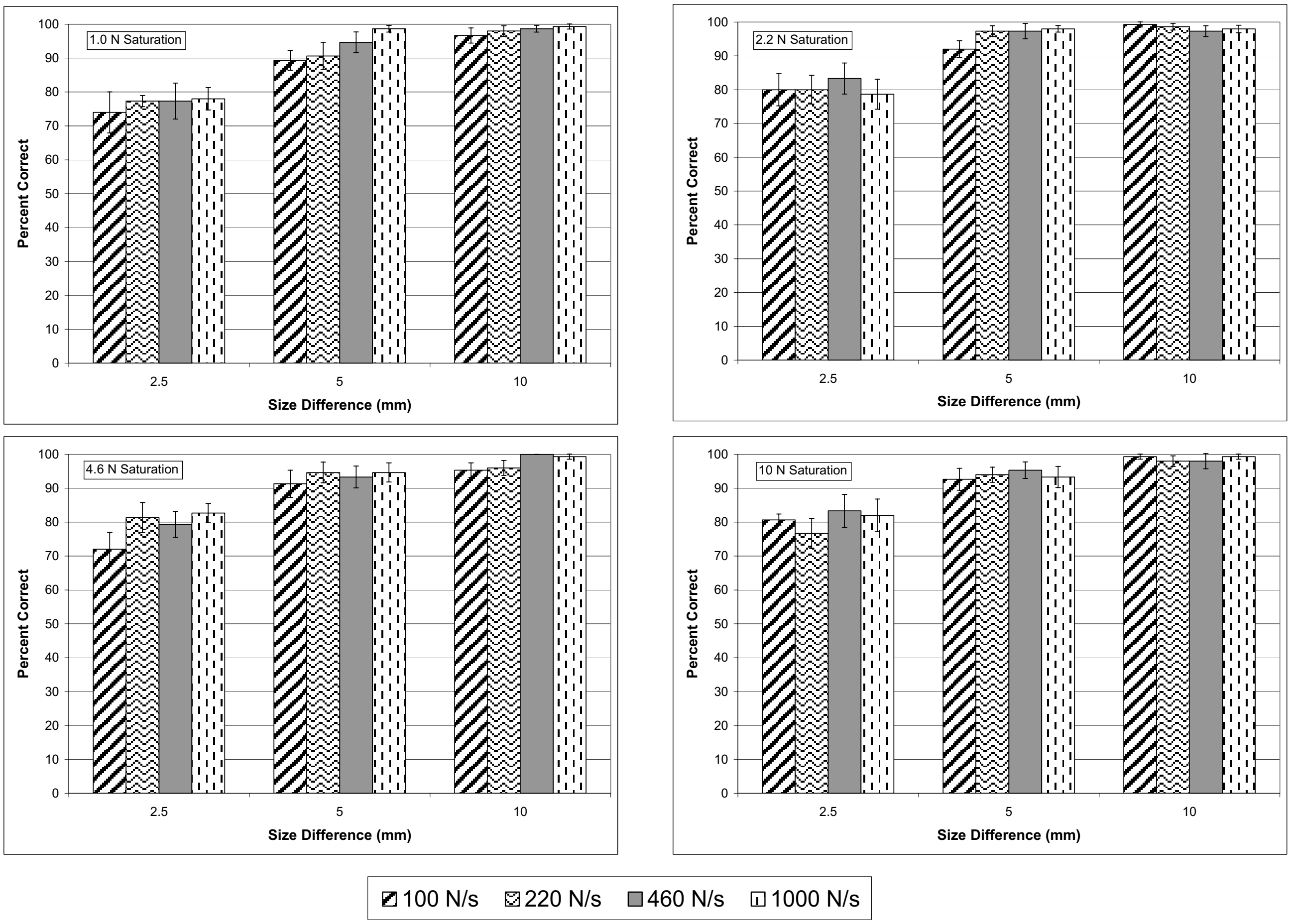

Figure 3. Results for size discrimination experiments for all force saturation values tested: 1 N (upper left), 2.2 N (upper right), 4.6 N (lower left), 10 N (lower right).

3. Results

3.1 Perception Test Results

Results for all experiments are presented in Figure 3. 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 shown with error bars.

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

Varying stiffness resulted in significant variations in performance [$F(3, 17) = 5.03$, $P = 0.0019$]. Upon investigation of the pair wise combinations, only 100 N/m versus 460 N/m and 100 N/m versus 1000 N/m were significant with 95% confidence. When comparing performance in environments with maximum virtual surface stiffness of 100 N/m and 220 N/m, significant differences were not noted. However, when comparing 100 N/m to higher levels of virtual surface stiffness, performance is significantly improved. This leads us to conclude that stiffnesses in virtual environments should be at least 220 N/m and possibly above 460 N/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

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from prior work by the third author [3, 4]. It was hypothesized that such compounded degradation of the environment fidelity may have a detrimental effect on performance, but this is not the case, at least for the size discrimination tasks investigated here.

Figure 4. PHANToM Premium 1.0A with load cell for force measurements.

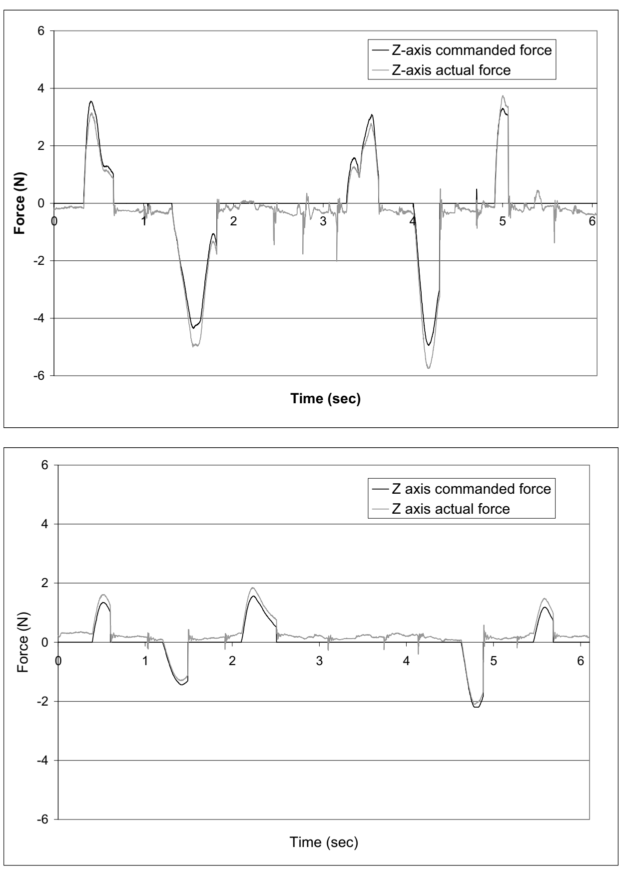

Figure 5. (top) Unsaturated case (bottom) Saturated (2.2 N) and limited stiffness (220 N/m) case

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 1 mm for reference lengths of 10 to 20 mm [21]. This correlates to results from prior work by the third author [3, 4] and the results presented here. Size differences of 1.25 mm were tested in prior work, but performance was no better than guessing.

3.2 Force Data

For this part of the experiment, the Phantom Premium 1.0A outfitted with an ATI Nano17 six-axis load cell was used in place of the Phantom Desktop. The Phantom Premium has a maximum output force of 8.5N and a workspace of 13 x 18 x 25 cm. The second link, the link connecting the end point of the stylus and the two parallel links, was machined to include the ATI Nano17 force sensor, as shown in Fig. 4. This can be used to measure the actual force the user perceives.

Three experienced Phantom users were told to probe a square ridge without visual feedback for approximately five seconds. The ridge was of the same dimensions as those in the size discrimination experiments. The same force output and virtual stiffness limitations were imposed on this environment. Each subject explored two environments. The first displayed the ridge with a maximum force output of 2.2 N and a virtual surface stiffness of 220 N/m. The second environment was not varied, so that the virtual surface stiffness was 1000 N/m and the force output was limited only by the capabilities of the Phantom 1.0A hardware. Both the force sensor reading and the output signal was recorded and transformed to the world coordinate with up being positive in y and the long side of the ridge parallel to the x-axis.

The commanded signal to the Phantom coincided very closely with the measurements from the force sensor. The small (under .5 N) noise in the measured data most likely results from the movement of the stylus and not actuated motor torques. The slight offset is most likely due to unmodeled dynamics of the haptic device, which will affect the actual force conveyed to the user.

Most users did not exceed the force limit on either of the experiments. In fact, no one exceeded 6 N in the unsaturated experiment which is well below the machine limit of 8.5 N. Figure 5 shows z-axis force data for one of the users in both the low and high fidelity environments. The effect of lowering virtual surface stiffness can be seen with the decrease in slope upon contact with the virtual ridge. Saturation is noted for one pass over the virtual ridge for the 2.2 N case. Finally, the force output results indicate that even when users have the full range of force output of the Phantom, it is not used for the exploration of a single square ridge.

4. Conclusions

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 220 N/m and 1000 N/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.

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