Scratching the Surface: Preliminary Investigations of Haptic Properties for Data Representation

Abstract. Research has shown that haptic devices such as the PHANToM are effective at displaying graphical information to blind people. However the techniques used so far have been direct analogies with traditional visual representations, which may not be appropriate for the haptic sense. It is proposed that graphical data could be made more easily accessible to blind people by scaling data values to haptic properties of chart elements, such as friction, stiffness and texture qualities. Two experiments are described that investigate the appropriateness of these qualities for display of numerical information. Haptic properties were compared using a forced choice discrimination paradigm and a magnitude estimation style design. Both studies indicated that sighted subjects were better at discriminating friction than both stiffness and spatial period of texture.

1 Introduction

Visualisations such as line graphs and bar charts are frequently used to illustrate trends and distributions of data in a simple and intuitive way. They are commonly used in subjects such as economics, mathematics and the sciences. Being unable to access graphical information is a common obstacle to blind people who wish to pursue scientific based studies or careers. Traditional methods to overcome this include presenting graphs as raised lines on specially prepared paper. The commercial availability of haptic devices, such as the PHANToM, has presented the opportunity to render data stored on a computer as haptic graphs for blind users. This provides a richer and more flexible way for blind students to access the information.

1.1 Previous Work

Current implementations of haptic graphs for blind and visually impaired computer users have adopted a direct analogy with their visual counterpart [1]. A haptic device is used to explore the height of bars, shape of lines or the contours of a surface plot. However, visualisations such as these rely on the distributed nature of the visual sense to identify trends in the data through perception and comparison of shape and size. Conversely, the touch sense is very localised. The rich, spatially distributed nature of visual cues is not available; hence, users must successfully integrate "temporally varying" cues as they traverse the objects or surfaces. For large or complex data, this places considerable short-term memory demands on the user, thus reducing performance, and comprehension of the data. The "point interaction" nature of devices such as the PHANToM further exasperates the problem by limiting the cutaneous feedback available to the user. Studies by Lederman and Klatzky [6] and Jansson et al. [2] have indicated that in the absence of visual information, the point interaction nature of the PHANToM greatly impedes users' perceptions of shape and size. The most efficient exploratory procedure for extracting size and shape information is enclosure [5] which is unavailable with the single point of contact afforded by the PHANToM. Instead, the user must adopt a "contour following" style procedure. However, the lack of spatially distributed cutaneous information on the fingertip is detrimental to the task of edge detection – a fundamental component of the contour following exploratory procedure [7].

These results imply that a visualization system for use with a haptic device that is based on discrimination of shape and size cues will be difficult and time consuming for users. A more successful approach may be to display the data by scaling properties that are more quickly and easily perceived by the haptic sense. Klatzky, Lederman and Reed [3] showed that during a sorting task with real objects, subjects discriminated stimuli visually using structural properties (size and shape cues), whereas when working haptically they relied more on material cues such as compliance and texture. Further, it has been shown that the lack of cutaneous information when exploring via a probe or other intermediary link (remote contact) does not greatly impede the perception of texture [4], stiffness [6] or other material properties.

Thus, in an application to display bar charts to blind users, more haptically salient material properties could be scaled to the data value of the bar, as opposed to the height. For example, bars with a low value could be very compliant (low stiffness), whilst those with a high data value could be rigid to touch (high stiffness).

1.2 Motivation

The experiments described in this paper were designed to investigate the feasibility of this approach, while providing a better insight in to the relationship between virtual objects represented by a PHANToM and our perception of their properties. As such, the results described can be generalized to other haptic applications that rely on perception of material cues. It was decided to adopt stiffness, friction and texture for the following studies. These three properties were chosen as they could easily be manipulated through the GHOST API (friction and stiffness) and have previously been considered in other studies (texture). Texture has been shown to be a complex, multi-dimensional phenomenon, therefore the investigations focused on one aspect of a simple sinusoidal representation of textures. The "spatial period" (distance between peaks on the sinusoid) was the only measure considered. "Roughness" was deliberately not referred to, as previous studies have shown the relationship between perceived roughness and parameters of virtual textures to be non-linear and complex [8].

The ability to discriminate properties such as these has been well documented for physical objects, but has not been investigated using virtual stimuli presented with a PHANToM device. Initially, a forced choice paradigm was adopted to investigate the ability of sighted subjects using a PHANToM to discriminate the properties. The results obtained suggested a magnitude estimation approach may provide greater insights. As such, both sets of results are described and compared here.

2. Experimental Stimuli

The same haptic stimuli were employed in both studies. They were rendered using the GHOST SDK from Sensable technologies. For the stiffness condition, the surface spring stiffness of the node was varied. For the friction condition, both the static and dynamic friction were varied equally. For the texture condition, a ghost force field effect was created that rendered lateral sinusoidal forces when the PHANToM was in contact with the surface. Thus, no normal forces were involved in the rendering of the texture, only forces parallel to the surface. It has previously been shown in other studies that purely lateral forces can create an illusion of texture or bumps [9]. It was decided to use purely lateral forces as it made rendering considerably simpler. A normal force tended to perturb the user from the surface that instigated the effect, thus causing unwanted instabilities. The parameter varied for the texture condition was the spacing between the peaks of the sinusoidal texture, also referred to as the spatial period.

3. Forced Choice Experiment

Twelve sighted subjects participated in the experiment. They were all recruited from the student population of the Department of Computing Science, and were all paid for their participation. The experiment adopted a within-subjects forced choice methodology, whereby participants chose the “odd one out” from three surfaces that varied in one of the three parameters for each condition.

3.1 Experimental Procedure

During each step of the experiment, subjects were presented with the three surfaces that were represented both visually on a monitor, and using the PHANToM haptic interface. The tip of the PHANToM’s stylus was represented on screen using a small sphere. The visual feedback was included purely for guidance purposes, as it proved difficult for people to locate and differentiate between the surfaces without visual feedback. Accordingly, the sphere “cursor” disappeared whenever the subject contacted one of the surfaces, such that they could not obtain any visual cues regarding the object’s properties. No visual cues were provided regarding the properties of the surfaces.

The following values were assigned to the three properties as “standard” values: stiffness 500N/m, friction 0.5 Ns/m, sinusoid spatial period 3mm. Prior to each experimental condition, the subject was instructed that the stiffness, friction or texture would be varied. The parameters that were not varied in a condition were held constant at the standard values (except for texture, which was not present in the stiffness and friction conditions). The subject was also instructed how best to explore the surfaces in order to perceive the relevant quality. These were based on the exploratory procedures (EP) of Lederman and Klatzky [2]. For stiffness, the subjects were instructed to tap on the surface. Tapping was recommended as opposed to applying pressure, so as not to cause the PHANToM's motors to overheat. It was found during piloting the study that applying pressure over a protracted period often caused the motors to overheat. It was also noted from the pilot studies that subjects could still reliably perceive the relative stiffness of the surfaces by adopting the tapping EP. For both friction and texture, the subjects were instructed to move the stylus laterally, up and down the surface.

For each step in a condition one of the three surfaces, chosen at random, was designated as the "test surface". The test surface varied in the relevant parameter (friction, stiffness or spatial period) by ±10%, ±20%, ±30%, ±40% or ±50% from the standard value. Each difference was presented nine times, resulting in 90 steps per condition. The task for each step was to select which of the surfaces was the test surface. Each subject took part in three conditions, one for each surface property. The order of conditions was counterbalanced between the subjects. For all conditions the subject wore headphones playing filtered white noise ("wave" noises) in order to mask the audible cues produced by the PHANToM during operation. The noise played was filtered so as not to be too uncomfortable for the subjects, as the experiment took around 90 minutes to complete.

Prior to the experiment, each subject was given written instructions on how to explore the surfaces, a description of the material property they would be exploring in the particular condition, and instructions as to how to give their responses. Subjects were then given a training session, during which they were given ten sets of test stimuli in exactly the same fashion as the experiment described above. For the purposes of the training, subjects were advised that the first five stimuli had a test surface of difference +50% from the standard, and for the last five stimuli, the test surface would have a difference of –50% from the standard. The participant was given feedback as to their success rate by the experimenter immediately after the training and before starting the experiment itself. All participants performed very well across all training sets, generally identifying over 70% of the surfaces correctly. Participants who experienced difficulty identifying any of the training stimuli were given further training sets until they verbally informed the experimenter they were confident enough to continue to the experiment. Typically, subjects who encountered problems only required one additional training set to grasp the concepts involved and achieve a satisfactory level of performance. During the training, the experimenter also advised the subject verbally regarding their technique for handling the phantom stylus and performing the required exploratory procedures, as described above. Subjects were advised to hold the PHANToM stylus in a similar manner to holding a pen. Subjects were also advised, both in written instructions, and verbally by the experimenter, that there was no time limit on them to make a decision, but they were advised to be as quick as they could, and that they would be expected to have to guess at some stimuli due to the small differences in the parameters.

3.2 Results

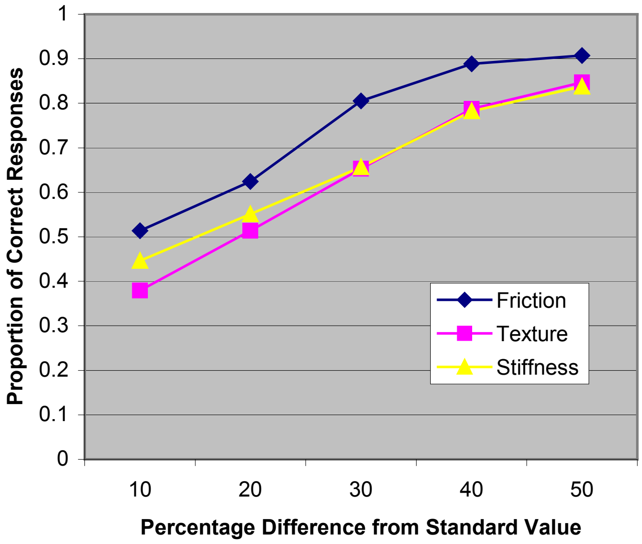

Fig. 1. Proportion of correct responses for percentage difference from standard.

Figure 1 shows the proportion of correct responses averaged across all subjects for the three conditions. A two-way repeated measures ANOVA was performed on the data, with the independent variables being stimuli (stiffness, friction or texture) and percentage difference between test and standard surface. The dependant variable was the proportion of correct responses given by the participants. It was found that the type of stimuli had a significant effect on performance ($F(2,165)=14.61$, $P<0.001$), as did the percentage difference from the standard ($F(4,165)=74.48$, $P<0.001$). There was no significant interaction between the two variables ($F(8,165)=0.473$, $P>0.05$). *Post hoc* Tukey tests revealed that the performance with friction was significantly better than with texture ($P<0.001$) or stiffness ($P<0.001$), however, there was no significant difference between texture and stiffness ($P>0.05$). Thus, participants were better able to resolve stimulus changes in friction than in either of the other two parameters.

To check for ordering effects, performance was also compared with the independent variables being the order of presentation, regardless of stimuli, and the percentage change in the surfaces. A two way ANOVA showed a significant effect of percentage difference ($F(4,165) = 63.67$, $P < 0.001$), but no significant effect of order ($F(2,165) = 1.14$, $P > 0.05$). Thus there were no significant learning effects as the participants progressed through the experiment conditions.

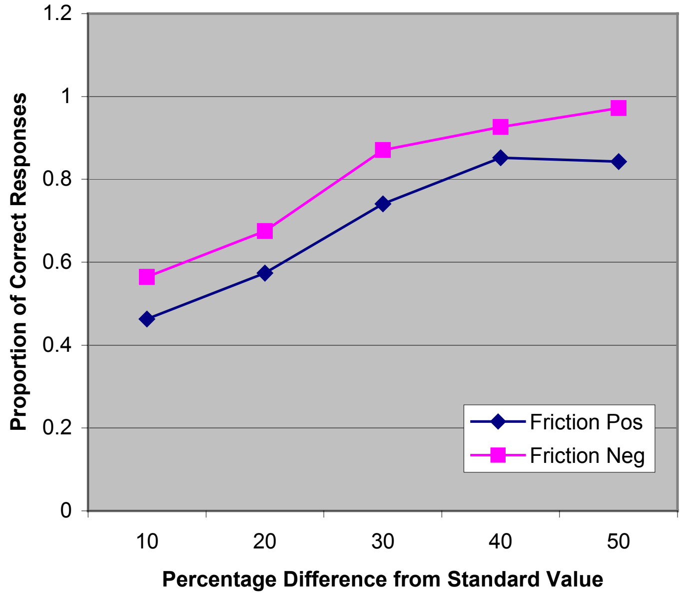

Fig. 2. Proportion of correct responses, friction stimuli, positive and negative differences

Separating the absolute differences in to positive and negative differences allows for testing as to whether there is a significant difference in positive and negative changes in the parameter. A two way repeated measures ANOVA was again performed on the data, this time for each parameter, with the independent variables as the sign of the change (positive or negative) and the percentage difference of the change.

For the friction condition (figure 2), there was a significant difference in positive and negative changes ($F(1,110) = 14.24$, $P<0.001$). Similarly, there was also a difference in the direction of change for stiffness (figure 3) ($F(1,110) = 15.87$, $P < 0.001$) and also texture (figure 4) ($F(1,110) = 7.05$, $P < 0.01$). For all conditions the effect of percentage difference was significant, and there was no interaction between the two variables.

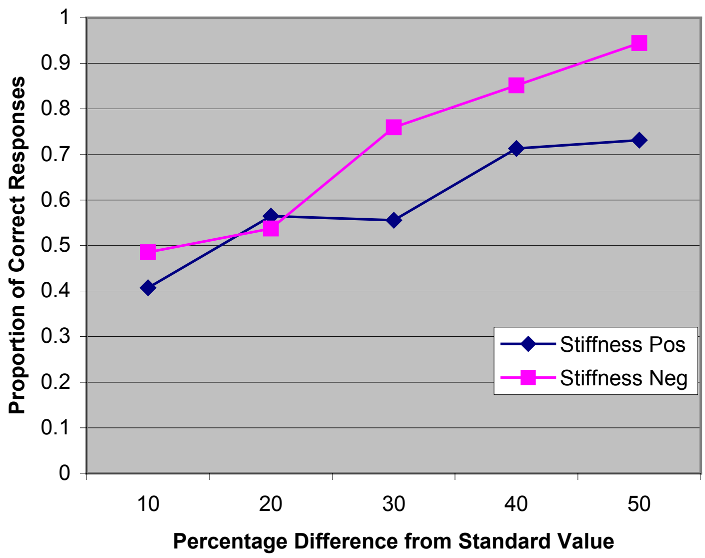

Fig. 3. Proportion of correct responses, stiffness stimuli, positive and negative differences

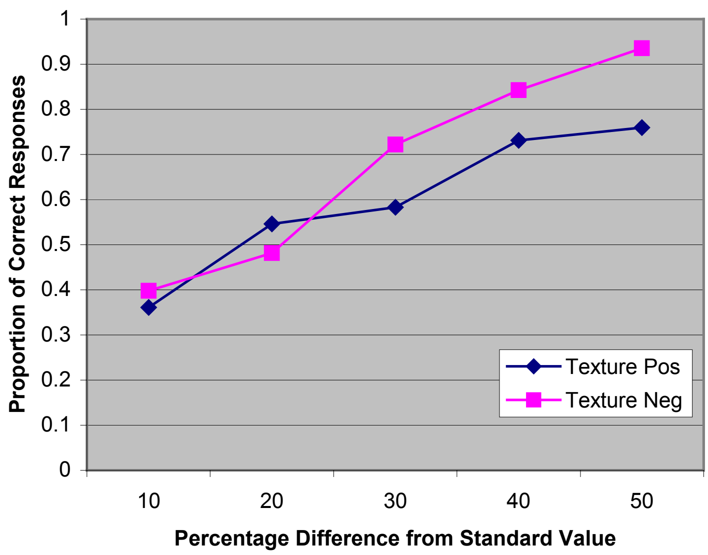

Fig. 4. Proportion of correct responses, texture stimuli, positive and negative differences

3.3 Discussion

For the chosen standard surfaces in the experiment, subjects were able to discriminate changes in friction significantly better than for both stiffness and spatial period of texture. In addition, it was also noted that that discrimination was significantly better for negative changes in stimuli relative to the standard value (lower stiffness, friction and spatial period) compared to positive changes. This suggests a non-linear relationship between the values of the haptic properties and the perceived magnitude. Hence, the second experiment described here adopted a magnitude estimation paradigm in order to establish a model of this relationship.

4. Magnitude Estimation

The purpose of this experiment is to quantify subjects' estimates of the perceived magnitude of common haptic properties represented by a PHANToM force feedback device. Haptic properties exhibiting a larger exponent of perceived magnitude would necessarily be more discriminable, as a change in actual magnitude will lead to a larger change in perceived magnitude, thus allowing for a greater number of discriminable discrete quanta on a continuous scale.

The advantage to the magnitude estimation approach is that each value of a property is systematically compared with all other values. In the forced choice discrimination experiment previously described, all comparisons were with an arbitrary "standard" surface. The disadvantage of this approach is that less iterations of each individual comparison can be performed due to the large number of permutations.

Twelve sighted subjects participated in the experiment. They were all recruited from the student population of the Department of Computing Science, and were all paid for their participation. They were a different set of subjects to those that participated in the forced choice study. The methodology was adopted from earlier studies on roughness perception by McGee et al. [8].

4.1 Experimental Procedure

The experiment was divided in to three conditions, each pertaining to one of the three haptic properties.

During each step of the experiment, the participant was presented with two surfaces that were represented both haptically and visually (again, purely for guidance purposes). The two surfaces differed in the value of the haptic property particular to the experiment condition. Prior to beginning the experiment the subject had been instructed how best to explore the two surfaces in order to perceive the relevant property, based on the E.P.s of Lederman and Klatzky. The participant's task was to explore the two surfaces and determine which of them had the highest value in the relevant property. Thus, which surface had the highest friction or stiffness, or the largest spatial period? Participants had completed a supervised training session prior to commencing the formal experiment where the experimenter could verify they were correctly perceiving the properties and responding to the question.

The possible values of the properties in each step of the experiment are indicated in Table 1. Each value was compared with each other in the experiment twice, thus giving a total of 56 trials per condition. The order of the trials was randomised prior to the experiment, and was the same for each participant. The values were selected to give eight discreet quanta over the range of values used. The range of stiffness and friction values were set in accordance with limits imposed by the manufacturer, given stability and power constraints of the device. The values for spatial period were set based on previous experiments using similar rendering, which had established informal limits on stability of texture representation using this method [8].

Table 1. Values of haptic properties used in experiment

Stimuli	Possible Values of stimuli
Stiffness	0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 (N/m)
Friction	0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 (Ns/m)
Spatial Period of Texture	1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5 (mm)

4.2 Results

Figures 5-7 show a scatter plot of the perceived magnitude averaged across all participants, versus the actual magnitude of the three stimuli. Power series models were developed for each of the properties; these are also indicated in the figures. Friction has the largest exponent (1.8052), illustrating that the perceived magnitude grows faster compared to the other two stimuli. Stiffness exhibited the second largest exponent (1.5647) and texture had the smallest (1.2501). This supports the results of the previous study, as the largest exponent will be the most easily discriminable, as its perceived magnitude changes the fastest.

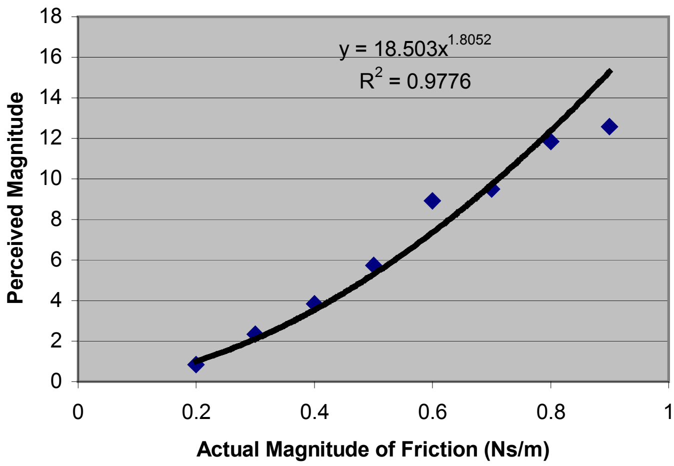

Fig. 5. Scatter plot and power series of friction magnitude estimates

Two way ANOVAS were performed on the magnitude estimation data for each haptic property. The independent variables were the subject number and the actual magnitude of the stimuli.

For the friction condition, the effect of the magnitude of the stimuli was significant ($F(7,77) = 232.856$, $P < 0.0001$), whereas the effect of the subjects was not significant ($F(11,77) = 0.170$, $P > 0.05$). This is a positive result as it shows that subjects tended to agree in their perception of the friction. Post-hoc Tukey tests (summarised in Table 2) revealed that all the magnitude estimates were significantly different except 0.6 and 0.7 ($T = 1.3$, $P = 0.8958$) and 0.8 and 0.9 ($T=1.67$, $P = 0.7045$).

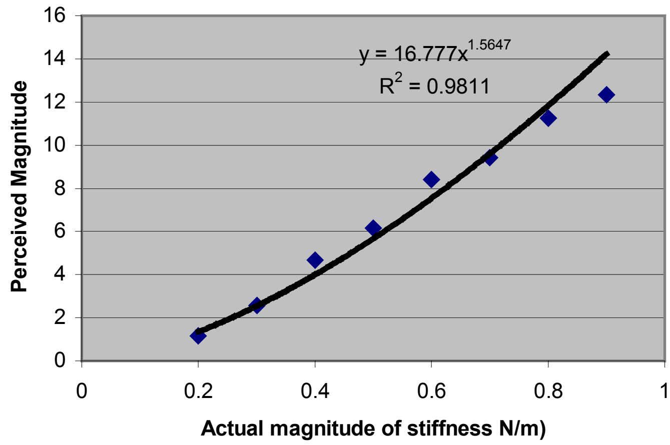

Fig. 6. Scatter plot and power series of stiffness magnitude estimates

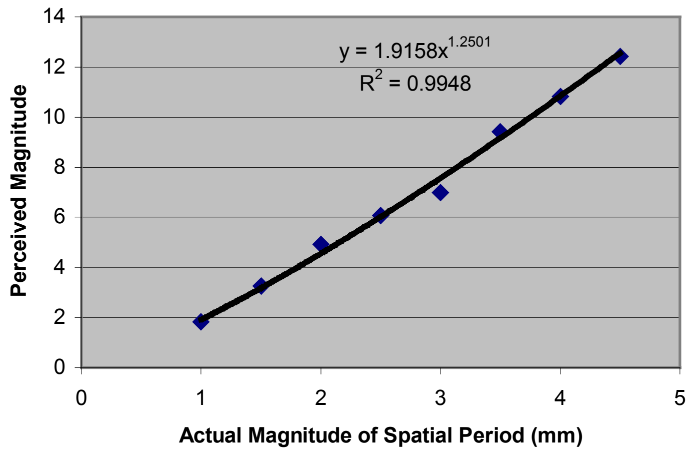

Fig. 7. Scatter plot and power series of spatial period estimates

Similarly for the stiffness condition, the effect of the magnitude was significant ($F(7,77) = 68.52$, $P < 0.0001$), and their was almost no difference between the subjects ($F(11,77) \cong 0$, $P \cong 1$). However, post-hoc Tukey tests showed that all the adjacent magnitudes were not significantly different. It was necessary to change the order of magnitude by two steps in order to obtain a significant difference (the results are summarised in Table 3). This shows that it is harder for subjects to discriminate stiffness than friction, as the perceived magnitude was not significantly different for two adjacent orders of magnitude, whereas generally there was a significant difference for the friction condition.

Similar evaluation was performed on the spatial period magnitude estimates. There was a significant effect of the magnitude of the spatial period ($F(7,77) = 20.39$, $P < 0.0001$) but no significant effect of subjects ($F(11,77) = 0.01$, $P > 0.05$). Post-hoc Tukey tests (summarised in Table 4) showed that spatial period was the least discriminable of the three properties. Generally, it was necessary for a three-step change in order of magnitude to produce a significantly different magnitude estimate.

Table 2. Post-hoc Tukey test results for friction magnitude estimates (P-values). Key: black = n/a, gray = not significant, white = significant

Magnitude	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.2 Ns/m	0.0266	0.0	0.0	0.0	0.0	0.0	0.0
0.3 Ns/m		0.0266	0.0	0.0	0.0	0.0	0.0
0.4 Ns/m			0.0014	0.0	0.0	0.0	0.0
0.5 Ns/m				0.0014	0.0	0.0	0.0
0.6 Ns/m					0.8958	0.0	0.0
0.7 Ns/m						0.0001	0.0
0.8 Ns/m							0.7045

Table 3. Post-hoc Tukey test results for stiffness magnitude estimates (P-values). Key: black = n/a, gray = not significant, white = significant

Magnitude	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.2 N/m	0.4532	0.0001	0.0	0.0	0.0	0.0	0.0
0.3 N/m		0.0640	0.0001	0.0	0.0	0.0	0.0
0.4 N/m			0.378	0.0	0.0	0.0	0.0
0.5 N/m				0.0335	0.0003	0.0	0.0
0.6 N/m					0.8307	0.0024	0.0
0.7 N/m						0.1515	0.0016
0.8 N/m							0.7657

Table 3. Post-hoc Tukey test results for spatial period magnitude estimates (P-values). Key: black = n/a, gray = not significant, white = significant

Magnitude	1.5	2.0	2.5	3.0	3.5	4.0	4.5
1.0 mm	0.9227	0.1508	0.00101	0.0007	0.0	0.0	0.0
1.5 mm		0.8364	0.2351	0.0361	0.0	0.0	0.0
2.0 mm			0.9721	0.6233	0.0051	0.0001	0.0
2.5 mm				0.9931	0.0917	0.0025	0.0
3.0 mm					0.4332	0.0295	0.0003
3.5 mm						0.9227	0.1759
4.0 mm							0.8694

4.3 Discussion

The results of the magnitude estimation study have established a power series relationship between the actual magnitude of the haptic properties and the perceived magnitude. Friction had the largest exponent, indicating that the perceived magnitude grew fastest with increasing actual magnitude out of all the properties. This supports the earlier findings from the forced choice study that friction was the most easily discriminable of the three properties. For the purposes of the analysis, each property was divided in to eight discrete quanta over the approximate range of continuous values. Post-hoc Tukey tests showed that for the magnitude to be of a significantly different value it was necessary to move three steps for texture, two steps for stiffness and one step for friction. Hence, more discrete, distinguishable values can be achieved with friction than the other two properties, within the range considered in this study. Similarly, stiffness has more possible discrete, distinguishable values than spatial period of texture does.

5. Conclusion

In summary, this paper has described two experiments which assess the appropriateness of haptic properties of virtual objects for presenting numerical data.

The results of the forced choice experiment showed that subjects' discrimination of friction was significantly better than that of stiffness or spatial period of texture. This implies that friction may be more useful than the other two stimuli in a haptic visualization system. For example, the friction of bars in a bar chart or slices in a pie chart could be scaled to the data value in order to provide an additional haptic based cue, which is quicker and easier to perceive by haptic exploration alone. The results also showed that subjects had a greater success rate at identifying surfaces of less magnitude than the standard, compared to those of a greater magnitude, which led to the hypothesis that the users' perceived magnitude of such properties is non-linear in nature.

The magnitude estimation experiment divided the continuous scale of each variable in to eight discrete quanta that were systematically compared. Post-hoc Tukey tests showed that for the perceived magnitude to be significantly different, it was necessary to move three steps for texture, two steps for stiffness and one step for friction. Hence, a greater number of discrete, distinguishable values can be achieved with friction, which supports the results of the forced choice study. Power series models were also calculated using the averaged perceived magnitude across all subjects. Friction showed the largest exponent, followed by stiffness then texture.

In conclusion, the results presented here suggest the friction would be the most suitable property out of the three investigated to employ in future work in a haptic based visualization tool. In our future publications we will describe the results of a study in which blind and visually impaired users assessed a haptic bar chart system where the friction of the bars was scaled to their data values. This was empirically compared to an analogy of a standard, visual bar chart where height of bars is scaled to the data value.

These results can also be generalized other haptic based applications where designers wish to evoke perceptions of specific magnitudes of these haptic properties using a PHANToM device. For example, in a simple medical application, values of stiffness can be set according to the power series model in order to replicate relative perceived magnitudes of bone and different types of tissue.

In future, it would also be beneficial to designers of haptic applications to establish similar results for other haptic devices. Electromechanical properties of different devices (mechanical construction, bandwidth, max. power output, encoder resolution) may have a direct effect on the user's perceived magnitude of properties. Such results would also help to ground this study better by providing a comparison between two devices. Similarly, provision of cutaneous distributed forces on the finger pad is important for perception of properties such as friction, stiffness and texture. Discrimination capabilities would likely improve if these facilities were added to existing hardware.

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