The influence of changing haptic refresh-rate on subjective user experiences - lessons for effective touch-based applications.

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Abstract. When producing haptic renderings, it is important to know the minimum subjectively acceptable refresh rate to avoid simulation of overly complex materials. In doing so, factors such as speed/force of hand movements or material stiffness must be taken into account. An experiment was conducted to identify minimum acceptable haptic refresh rate as a function of the latter factor. A threshold of around 500Hz was found although, surprisingly, no effect of material stiffness occurred. This may have resulted from variations in participants' response strategies. A second experiment used a modified procedure to avoid this problem. However, the predicted effect was still not found. The study highlights the importance of cognitive factors in users' interpretations of sensations derived from touch and the need to account for them when designing experiments.

1 Introduction

In recent years a range of haptic devices have emerged aimed at facilitating human-computer interactions through the use of touch-based representations. For example, 2D feedback devices, such as the haptic mouse [1,2] provide simple mechanical stimulation of the hand, whilst 3D tools allow more complex simulations [3,4]. One of the most commonly used haptic devices is Sensable Technologies's PHANTOM [5]. This is a force-feedback device permitting touch-based representation in 3D through user movements of a stylus or thimble.

In its normal mode of operation it has become the *de facto* standard to use a haptic refresh rate of 1000Hz with PHANTOM devices. Indeed, this is the only rate supported by Sensable technologies. In some circumstances, however, it may be desirable to use a lower refresh rate. For instance, when computational demands are high it might be necessary to reduce the rate of haptic feedback. A good example of such a scenario is the simulation of non-rigid materials. In such situations haptic renderings may take longer than 1 msec and, as a result, feedback rates are effectively reduced [6]. It is, therefore, desirable to provide systematic assessment of the minimum acceptable refresh rate in order to avoid simulation of materials that are too complex to sustain it.

Various factors are likely to affect the quality of feedback provided by PHANTOM devices. For example, as simulated surfaces become stiffer vibrations may occur. Indeed, it has even been suggested that frequencies as high as 6000 Hz should be used to avoid buzzing effects when very stiff (>2000 N/m) surfaces must be rendered [7]. The present investigation therefore aimed to assess the minimum acceptable refresh rate as a function of stiffness - chosen because of its importance in the simulation of non-rigid materials. It did so through a method based upon the use of psychophysical staircases.

2 Experiment 1

2.1 Method

2.1.1 Participants

12 male participants took part in the experiment on a voluntary basis. All were students of the Università degli studi di Parma, Italy and had normal or corrected to normal vision. Their ages ranged from 21 to 32 years with a mean of 26.17 years.

2.1.2 Apparatus

A PHANTOM Premium (1.5 model) was used connected to a 200MHz Dual P-Pro PC with a 21 inch monitor operating at 101Hz and 1152 X 864 screen resolution (Figure 1). Participants were positioned directly in front of the PHANTOM using their right hand to operate the thimble. The computer keyboard was placed on a table at their left side, so that they could press the space bar with their left hand. The monitor was positioned at a height of 100cm, approximately 50cm in front of the subject, with the PHANTOM directly beneath at a height of 65cm.

Fig 1. The PHANTOM installation used in the experiments.

2.1.3 Stimuli

The haptic environment consisted of a horizontal surface extending forward into the depth plane. This was divided into left and right halves. It was possible to alter the refresh rate of each of the two halves independently. The visual display measured 160mm by 110mm (matching the size of the haptic display) and was presented in the centre of the screen. It consisted of two grey circles (seen as ellipses in 3D) within a black scene, each being located on opposite halves of the horizontal surface. A green ball with a radius of 5mm moved on the display in synchrony with the PHANTOM thimble. Haptic feedback would occur whenever the ball came into visual contact with either of the two circles. In order to avoid the appearance of it passing through a circle, the ball was made invisible whenever the thimble reached a position beneath the horizontal surface.

In addition, two 20mm by 20mm grey boxes were displayed, one at the top left corner of the display and the other at the top right. The former was marked with a "U" for 'Uguale' (Italian for 'Same') and the latter with "D" for 'Diverso' ('Different'). These were included for participants to make their responses.

The experiment was conducted using a Windows installation with its standard driver. The rendering frequency was therefore fixed at 1000 Hz. As the experiment required the presentation of lower frequencies these were generated at application level by sending the same force vectors to the device more than once through the standard windows driver.

This permitted the simulation of frequencies at 1msec temporal resolution, and posed an upper limit of 1000 Hz on the generated frequency.

2.1.4 Procedure

Participants were required to make judgements about whether the two halves of the horizontal surface were the 'Same' or 'Different' from one another. They did so using movements of their forefinger placed within a single PHANTOM thimble. Participants were instructed to move their hand in a natural manner by hitting (bouncing) each surface in the centre of their respective circles several times in turn at a moderate speed and force. No restrictions were placed upon the time given for them to do so, however, they were encouraged not to deliberate for a long period on each trial. Although variations between participants and within individuals could be expected due to the relatively unconstrained nature of the haptic exploration task, it was hoped to average over these in order maintain a relatively realistic PHANTOM scenario.

On each trial one half of the horizontal surface was designated as the 'Comparison' stimulus and the other as the 'Test' stimulus. These were switched from left to right at random from trial to trial without the participant's knowledge. Comparison stimuli consisted of a horizontal surface at a fixed refresh rate of 1000Hz across presentations. Test stimuli were similar except that their refresh rates could be raised or lowered according to one of two psychophysical staircases. The 'Ascending' staircase began at a refresh rate of 150Hz and increased in 50Hz steps with each successive trial up to a theoretical maximum of 1000Hz. The 'Descending' staircase, in contrast, began at 1000Hz and reduced on each trial down to a potential minimum of 150Hz. The staircase presented on each trial was chosen at random without the participant's awareness.

Participants were required to compare the two halves of the horizontal surface in the instructed manner. They then responded according to whether the two were the 'Same' or 'Different' from one another by moving the green ball (using the PHANTOM thimble) to the relevant box at either of the two corners of the visual display. Whenever responses on two successive trials on a given staircase were the same (i.e. either both 'Same' or both 'Different') the next step on that staircase continued moving 50Hz in its usual direction. If, however, a response reversal occurred between two trials on the same staircase (i.e. a change from 'Same' to 'Different' or vice versa), the direction of the next step on that staircase was reversed. Responding continued until five response reversals had been obtained on each of the two staircases.

This procedure was followed three times with each subject, once each at three levels of simulated surface stiffness: 1.2 N/mm; 0.8 N/mm; and 0.2 N/mm stiffness (1.2 = hard, 0.8 = still hard, 0.2 = soft). The order in which the three levels of hardness were tested was randomised for each subject.

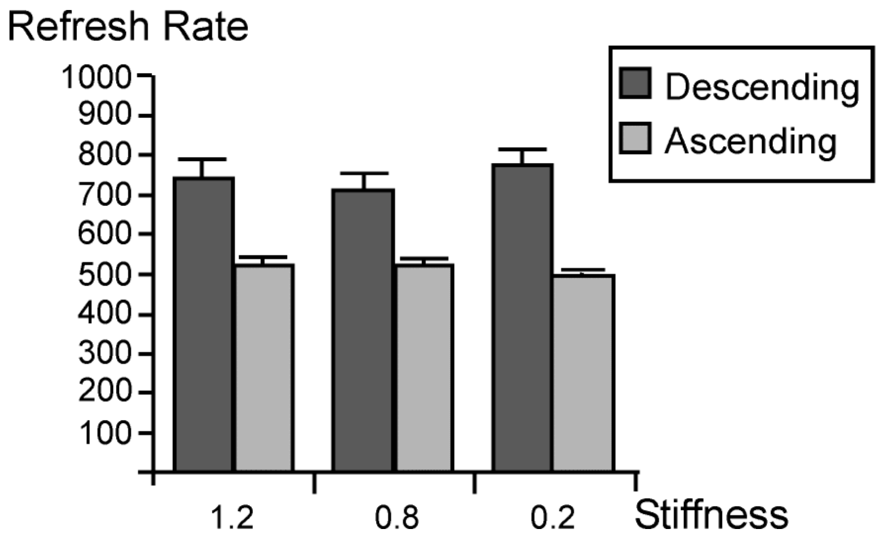

Fig. 2. Mean average minimum acceptable refresh rates at each level of hardness on the two staircases across the 12 participants in Experiment 1. Standard Error bars are indicated.

2.2 Results of Experiment 1

The refresh rates at which response reversals occurred were identified for all 12 participants separately at each of the three levels of stiffness for both the ascending and descending staircases. The median average of these was then calculated. This statistic was selected in preference to the mean in order to avoid the influence of accidental outlying responses. Figure 2 illustrates the average of these values across participants at each level of hardness separately for the two staircases. A clear difference can be seen between the two staircases, irrespective of hardness. As pointed out by an anonymous reviewer, it is not unusual to obtain differences between thresholds using staircases procedures. However, in the present instance the size of the discrepancy was much larger than might normally be expected. On the ascending staircase the average threshold was around 500Hz, with minimal error. In contrast, on the descending staircase, the corresponding threshold was much higher at around 750-800Hz and the error was larger. A Wilcoxon signed ranks test confirmed this difference statistically [$z = -4.535$, $p < .001$].

Further analysis indicated the source of the discrepancy between staircases. Whilst the data on the ascending staircase were approximately normally distributed around a single point, those obtained on the descending staircase demonstrated a binomial distribution. There appeared to be a cluster of threshold values around the same 500Hz point seen on the ascending staircase, but also a large number of responses at between 900-1000Hz.

Strangely this meant that response reversals had occurred on a number of occasions when comparison and test stimuli had the same or nearly the same refresh rate. In consequence there appeared to be a qualitative difference between the results obtained on the two staircases. As a result, they were treated separately for the purposes of further data analysis.

A single factor repeated measures analysis of variance was conducted on the ascending staircase values in order to assess the influence of stimulus stiffness. Surprisingly no effect was found [*F*(2,22)=.699, *p*=NS, *MSE*=2986.11]. As the descending staircase data were non-normal, a Friedman test was applied as a non-parametric equivalent to a single factor repeated measures analysis of variance. Again, no effect of stimulus hardness was found $[X^2_F(2) = .542,\ p = \mathrm{NS}]$. This confirms the nature of the data seen in Figure 1 where the heights of the columns on each of the two staircases remain the same across levels of stimulus stiffness.

2.3 Discussion of Experiment 1

With the benefit of hindsight, the finding that responses differed between the two staircases might have been expected. This is because the 'Same/Different' response criteria used may have been too vague for participants to produce consistent judgements. As a result, they might have adopted different response strategies on each of the two staircases. In the case of the ascending staircase, the comparison and test stimuli were different from one another at the start of the experiment, becoming progressively similar with each successive trial. Participants would therefore have been encouraged to make relatively coarse comparisons between them. In contrast, on the descending staircase, the comparison and test stimuli were almost identical to one another at the start of the experiment, gradually becoming dissimilar across trials. In consequence, participants may have made relatively detailed comparisons between them. Given that the haptic feedback experienced was dependent on participants' unconstrained finger movements, very minor, but genuine, differences would have been experienced, even when comparing stimuli that both had a 1000 Hz refresh rate. In addition, it is possible that minor mechanical artifacts resulting from differences in lateral stimulus positions (left v right) produced confounding effects. These differences would have become apparent to those participants adopting a 'detailed' comparison strategy on the descending staircase, but not to those using a 'coarse' approach. The result was the observed binomial distribution.

This interpretation of the results suggests that high-level cognitive factors have important affects on haptic judgements. Indeed, the present authors have previously suggested that, from a theoretical point of view, high-level cognitive processing may be involved in haptic perception [8,9]. It is therefore important to account for such factors when developing appropriate experimental methodologies. A second experiment was conducted to achieve this within the present context.

3 Experiment 2

3.1 Method

3.1.1 Participants

12 participants took part in the experiment (11 male and 1 female) on a voluntary basis. All were students of the Università degli studi di Parma, Italy and had normal or corrected to normal vision. Their ages ranged from 23 to 34 years with a mean of 26.33 years.

3.1.2 Procedure

Several alterations were made to the staircases design. Firstly, a change was made in the type of response required. Rather than judging whether stimuli were the 'Same' or 'Different' from one another, participants were asked to indicate the side ('Left' or 'Right') on which the most *vibration* occurred. Before testing began, demonstrations were given at reduced refresh rates of the types of mechanical effects to look for. It was hoped that this might encourage participants to make a more focused assessment of the stimuli presented, thereby avoiding potential confusion caused through the previous use of vague criteria. However, the change of response question meant that is was no longer meaningful to use descending staircases, as participants would be unable to judge between comparison and test stimulus when presentation of both began at an identical 1000 Hz refresh rate. Instead, two ascending staircases were used, each starting at 150Hz, one in which the test stimulus appeared on the left and the other in which it appeared on the right side.

Responses were collected in the same manner as in Experiment 1. However, the grey response boxes had no writing on them, as their spatial positions (above left and above right of the two stimulus circles) provided sufficient data to allow participants to produce appropriate responses.

In addition, in order to avoid interference from mechanical artifacts, the orientation of the PHANTOM was changed so that, rather than being placed to the left side of the participant’s position, it was positioned directly ahead with the thimble arm set perpendicular to the individual's body. It was hoped that this would result in identical, though laterally reversed physical feedback.

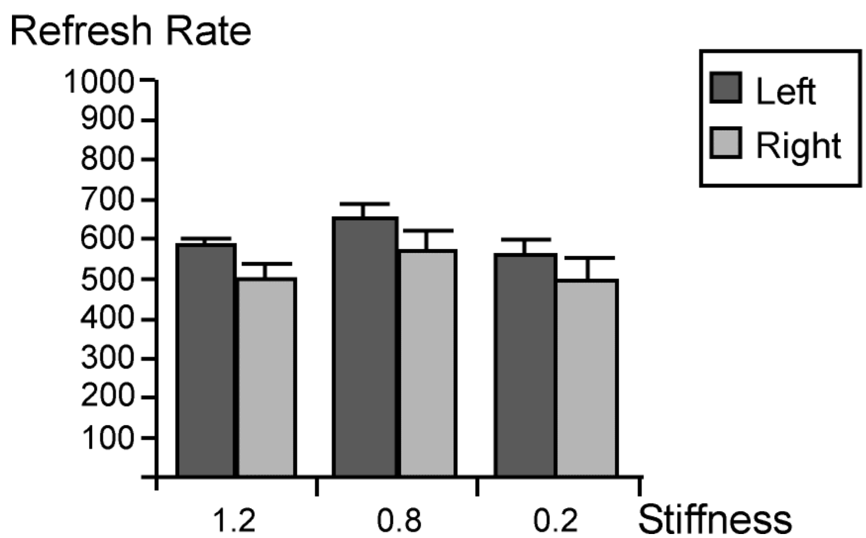

Fig. 3. Mean average minimum acceptable refresh rates at each level of hardness on the two staircases across the 12 participants in Experiment 2. Standard Error bars are indicated.

3.2 Results of Experiment 2

Responses were compiled in the same manner as Experiment 1. Figure 3 illustrates the mean threshold across the 12 participants for each of the two staircases and at the three levels of material stiffness. In contrast to Experiment 1, the values obtained were normally distributed across conditions and it was therefore possible to conduct a two-way within participants analysis of variance (Staircases Side V Material Stiffness). Once more, no effect of material stiffness was found [$F(2,22)=1.215$, p=NS, $MSE=21640.63$], although a marginal difference was observed between the two staircases (left and right) in terms of the threshold refresh rate at which vibrations became noticeable [$F(1,11)=5.145$, $p<.05$, $MSE=64201.39$]. There was no interaction between the two factors [$F(2,22)=.743$, p=NS, $MSE=6519.1$].

3.3 Discussion of Experiment 2

As in Experiment 1, no effect of material stiffness occurred. It appears that, at least within the current experimental conditions, it does not affect minimum acceptable refresh rate. This is surprising given the prior expectation that increasing stiffness would lead to an earlier awareness of surface vibrations. One reason for this may be the use of a simulated decrease in refresh rate. If a genuine change in the rate of haptic feedback were implemented, quite different subjective effects might be produced. Alternatively, the results may reflect a genuine failure of material stiffness to exert an effect. If so, it is important not to generalise beyond the present experimental circumstances. For example, the use of a wider range of material stiffness may produce the predicted effect. However, the levels used covered a wide spectrum of subjective effects, observer perceptions ranging from 'very hard' through to 'very soft'. It can therefore be concluded that, in the present instance, the minimum acceptable refresh rate must lie within the 600 to 550Hz range, irrespective of material stiffness.

4 General Discussion

Taken together the results of the two experiments suggest that, at least within the present stimulus conditions, material stiffness does not affect minimum acceptable haptic refresh rate. It is important, however, not to generalize this finding to other situations. For example, it is possible that other types of stimuli or hardware devices may produce different effects. Instead, the primary utility of the present results is in providing important lessons for the design of haptic experiments. When designing studies it is important to consider differences in response strategies adopted by participants (such as those observed in Experiment 1). This is because observers appear to engage in high-level cognitive processing of haptic phenomena. Through the use of carefully designed methodologies and precise response instructions (such as those used in Experiment 2), it becomes possible to constrain processing to the problem of practical interest and provide accurate assessments of specific response variables.

5 Conclusion

Although it might be expected that minimum acceptable haptic refresh rate would vary according to level of simulated material stiffness, no such effect was found in either of the two experiments reported here. This may reflect a genuine lack of effect or result from the use of simulated refresh rates of below 1000Hz. Importantly, evidence was found for cognitive interpretations of haptic stimuli on the behalf of observers. It is therefore important for experimental methodologies to take such effects into account through the use of properly constrained and precise procedures. The results, whilst obtained using a PHANTOM, have implications for the development of haptic devices in general.

7 Acknowledgment

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