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Perception of Mechanically and Optically Simulated Bumps and Holes

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Abstract

In this contribution we investigate the perception of optically simulated haptic feedback. The perception of optically and mechanically simulated bumps and holes was tested experimentally. In an earlier paper we have described the active cursor technique, a method to simulate haptic feedback optically without resorting to special mechanical force feedback devices, commonly applied to produce haptic percepts in computer interfaces. The operation of the force feedback device is substituted by tiny displacements on the cursor position relative to the intended force. This method exploits the domination of the visual over the haptic modality. Results show that people can recognize optically simulated bump and hole structures, and that active cursor displacements influence the haptic perception of bumps and holes. Depending on the simulated strength of the force, optically simulated haptic feedback can take precedence over mechanically simulated haptic feedback and also the other way around. When optically simulated and mechanically simulated haptic feedback counteract each other, however, the weight attributed to each source of haptic information differs from user to user. It is concluded that active cursor displacements can be used to simulate the operation of mechanical force feedback devices.

Categories and Subject Descriptors: Information Systems, User Interfaces, Haptic I/O, Input devices and strategies, Interaction styles
General Terms: Design, Experimentation, Human Factors
Additional Key Words and Phrases: Optically simulated haptic feedback, simulation, force feedback, experimentation, multisensory perception.

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1 INTRODUCTION

Before the prevalent use of computers, almost all human tasks involved the use of exquisite sensory-motor skills. By and large computer interfaces have not taken advantage of these deep-seated human capabilities. The touch feedback that did exist in older analogue technologies through mechanical mechanisms such as knobs, switches and dials has for the most part been replaced by digital electronics and visual displays. Since the invention of the mouse [English, Engelbart, Berman, 1967] and direct manipulation interfaces [Shneiderman, 1983], desktop metaphor computer interfaces based on windows, icons, menus and pointing, so called WIMP interfaces, have become the dominant paradigm in human-computer interaction. From a perceptual point of view, these interaction paradigms are extremely limited in their abilities to make use of human sensory-motor and cognitively-driven interactions. They engage only a fraction of the human sensory bandwidth. Although the lack of significant physical forces of the digital environment has some major advantages, few may doubt the intrinsic value of touch perception in everyday interactions. Research in human-computer interfaces has addressed this issue with the development and evaluation of several force feedback

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devices [Akamatsu & Sato 1994; Akamatsu et al., 1994; Brooks et al., Burdea 1996; Engel et al., 1994; Kerstner et al., 1994; Rosenberg, 1996]. These devices are used to simulate a wide range of object properties such as their elasticity, hardness, stiffness and textures, which can be used to communicate with the user through the haptic channel. Although many force feedback devices are commercially available in specialist- and gaming environments, and commonly applied to support visually impaired people, they are not part of the standard desktop computer setup. Not much software has been developed that uses direct haptic feedback as a primary communication channel. Here a vicious circle becomes visible: On the one hand force feedback devices are not part of the standard computing setup, because there are hardly any interaction styles developed that use haptic feedback as a primary communication channel. On the other hand, there are hardly any interaction styles developed that use haptic feedback as a primary communication channel, because force feedback devices are not part of the standard setup.

In an earlier paper [Mensvoort, 2002] we presented optically simulated force feedback, a method aimed at evoking a percept of touch in a standard GUI desktop setting, without resorting to special and haptic input/output devices. This simulation of touch is realized by tiny displacements of the cursor position. The displacements speed up the cursor movements for force feedback in the direction of the movement, and slow it down or become negative for forces in the opposite direction. For forces in other directions similar mechanically plausible rules apply. The disparity between the visual information, i.e., slowing down the speed of the cursor, and the increasing reaction force applied to the input device to compensate for this, appears to induce an illusion of haptic feedback. Optically simulated force feedback has much in common with existing force feedback systems, except that in force feedback systems the location of the cursor is manipulated as a result of the mechanical manipulation of the haptic input/output device, whereas in our system the cursor location is manipulated directly.

Like force feedback devices, the active cursor displacements can guide the user towards preferred positions or communicate properties of the interface to the user. Among the virtual haptic objects we have created are 'holes' and 'bumps'. If the cursor moves over a hole, it is dragged towards the centre. When rolling over a bump, the cursor is pushed away from the centre. Due to these cursor displacements a hole becomes an easily accessible part of the screen, whereas a bump area is hard to access. We suggested that this technique can be applied to simulate the functioning of mechanical force feedback devices and established the usability benefits of the active cursor technique in a pointing task [Mensvoort et al. 2008]. An interactive demonstration, requiring a Flash plug-in, as well as a toolkit which allows interaction designers to apply optically simulated force feedback to their own interfaces, is online at www.powercursor.com [Mensvoort, 2007].

In the current study we assess the perception of bumps and holes, generated with active cursor displacements in comparison with the perception of bumps and holes generated by a mechanical force feedback mouse device. The experimental setup was inspired by the work of Robles-De-La-Torre and Hayward [2001], who assessed the perception of bumps and holes and, by using an ingenious robotic device, were able to uncouple force feedback from geometric information. Through this uncoupling they were able to generate stimuli with the geometric properties of a hole, but with the force feedback properties of a bump, and visa versa. Think for instance of a contradictionary structure that, when explored geometrically by moving your finger, makes your finger go down just as it would when the finger passes into a hole, but at the same time pushing it away from its centre with force feedback, just as it would when a bump structure would be passed. They found that force cues — not geometric cues — determine perceived shape. Likewise, we in our study uncouple the visual force information, i.c. cursor displacements seen on the screen, from the haptic force information generated by the mechanical haptic device. In a factorial design we compared the perceptual effect and interaction of both types of simulated haptic feedback, and determined how optical and mechanical haptic feedback independently and jointly contributed to this topographical experience.

In this respect we formulated two hypotheses. Our first hypothesis is that optically simulated haptic feedback can be applied to create perceivable 'bump' and 'hole' structures and that people are able to judge the heights of the bumps and the depths of the holes to an extent comparable to that obtained with mechanically simulated haptic feedback.

Our second hypothesis is that optically simulated haptic feedback can be used to enhance or decrease the perceived height of 'bump' and 'hole' structures generated with a mechanical force feedback device. In other words, our second hypothesis states that optically simulated haptic feedback can influence the perception of mechanically simulated haptic feedback.

2 OPTICALLY SIMULATED HAPTIC FEEDBACK

2.1 Related Work

The active cursor technique [Mensvoort, 2002] aims at evoking haptic effects, while using a normal mouse not capable of producing any force feedback except that involved in resistance as the mouse is moving over a surface. Comparable techniques of simulating touch through manipulation of the graphical element that represents the user have been intuitively applied earlier in videogames. For example, in the classic racing game Outrun [Suzuki, 1986] the players must, when the road bends, exert force on their input devices to keep the car in the middle of the road. This effect provides the players with the sensation of being "pushed" off the road. Apparently, the visual domain dominates the haptic domain in this situation, and this induces the illusion that the input device exerts a force in the direction of these additional cursor displacements. In this way haptic percepts like stickiness, touch, or inertia can be evoked.

Numerous studies on human perception also indicate that stimuli in one modality can evoke percepts in another [Marks, 1978; Stein, 1993; Welch, 1986]. We know that humans exhibit distal attribution, which is the tendency to quickly integrate multi-modal sensations into single meaningful events in the external world. Gibson [1966] describes our senses as active interrelated systems providing information for our perception of the real world. It is well know that vision can influence haptic perception [Heller et al. 1999; Klatzky et al. 1987; Lederman et al. 1986; Rock and Victor 1964]. A classic and robust example of visual-to-haptic intersensory interaction is the size-weight illusion, documented by Charpentier [1894] and Flourney [1891] over 100 years ago [Murray, 1999]. When lifting two objects of different volumes but equal weights, people judge the smaller object to be heavier. In this example, haptic feedback still plays a role, since the volume of the object is not only seen, but also felt by the hand. Runeson and Frykholm

[1981] showed that an external observer, watching another person handling a heavy box, is able to infer the weight of the lifted object. They concluded that visual information passed through the optic array and representing the kinetic pattern of the movement can also play a role in extracting higher-order properties within the haptic domain. Vision is thus assumed to contribute to what is generally taken to be the privileged domain of the haptic sense combining tactile and proprioceptive cues. Carr and Lederman [1995] have demonstrated the dominance of vision over haptics in various experiments. Research by Miner [1996] demonstrates that visual stimuli can influence haptic perception in virtual environments. More recently, Ernst and Banks [2002] showed that humans integrate visual and haptic information in a statistically optimal fashion.

2.2 Application in WIMP interfaces

In WIMP based graphical user interfaces, an early application of what in retrospect can be considered as optically simulated haptic feedback is the use of *sticky icons* introduced by Keyson [1997] and Worden [1997]. With sticky icons the cursor’s control/display ratio, which determines the mapping between the physical mouse movement and the cursor movement on the screen, is reduced as the cursor enters a target, and then returns to normal after passing the target. Inside the target, equal mouse movements result in smaller cursor movements due to the change in cursor gain. In this way, the cursor speed diminishes, when the user enters a target, though keeping the mouse speed constant. Like with the active cursor technique [Mensvoort, 2002] this reduction effectively results in an enlargement of the motor space underneath the target, while the visual space remains unchanged. The decoupling of motor space and visual space induces the ‘sticky’ feeling. Ahlström [2002] suggested that the cursor gain technique, manipulation of cursor gain, could also be used to simulate more complex slopes like holes and hills and that these could be applied to guide a user in a graphical user interface. Lécuyer et al. [2004] conducted a perceptual experiment confirming that subjects indeed could identify various types of bumps and holes by seeing the variation of the cursor gain. In a more recent study Lécuyer et al. [2008] showed that bump and hole structures can also be recognised by altering the size of the cursor according to the height of the slopes, as it moves over.

Various experiments have been conducted to assess the benefits of cursor manipulation techniques in WIMP interface. Keyson [1997] compared mechanical force feedback, consisting of a pulling force towards the centre of a target, with sticky targets, consisting of a reduction of the cursor gain within the target. The results of the experiment showed that target acquisition performance was generally higher in the tactile-feedback condition, followed by cursor-gain feedback, and then normal cursor control. In research by Worden [1997], the sticky icons had no effect on accuracy, but substantially improved the speed of performance over the traditional pointer. Older users especially benefited from the adaptive technique. Given the pervasiveness of pointing in graphical interfaces, every small improvement in the target-acquisition task, represents a substantial improvement in usability. Blanch et al. [2004] formalized the cursor gain technique and showed its performance in a pointing task is given by Fitts' index of difficulty in motor rather than visual space. Baudisch,et al. [2005] showed the benefits of the cursor gain technique in a snapping task. The benefits of the active cursor technique have been established experimentally in targeting tasks [Park et al. 2006; Mensvoort et al. 2008] and steering tasks [Ahlström 2005].

While pointing in the physical world is governed by Fitts' law and constrained by physical laws, pointing in the virtual world does not necessarily have to abide by the same constraint [Balakrishnan 2004]. Both the cursor gain and the active cursor technique are aimed at decoupling the visual space and motor space through cursor manipulation. The active cursor technique differs from the cursor gain technique in that the direction of adjustment is not necessarily parallel to the direction of the mouse movement. Although the cursor gain technique [Keyson 1997; Worden 1997; Ahlström 2002; Blanch et al. 2004; Lécuyer et al. 2004; Baudish et al. 2005] is easy to implement, it only works when the mouse is being moved by the user and is limited to the direction of the users' movement. Just as for mechanical force feedback devices, the active cursor technique [Mensvoort 2002; Ahlström 2005; Park et al. 2006; Mensvoort et al. 2008] also works when the user is not moving the mouse. From a mathematical perspective, the manipulation of cursor gain is a more restricted way to simulate force feedback than actively displacing the cursor; the active cursor algorithm can, by constraining the cursor displacements within the vector of the user's mouse movement, be set to generate the same effects as the cursor gain technique but not the other way round. Ahlström [2006] compared the active cursor technique (force fields] with the cursor gain technique (sticky targets] in two realistic pointing situations which involve several closely placed targets and found that the force fields improve pointing performance and that the sticky target technique does not. However, this does not mean that the active cursor technique's more realistic way of simulating force feedback will in all cases lead to advantages for the user; having the cursor move without the user's action may also lead to drawbacks in some cases. Further research, which falls outside the scope of the current study, is required in this regard. Our current contribution focuses on a comparison between optically and mechanically simulated force fields.

2.3 Terminology

Within haptic- and human computer interaction literature various terms are often used with different meanings that change over time. Haptics is often used as a catchall term to cover a variety of distinct sub-types, including proprioceptive (general sensory information about the bodily position and relative position of neighbouring bodyparts], vestibular (the perception of head motion], kinaesthetic (the feeling of motion in the body], cutaneous (sensory information from the skin like heat, cold and pain], and tactile (the sense of pressure experienced through the skin]. In the context of computers, haptic feedback can refer to the simple feel of a keyboard or mouse, or to more sophisticated forms of force feedback employed by mechanical devices.

When the first mechanical force feedback devices were invented the term 'force feedback' was still reserved for unmediated haptic feedback, resulting from direct contact between the human body and some object in the physical environment. At that time, device-generated haptic feedback was referred to as 'simulated force feedback' or 'virtual force feedback' [Bejczy et al., 1990; Burdea and Langrana, 1993], emphasizing that the device simulated a haptic effect; not the real thing, but a substitute. With the acceptance of such mechanical force feedback devices the adjectives 'simulated' and 'virtual' were dropped in the literature. Nowadays, when using the term 'force feedback', one usually means the haptic feedback generated by a mechanical device. In the literature and popular language, these devices are usually described as ‘force feedback devices’, ‘haptic devices’, or sometimes redundantly as ‘haptic force feedback devices’.

Regarding techniques that produce haptic percepts by optical means, various terms have been suggested; sticky icons [Worden 1997] simulated force feedback [Mensvoort 2002], pseudo haptic feedback [Lécuyer 2000], force fields [Ahlström 2005], gravity [Park et al. 2006]. Although terms like ‘sticky’, ‘force’ and ‘gravity’ are easy to understand, they overlook that the haptic perception is simulated. Terms like ‘simulated’ and ‘pseudo’ are more precise in this regard, but still lack for not specifying the means of the simulation. Especially when techniques are compared across modalities the lack of precise terminology becomes problematic. Given that in the current study haptic percepts are simulated both mechanically and optically, we need to use a terminology descriptive enough to distinguish between the two techniques. In order to meet this requirement we speak of ‘mechanically simulated haptic feedback’ and ‘optically simulated haptic feedback’. We chose this terminology because it precisely and transparently describes both techniques; haptic percepts are simulated by mechanical/optical means.

3 METHODS

3.1 Subjects

Thirty volunteer subjects participated. There were 19 male and 11 female subjects, ranging in age from 20 to 36 years. Of the 30 participants 23 were right-handed and seven were left-handed. All subjects were regular users of mice in their daily work. The subjects were not informed about the goal of the experiments in advance. During the experiment, subjects were presented with various bump/hole structures which they could explore with the mouse in order to determine their heights/depths. The slopes of some bump/hole structures were generated through optically simulated haptic feedback, those of others through mechanically simulated haptic feedback, and some through, matching or conflicting, combinations of both techniques. The subjects were not informed about the different techniques used to generate the haptic structures. We divided the subjects randomly into three groups of ten people; each group being assigned a different combination of ranges of the mechanical and optical nominal force setting.

3.2 Apparatus

The experiment was conducted using the Logitech Wingman force feedback mouse, a mouse attached to a mouse pad replacing the mouse mat and with two motors supplying force feedback to the user [Rosenberg, 1997]. This mouse was used in all experimental conditions. The host computer was a Pentium III class PC with a screen resolution of 1024x768 pixels on a 17-inch monitor. The default Windows XP cursor was used. The experiment was implemented in C++. The data were collected with 1-pixel and 1-ms resolution and saved in output files for subsequent analysis. The subjects sat in a quiet, isolated room. During the session the experimenter waited at the other side of the room. For the mechanically simulated haptic feedback condition, the motors in the Logitech Wingman force feedback mouse were used to create hole-shaped and bump-shaped force-fields, pushing the pointing device and consequentially the cursor towards the centre of the target or away from the centre. In the optically simulated force feedback condition the same force field was simulated directly with cursor displacements. Since the mechanical simulation outputs to the pointing device, while the optical simulation outputs to the cursor position, both feedback conditions could be easily intervened. Both techniques derive their own force vector from the steepness of their own slope definition underneath the current cursor position – note that this cursor position can be altered by the user as well as by the forces exercised by one or more of the techniques.

For the experiment we needed a formula that could render fluent bumps and holes and without artefacts that could function as unintended cues for the subjects to recognise the shapes. We tried different mathematical means of rendering the bumps and holes: linear, polynomial, Gaussian, and sinusoid. The polynomial shapes were not chosen because they have discontinuous derivatives at their boundaries at the zero plane that could become an unintended cue for the subjects. The linear shape has discontinuities both at the zero plane and at the top. The Gaussian shape is completely continuous, but is zero nowhere. For the current experiment we chose to use a squared cosine shape since this shape results in a bump or hole with a clear but not too abrupt boundary and a smooth top (figure 1).

$$f(x) = \cos^2(x) \quad 0 \le x \le \tfrac{1}{2}\pi$$

$$f(x, y) = \cos^2(\sqrt{(x^2 + y^2)})$$

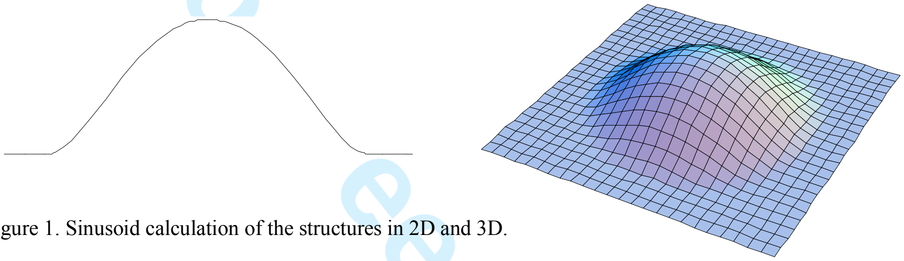
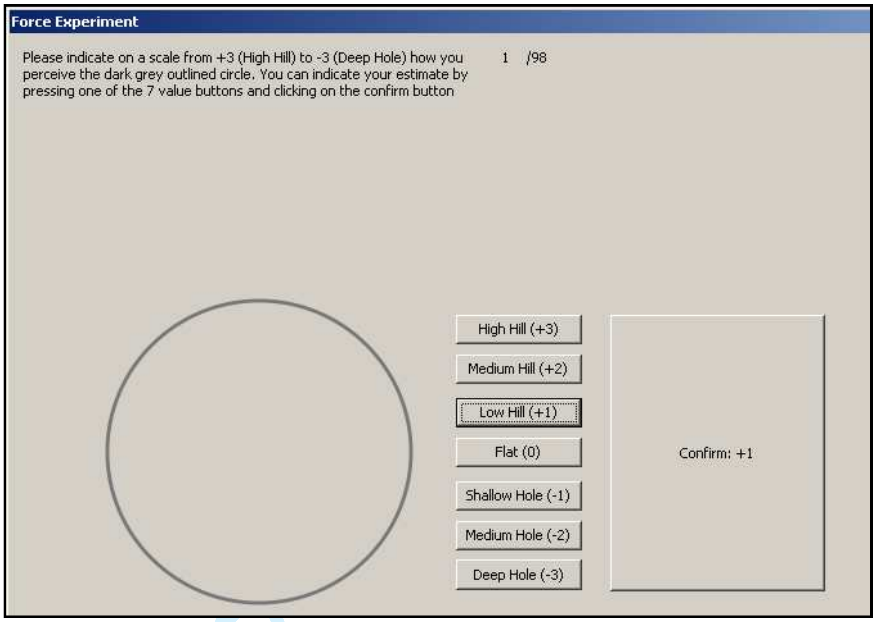


Figure 1. Sinusoid calculation of the structures in 2D and 3D.

The circular area where the force field was applied had a diameter of 240 pixels, the same as the diameter of the area occupied by the visually displayed target. The range of the mechanical forces applied to the mouse and the range of the force gains of the optically simulated haptic feedback was set by a committee of four people that were involved in similar projects and had knowledge of the techniques used. They preset the optically and mechanically simulated strength so that they were, in their perception, individually equal. This was done by conducting a series of mini-experiments in which these four people compared different mechanical strengths to different optical strengths up to the point where they believed the most extreme slopes (deep hole and high bump) to be equal across the two conditions. The values resulting from this cross-modal matching are called the nominal values. During the experiment this setting was varied between the three different groups.



Please indicate on a scale from +3 (High Hill) to -3 (Deep Hole) how you perceive the dark grey outlined circle. You can indicate your estimate by pressing one of the 7 value buttons and clicking on the confirm button

Figure 2. Screenshot of the experiment.

3.3 Procedure

In the experiment the subjects were presented with a series of ‘bump’ and ‘hole’ shaped force feedback fields centred in an area indicated by a circle 240 pixels in diameter (figure 2). The force fields were generated as a combination of mechanically and optically simulated force feedback in independently varying strengths. Subjects were instructed to move the cursor over the circle on the screen and asked to indicate how deep or high the structure was they perceived within the outlined circle. They were asked to do this at their own pace. They were not informed in advance about the different feedback conditions.

After the experiment the subjects were asked if they experienced different ways of representing the bumps and holes and if so, which ones. In addition, they were asked what strategy they used to determine the height or depth of a field and, finally, if they had had previous experiences with force feedback before the experiment.

3.4 Design

The experiment was a 7x7 within-subjects design. The two factors, optically simulated haptic feedback (OSHF) and mechanically simulated haptic feedback (MSHF), were varied over seven levels:

OPTICALLY SIMULATED HAPTIC FEEDBACK	-3,-2,-1,0,+1,+2,+3
MECHANICALLY SIMULATED HAPTIC FEEDBACK	-3,-2,-1,0,+1,+2,+3

The mechanically and optically simulated components both have seven different height settings: deep hole (-3), medium hole (-2), shallow hole (-1), flat (0), low bump (1), medium bump (2), high bump (3). Combining these settings into a factorial design, results in 49 combinations of optical and mechanical force field stimuli. In the first half of the experiment, all 49 combinations were presented to the subjects in random order. In the second half the same series of combinations was shown but in reversed order, resulting in a total of 98 trails. For each of these trails the user had to estimate the height of the force feedback texture underneath the disk on an integer scale from -3 to +3, where -3 represents a strong hole and +3 a strong bump. Note that in a part of these combinations the various types of feedback reinforce each other, whereas in other combinations they counteract. For instance, a medium bump in mechanical force feedback (+2) combined with a deep hole (-3) with optically simulated force feedback will result in a contradictory hole/bump situation (+2,-3) in which the subject has to integrate between the different modalities.

We introduced a test phase at the beginning of the experiment, to let the users know what kind of heights they would encounter during the experiment. During this phase the nine most extreme values (+3,+3),(+3,0),(+3,-3), (0,+3),(0,0),(0,-3), (-3,+3),(-3,0),(-3,-3) from the main experiment were presented to the subjects in a setting that is identical to that of the main experiment. Likewise these values were displayed in a randomized order.

In order to gain insight into a possible turning point between the dominance of the different modalities, we divided the subjects into three groups of ten people; each group conducted the experiment with different ranges of the mechanical and optical nominal force settings.

- Group 1 : 100% nominal optical strength, 80% nominal mechanical strength
- Group 2: 100% nominal optical strength, 100% nominal mechanical strength
- Group 3: 80% nominal optical strength, 100% nominal mechanical strength

We thus conduct three experiments – one for each group – which only differ in the strength settings of the various forces. As mentioned, these nominal settings were determined on the basis of four informed judges who tried to balance the perceived relative strengths of the two feedback conditions in such a way that, on average, they would play an equal role.

Another more fundamental reason to carry out the experiment for three different ranges of the optical and the mechanical strength is to control for the possible strategy participants may adopt to adapt their estimations to these ranges. So, their strategy might be, after the practice trials, to rate the depth of a hole with -3 when both the optical and the mechanical strength are minimum, and to rate the depth of a hole with +3 when both optical and mechanical strength are maximum, more or less independent of the actual settings of these ranges. If the participants would follow this strategy the results for the three experiments will be the same. If not, the estimations by the participants will vary in accordance with the different ranges of the optical and the mechanical strengths of the simulation.

4 RESULTS

It appeared that participants easily recognized the condition in which both optical and mechanical feedback were 0; in all cases they indicated the height of the object as 0. This means that the variance for this data point is zero, and so it was excluded from the following analyses of variance.

The data were subjected to a 3-way analysis of variance with the estimations (ESTIM) of the height of the virtual object as dependent variable, and the factor EXP, experiment, representing the three nominal settings of the ranges of the two kinds of feedback, the factor OSHF, the strength of the optically simulated haptic feedback, and the factor MSHF, that of the mechanically simulated haptic feedback MSHF. The results are presented in Table I. There are significant effects of MSHF (F (6, 2736) = 143.152; $p< 0.001$) and OSHF (F (6, 2736) = 958.367; $p< 0.001$), but not of EXP (F (2, 2736) = 0. 272; $p= 0.762$). On the other hand, there is no significant first-order interaction between MSHF*OSHF (F (35, 2736) = 0. 619; $p=0.961$); but there are significant first-order interactions between MSHF*EXP (F (12, 2736) = 8.622; $p<0.001$) and OSHF*EXP (F (12, 2736) = 5.205; $p<0.001$).This shows that the effect of both mechanically and optically simulated haptic feedback depends on the factor EXP, experiment. So, the different ranges used for the three experimental set-ups lead to significantly different estimations of the height of the virtual objects. The data of the three experimental conditions will, therefore, be analysed separately. Finally, there was no significant three-way interaction between MSHF, OSHF, and EXP. We will discuss the results of Experiment I, representing the 10 subjects of group 1, in detail and then only deal with the differences found for the other experiments II and III, which represent the subjects of group 2 and 3.

Tests of Between-Subjects Effects(b)

Dependent Variable: ESTIM

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	6292,388(a)	143	44,003	47,858	,000
Intercept	28,631	1	28,631	31,139	,000
EXP	,500	2	,250	,272	,762
MSHF	789,719	6	131,620	143,152	,000
OSHF	5286,993	6	881,165	958,367	,000
EXP * MSHF	95,126	12	7,927	8,622	,000
EXP * OSHF	57,433	12	4,786	5,205	,000
MSHF * OSHF	19,934	35	,570	,619	,961
EXP * MSHF * OSHF	42,738	70	,611	,664	,986
Error	2515,600	2736	,919		
Total	8838,000	2880			
Corrected Total	8807,988	2879			

a R Squared = ,714 (Adjusted R Squared = ,699)
b Weighted Least Squares Regression - Weighted by MSHF ~= 0 | OSHF ~= 0 (FILTER)

Table 1: ANOVA table for the 3-way analysis of variance with the factor EXP for Experiment, the factor MSHF for the strength of the mechanically simulated haptic feedback, and OSHF for the strength of the optically simulated feedback.

4.1 Experiment I

The results of Experiment I, belonging to group 1, in which the participants received 100% nominal optically simulated haptic feedback and 80% nominal mechanically simulated haptic feedback, are presented in figure. 3. The vertical lines indicate for each combination of mechanically- and optically simulated haptic feedback the standard deviations of 20 estimations, 2 estimations for all 10 participants.
The estimations by the participants of Experiment I were subjected to a two-way analysis of variance with MSHF and OSHF as fixed factors. There were significant main effects of both MSHF (F (6, 912) = 27.672; $p<0.001$) and OSHF (F (6, 912) = 427.526; $p<0.001$). There was no significant interaction (F (35, 912) = 0.503; $p=0.993$). Hence, we can collapse the data over MSHF and over OSHF, resulting in two marginal means. The results are shown in Fig. 4. It can be seen that, for mechanically simulated haptic feedback, with the data collapsed over optically simulated haptic feedback, the range of the estimations is much smaller than for optically simulated haptic feedback, while the standard deviations of the result are much larger. This shows that in this experimental configuration the participants attributed more weight to the values of the optically simulated haptic feedback than to those of the mechanically simulated haptic feedback. This is substantiated by the linear regression analysis on the data which shows that the regression coefficient was 0.739 for OSHF and 0.188 for MSHF; the intercept was 0.101. The correlation coefficient between OSHF and the estimations of the participants was 0.831, whereas it was 0.211 for MSHF, which is highly significant according to the difference test for correlations coefficients based on Fisher's z-transform ($z = 21.37$, $N = 960$; $p< 0.001$).

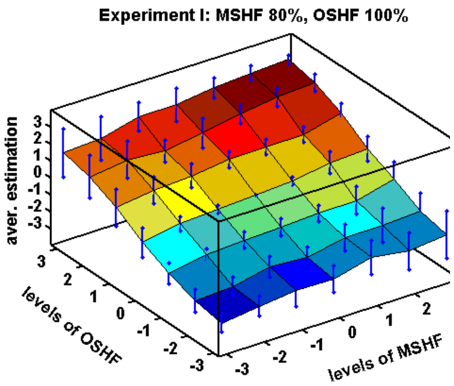


Figure 3: Average estimations of the height of the virtual bumps and holes for the feedback conditions of Experiment I, in which the mechanically simulated haptic feedback (MSHF) varied over 80% of its maximum range and optically simulated haptic feedback (OSHF) over 100%.

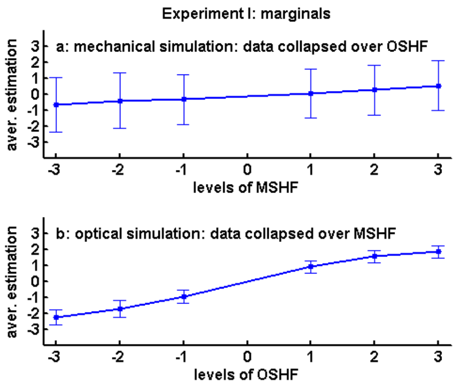


Figure 4: Marginal means of the estimations shown in Figure 3. In the results for mechanically simulated haptic feedback are presented; hence, the data are collapsed over optically simulated haptic feedback. In b the results are collapsed over mechanically simulated haptic feedback, showing the results for optically simulated haptic feedback. The vertical lines represent one standard deviation up and one down.

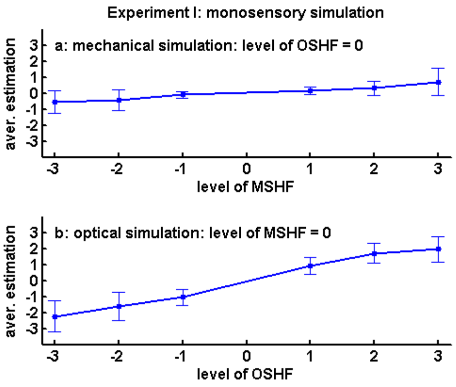


Figure 5: Average estimations for the monosensory stimulation conditions, which means that either optically simulated haptic feedback was zero (a) or mechanically simulated haptic feedback was zero (b). Note that these graphs are the same as the vertical cross sections of figure 9 along the two horizontal axes.

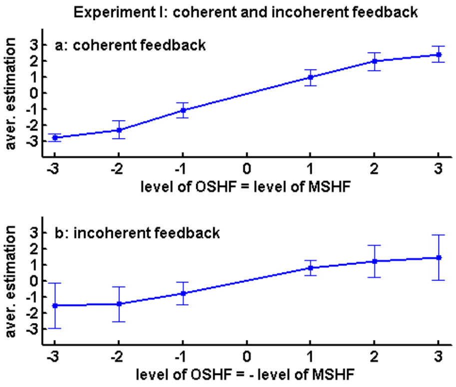


Figure 6: Average estimations of the data shown in Figure 3 for which the optically simulated haptic feedback was equal to the mechanically simulated haptic feedback, the coherent condition, compared with the incoherent condition for which the optically simulated haptic feedback was opposite to the mechanically simulated haptic feedback. Note that these represent the diagonals shown in Figure 3. In (a) the results for the coherent feedback are presented; in (b) the results for the incoherent feedback.

The finding that in this experimental configuration the participants attributed more weight to the values of the optically simulated haptic feedback than to those of the mechanically simulated haptic feedback can also be seen by comparing the conditions in which there is only mechanically simulated feedback with those in which there is only optically simulated feedback. The average results for these mono–sensory conditions are shown in Fig.5, in 5a for the purely mechanical simulations and in 5b for the purely optical simulations. Notice that in the purely mechanical simulation shown in Fig.5a, the standard deviations are much smaller than in the collapsed data shown in Fig. 4a, which demonstrates that the large variance represented by the high standard deviations of figure 4a is induced by the variance introduced by the levels of the optical simulations. This in contrast with the conditions of purely optical simulations shown in Figs 4b and 5b.

Another interesting aspect becomes apparent when one looks at the diagonals of Figure 3. The diagonal from the front corner, the point (-3, -3), to the back corner left to right, the point (3, 3), shows the estimations by the participants for those feedback conditions in which the numerical category of the mechanically simulated haptic feedback was equal to that of the optically simulated haptic feedback; so, mechanical and optical feedback reinforce each other. This will be called *coherent feedback*. The other diagonal, running from the left to the right corner, on the other hand, shows the conditions in which mechanical and optical simulations oppose each other. This will be called *incoherent feedback*. Notice that the standard deviations for the values on the latter diagonal look larger than for those on the former. This is substantiated by the amount of explained variance in both conditions as determined by the correlation coefficients between feedback and the estimations by the participants. In the coherent feedback condition it is 70%, whereas in the incoherent condition it is only 4%. This is highly significant ($z = 5.70$, $N = 120$; $p < 0.001$).

It is concluded that in the incoherent condition the variability of the responses is much larger than in the coherent condition. In addition, a three-way ANOVA with MSHF and OSHF as fixed factors, and participant (PP) as random factor resulted in no main effect of PP, but there was a significant interaction between both MSHF and PP ($F(54, 315)=5.285$; $p < 0.001$), and OSHF and PP($F(54, 315)=9.026$; $p < 0.001$). This shows that different participants reacted differently to the different combinations of feedback. The much smaller amount of explained variance in the incoherent stimulus condition shows that this is to a large extent due to the different responses in the incoherent stimulus conditions, whereas participants are more consistent with each other in the coherent condition.

4.2 Experiments II and III

The main difference between the results of the three experiments corresponded with the larger range covered by the strength of the mechanical simulation relative to that of the optical simulation. In Experiment II the nominal range of the mechanical simulation was increased from 80% to 100%, while in Experiment III the range of the optical simulation was reduced from 100% to 80%. This expressed itself in a higher weight the participants attributed to the mechanical component of the stimulus in Experiment II and III. Hence, the results were similar to those of Experiment I except for shifts according to the different balance between the mechanical and optical contribution to the simulations. This will be discussed in detail now.

Indeed, in Experiment II there were significant main effects of both MSHF (F (6, 912) = 32.847; $p<0.001$) and OSHF (F (6, 912) = 346.737; $p<0.001$), while there was no significant interaction (F (35, 912) = 0.672; $p=0.928$). In Experiment III, with similar results, the statistics were F (6, 912) = 91.905; $p<0.001$, for MSHF, F (6, 912) = 217.535; $p<0.001$, for OSHF, and F (35, 912) = 0.749; $p=0.855$ for the interaction. Hence, we can collapse the data over MSHF and over OSHF, resulting in two marginal means. The results are shown in Fig. 13 for Experiment II and in Fig. 14 for Experiment III. It can be seen that, again, for optically simulated haptic feedback, with the data collapsed over mechanically simulated haptic feedback, the range of the estimations is smaller, and the size of the standard deviations of the estimations is much larger, than for mechanically simulated haptic feedback, with the data collapsed over OSHF. This shows that, although the nominal contribution of the mechanically simulated haptic feedback was larger now, also in this experimental configuration the participants attributed more weight to the values of the optical simulation than to those of the mechanical simulation.

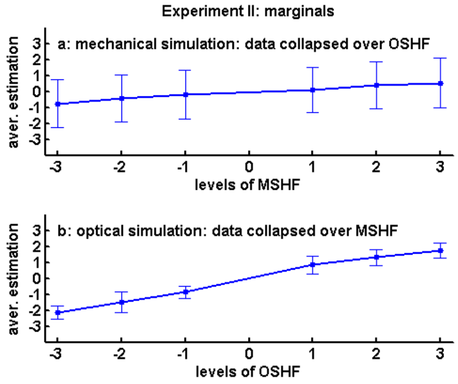


Figure 7: Marginal means of the estimations of Experiment II. In (a) the results for mechanically simulated haptic feedback are presented; hence, the data are collapsed over optically simulated haptic feedback. In (b) the results are collapsed over mechanically simulated haptic feedback, showing the results for optically simulated haptic feedback. The vertical lines represent one standard deviation up and one down.

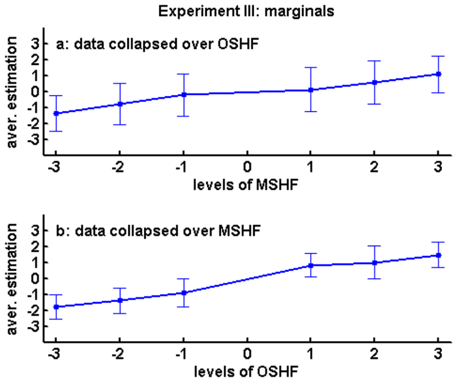


Figure 8: Marginal means of the estimations of Experiment III . For details see Fig. 7.

This is substantiated by a linear regression analysis on the data which for Experiment II yielded a regression coefficient of 0.678 for OSHF and 0.209 for MSHF; the intercept was 0.086. The correlation coefficient between OSHF and the estimations of the participants was 0.801, whereas it was 0.246 for MSHF, which difference is highly significant according to the difference test for correlations coefficients based on Fisher's z-transform ($z = 18.60$, $N = 960$; $p < 0.001$). Observe that the difference between the weights attributed to optically simulated haptic feedback and to mechanically simulated haptic feedback diminishes in correspondence with the larger range of the mechanically simulated haptic feedback which from Experiment I to II was increased from 80% to 100%. For Experiment III these regression coefficients were 0.581 for OSHF and 0.376 for MSHF, while the intercept was 0.119. The correlation coefficient between OSHF and the estimations of the participants was 0.675, whereas it was 0.437 for MSHF, which difference is again highly significant ($z = 7.69$, $N = 960$; $p < 0.001$). The smaller difference between the weights now corresponds with the smaller range of the optically simulated haptic feedback which from Experiment II to III was decreased from 100% to 80%.

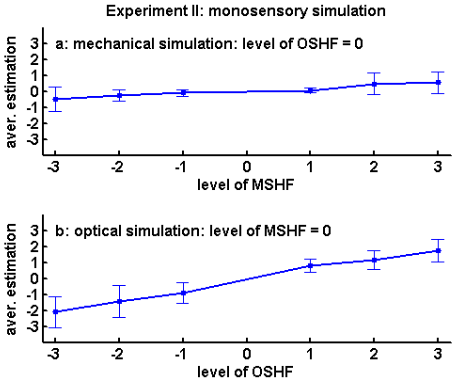


Figure 9: Average estimations of experiment II for the monosensory stimulation conditions, which means that either optically simulated haptic feedback was zero (a) or mechanically simulated haptic feedback was zero (b). Note that these graphs are the same as the vertical cross sections of figure 9 along the two horizontal axes.

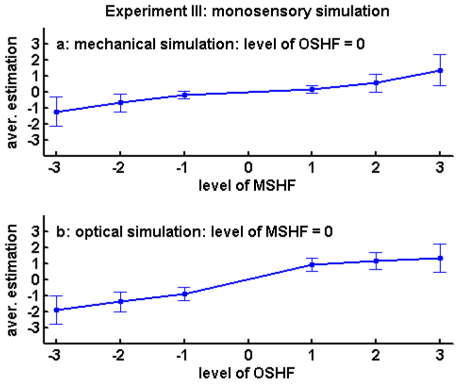


Figure 10: Average estimations of experiment III for the monosensory stimulation conditions, which means that either optically simulated haptic feedback was zero (a) or mechanically simulated haptic feedback was zero (b). Note that these graphs are the same as the vertical cross sections of figure 9 along the two horizontal axes.

Showing the results for the monosensory simulations gives a similar picture as for experiment I. This is shown in Figs. 9 and 10. Again the variance of the monosensory conditions with purely mechanical simulations, shown in Fig. 9a and 10a, is much less than that of the average conditions shown in Fig. 7a and 8a, which contrasts with the conditions of purely optical simulations. But note that the difference is less for Experiment III (Fig. 10) than for Experiment II (Fig. 9), which in its turn is less than for Experiment I (Figure 5). This must be due to the range of the mechanical levels now being relatively wider in Experiment III than in Experiment II, where it is wider than in Experiment I, this in relation to the range of optical levels. In other aspects the results are similar. Furthermore, the standard deviations in Fig. 10b are now larger when compared with Fig. 9b, where it is larger than in 5b. This shows that the effect on the participants' estimations of the mechanical simulation is now stronger than in experiment II, where it is stronger than in Experiment 1.

The results for the coherent and the incoherent stimulus conditions are presented in Fig. 11 for Experiment II and in Fig. 12 for Experiment III. A comparison between the coherent and the incoherent stimulus conditions in Experiment II gives a percentage of explained variance of 64% in the coherent feedback condition and of 6% in the incoherent feedback, which is highly significant ($z = 6.87$, $N = 120$; $p < 0.001$). For Experiment III the results are 46% for the coherent feedback condition and 19% for the incoherent feedback, which is highly significant ($z = 12.30$, $N = 120$; $p < 0.001$). So, it is concluded again that in the incoherent condition the variability of the responses is much larger than in the coherent condition. And as in Experiment I, another three-way ANOVA with MSHF and OSHF as fixed factors and PP as random factor resulted in no main effect of PP, but in significant interactions between MSHF and PP (Experiment II: $F(54, 315)=6.405$; $p < 0.001$; Experiment III: $F(54, 315)=4.548$; $p < 0.001$), and OSHF and PP((Experiment II: $F(54, 315)=10.843$; $p < 0.001$; Experiment III: $F(54, 315)=4.945$; $p < 0.001$). This shows that participants did not respond in the same way to the various feedback conditions. The much smaller amount of explained variance in the incoherent stimulus condition shows that this is largely due to the different responses in the incoherent stimulus conditions. Observe that the difference in explained variance between the coherent and the incoherent condition is larger, again, than in Experiment II, where it was already larger than that in Experiment I.

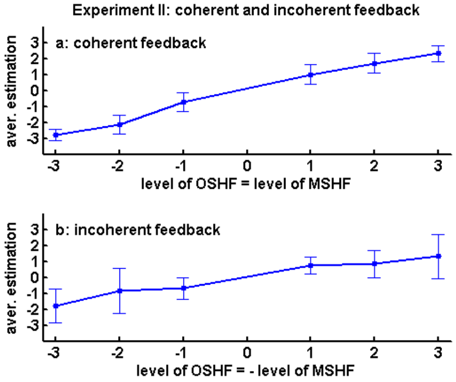


Figure 11: Average estimations of experiment II for the monosensory stimulation conditions, which means that either optically simulated haptic feedback was zero (a) or mechanically simulated haptic feedback was zero (b). Note that these graphs are the same as the vertical cross sections of figure 3 along the two horizontal axes.

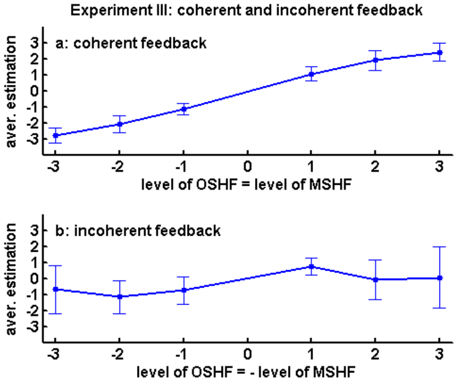


Figure 12: Average estimations of the data shown in Figure 11 for which the optically simulated haptic feedback was equal to the mechanically simulated haptic feedback, the coherent condition, compared with the incoherent condition for which the optical simulation was opposite to the mechanical simulation. Note that this represents the diagonals shown in Figure 11. In (a) the results for the coherent feedback are presented. In (b) the results for the incoherent feedback are presented.

4.3 Comparison of Experiment I, II, and III

The results show that the three different experimental conditions, in which the range of the mechanically simulated haptic and the optically simulated haptic feedback was varied over 80% mechanical feedback and 100% optical feedback, 100% mechanical feedback and 100% optical feedback, and 100% mechanical feedback and 80% optical feedback – whereby 100% represents the nominal value set by the committee of experts –, correspondingly changes the weight the participants attributed to the mechanically and the optically simulated haptic feedback. This follows from the decreasing correlation coefficients between the estimations and the optically simulated haptic feedback condition, and the increasing correlation coefficients between the estimations and the mechanically simulated haptic feedback condition. Although initially the choice of the values for the ranges of the optical and the mechanical feedback was based on judgments by the committee of four experts that, in the conditions of Experiment III, optical feedback would not dominate, the results show that even then the participants on the average attributed more weight to the optical simulation. We do not have a single explanation for the unexpected result that participants attributed more weight to the optical simulation than the committee of four, who set the standard and were familiar to the different techniques. It could be that the experimenters, who had set the standard, subconsciously overweighed the optical simulation to make it more recognisable by the participants. Or it could be that uninformed participants who are not familiar with the two different techniques attribute more weight to the optical simulation than people who know the used techniques. Despite that we did not find a clear turning point where the optical outweighs the mechanical stimulation, the results clearly show that optically simulated haptic feedback is a powerful tool to complement or replace mechanical feedback, and that the relative role of each form of feedback can be adjusted.

Furthermore, the comparisons of the coherent with the incoherent feedback conditions show that the correlation coefficients for the coherent stimulus conditions slightly increase from Experiment I to III, hence with decreasing optically and increasing mechanically simulated haptic feedback, from 0.925, via 0.941 to 0.956. The difference between the first and the last correlation coefficients is statistically significant ($z = 2.10$; $N = 120$; $p<0.025$). This shows that in the coherent condition, mechanical and optical simulations of haptic feedback enhance each other. On the other hand, the correlation coefficients for the incoherent stimulus conditions decrease highly significantly from Experiment I to III from 0.705, through 0.690, to 0.281. The difference between the last correlation coefficient and the first is statistically significant ($z = 4.50$; $N = 120$; $p<0.001$), as is the difference between the last and the second ($z = 4.27$; $N = 120$; $p<0.001$). This shows that in the incoherent condition the 'disturbing' influence of the increasing contribution of the mechanical feedback on the participants' responses increases.

The three experiments were carried out by three different groups. In this between-groups design it would have been possible that each group would adapt the range of estimations to the range of the optical and the mechanical feedback. Since this did not happen we can conclude that the estimations were based on a real percept of the depth of a hole or the height of a bump, and not on a perceptual normalization of the estimations over the stimulus ranges. Note that in a between-subject design in which the trials of the three experiments would have been randomly mixed, this strategy is not possible, and the differences found would only have been more significant.

4.4 Prior knowledge

After the experiment the participants were asked if they were experienced or had heard of force feedback. Twenty eight participants said that they knew about mechanical force feedback either through computer games or through professional use. Among the subjects there were eight who said that they knew about optically simulated force feedback before the experiment. We compared the answers of these participants with their experimental results. We found no correlation between prior knowledge of the applied techniques and the outcome of the experiment.

4.5 Result summary

The results clearly show that, at least for the nominal values used in this study, mechanically and optically simulated haptic feedback complement each other in supplying information as to the depths of holes and heights of bumps in a GUI. Noticeably, in the ranges applied in the present study, optically simulated haptic feedback gives a stronger haptic illusion of force feedback than anticipated by the researchers, even to a degree that it can replace mechanical force feedback. In all three experimental conditions the variation of the optical simulation contributes more to the variance of the participants' estimations than does mechanical simulation.

The statistical interaction between the nominal values of mechanically and optically simulated haptic feedback was not significant, indicating that *on average* the haptic effects of mechanical and optical simulations are simply additive. On the other hand, for incoherent stimuli when one simulation method gives the haptic illusion of a hole and the other of a bump, the variance of the estimations is much higher than for coherent stimuli. This is due to the fact that the relative weight each subject attributes to the information coming in through the visual and the haptic modality is different. Most subjects attributed more weight to the visual information, but a minority of subjects, one in Experiment I, two in experiment II and three in Experiment III, predominantly paid attention to the haptic information generated by the mechanical force feedback device. Together with the findings discussed in section 4.3, this increase, though statistically not significant, again corresponds with the relatively increasing contribution of the mechanically simulated feedback and its larger range in Experiment II and III. Hence, the subjects did not adapt their estimations of the heights of the bumps and the depths of the holes to the ranges of the mechanical and the optical strength, but really based their estimations on the percept of depth and height as induced by the optical and the mechanical stimulus components. In the case of conflicting information some participants attributed other weights to the two stimulus components than others.

5 GENERAL DISCUSSION

We compared the perception of virtual bump and hole structures in a GUI, simulated mechanically with a force feedback device and optically by applying cursor displacements as if there was force feedback. The present study points out that, since active cursor displacements can induce strong haptic illusions, they are well suited for simulating bump and hole structures. Hence, the results are in line with our first hypothesis that optically simulated haptic feedback can be applied to create perceivable bump and hole structures and that people are able to judge the relative heights of the bumps and the depths of the holes to an extent comparable to that of mechanically simulated force feedback.

Our second hypothesis, that optically simulated haptic feedback can be used to enhance or decrease the perceived height of bump and hole structures generated with a mechanical force feedback device, is confirmed in the sense that, on average, the haptic illusions induced by mechanical and optical simulations are additive. On the other hand, for incoherent stimuli for which the illusions induced by mechanical and optical simulations oppose each other, a minority of subjects attributes more weight to haptic information than to visual information, as mentioned one for Experiment I, two for Experiment II and three for Experiment III.

These findings demonstrate that, at least for the structures and nominal values of feedback used in this experiment, optically simulated haptic feedback can replace mechanically simulated haptic feedback. However, this does not mean that optically simulated haptic feedback can be applied in all situations in which mechanical force feedback has shown to be beneficial. Optically simulated haptic feedback can naturally be applied only in situations in which the users of the GUI can direct their attention to the visual information presented on the screen, even more specifically to the position of the cursor on the screen where the haptic illusions are induced.

Furthermore, it is possible that optical simulations are especially beneficial for small targets, or for weak mechanical forces. In another study [Mensvoort et al., 2008] using a Fitts' type target-acquisition task, we have shown that optically simulated haptic feedback has a significantly higher usability than mechanically simulated haptic feedback, but the benefit of the optical simulation expressed itself mainly for smaller targets, less than 20 pixels in diameter. In the experiments presented here, the holes and bumps were 240 pixels in diameter, which is in the range where this usability benefit of optically simulated force feedback is no longer significant. Hence, it may very well be that it is not so much size of targets but strengths of forces that matters. In other words, the enhancing effects of optically simulated haptic feedback may express themselves especially when mechanical feedback is relatively weak.

5.1 Future work

The research presented here showed that users are able to interpret the simulated topographical structures correctly. So, the active cursor technique can be applied in today’s graphical user interfaces. But more research into the potential and limitations of optically simulated force feedback is needed. Further perceptual experiments might deal with the recognition of various objects, from simple forms, like ramps, squares, gutters, and triangles, to dynamic complex scenes. Other future work may consist of evaluations of the applications of optically simulated force feedback, in particular in more complex GUIs. The current interfaces are not designed with tactility in mind. The most important research path, therefore, is the design of completely new interaction styles based upon optically simulated force feedback. The cursor channel is no longer an input channel only, but is transformed into an input/output channel.

Before optically simulated force feedback can be fully applied in more complex interaction styles, an expressive language of satisfactory and tolerable active cursor behaviours needs to be developed. Interface designers and researchers need to experiment more with the technique in order to explore the affordances of the created objects and find out what works and what does not. Since the active cursor technique is not so easy to implement, we have developed a software toolset that enables designers to add optically simulated haptic feedback to their interfaces without difficult programming. The software toolset is implemented in Adobe Flash and can be downloaded at www.powercursor.com.

5.2 Conclusions

We conclude that, at least for the hole and bump structures and nominal values of feedback used in our experiment, optically simulated force feedback is a good alternative for mechanically simulated force feedback. Active cursor displacements, influencing the normal cursor movement linked to the user's mouse movements, can be applied to generate bump and hole structures. Participants in the experiments successfully identified the bump and hole slopes and estimated their sizes in a consistent way, in both the optically simulated haptic feedback condition, and in the condition using a mechanical force feedback device. Optically simulated haptic feedback can further be applied to alter the perception of mechanically simulated haptic structures. In some respects, e.g., for more subtle forces, optically simulated haptic feedback is likely to be even more expressive than mechanical simulations of force feedback, at least for the ranges tested and nominal values used in the present study. Furthermore we have learned that optically and mechanically simulated haptic feedback must be applied in a coherent way. If not, different users will react differently and, hence, unpredictably.

Hence, optically simulated haptic feedback can be applied to generate perceivable haptic structures in a standard cursor controlled graphical user interfaces, without resorting to special mechanical input/output devices. This technique of simulating haptic feedback optically opens up an additional communication channel with the user. Optically simulated haptic feedback is not expected, however, to replace mechanically simulated haptic feedback in general. Rather we expect that, since optically simulated haptic feedback can be implemented in a standard desktop set-up without special hardware, it could catalyse the development of novel physical interaction styles and the acceptance of mechanical force feedback devices.

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