Int. J. Human-Computer Studies 85 (2016) 47–56

Contents lists available at ScienceDirect

Int. J. Human-Computer Studies

journal homepage: www.elsevier.com/locate/ijhcs

Multisensory texture exploration at the tip of the pen ☆

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ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form
13 June 2015
Accepted 24 July 2015
Available online 17 August 2015

Keywords:
Pen-based interaction
Pseudo-haptics
Multisensory textures
Sonic interaction design

ABSTRACT

A tool for the multisensory stylus-based exploration of virtual textures was used to investigate how different feedback modalities (static or dynamically deformed images, vibration, sound) affect exploratory gestures. To this end, we ran an experiment where participants had to steer a path with the stylus through a curved corridor on the surface of a graphic tablet/display, and we measured steering time, dispersion of trajectories, and applied force. Despite the variety of subjective impressions elicited by the different feedback conditions, we found that only nonvisual feedback induced significant variations in trajectories and an increase in movement time. In a post-experiment, using a paper-and-wood physical realization of the same texture, we recorded a variety of gestural behaviors markedly different from those found with the virtual texture. With the physical setup, movement time was shorter and texture-dependent lateral accelerations could be observed. This work highlights the limits of multisensory pseudo-haptic techniques in the exploration of surface textures.

1. Introduction

In everyday interaction with the environment, we experience surface textures mostly through touch and vision, although audition can also contribute to forming multisensory percepts (Klatzky and Lederman, 2010). The importance of haptics for conveying a similar experience in virtual and augmented environments has been widely advocated (Robles-De-La-Torre, 2006), although force-feedback devices are impractical or expensive in many contexts. This explains the emergence of pseudo-haptics (Lécuyer, 2009; Mensvoort et al., 2010), that is the exploitation of multisensory illusions to render forces through alternative sensory channels. The present work belongs to the area of experimental pseudo-haptics, as it seeks evidence of the effectiveness of image, sound and vibration as sensory substitutes of lateral forces in texture exploration tasks. As opposed to most existing works in this area – which rely on physical separation between the pointing device and the locus of visual interaction – we consider interactions where action and feedback are co-located, though mediated by a tool (stylus). This is indeed the typical situation of many manual activities that afford the development of expressiveness and virtuosism, such as painting or drawing.

To show if and how modulations of visual, auditory, and vibratory feedback differently affect the perceived lateral forces during surface exploration, we designed a system based on a vibroacoustically augmented graphic tablet and on real-time physics-based simulation of contact mechanics. This apparatus can render surface textures by means of visual, auditory, and vibratory feedback. An experiment was designed to look for behavioral evidence of the effects of different kinds of feedback on constrained gestures. For this purpose, the trajectories and forces were measured by using the digitizing tablet itself. The assumption that these forces and trajectories may be affected by perceived (illusory) shear stresses was experimentally tested. The proposed experiment is markedly different from prior assessments of pseudo-haptic techniques, which were based on subjective estimation or magnitude production. It gives the possibility to further validate or to refute previous claims on the effectiveness of pseudo-haptics.

The proposed tool for the multisensory exploration of virtual surface textures qualifies as an abstract interactive object, that is an object designed with the goal of improving our understanding of some interaction primitives (Svanæs, 2013). In particular, we used a constrained steering task to quantify how the feedback in different sensory modalities affects the same surface-rubbing gesture. Since it has been shown that lateral forces do affect accuracy in steering tasks over physical textures (Sun et al., 2012), we looked for similar behavioral effects when multi-sensory pseudo-haptic feedback is used to substitute the actual lateral forces. A qualitative evaluation of the interaction under different

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☆ This paper has been recommended for acceptance by E. Motta.
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http://dx.doi.org/10.1016/j.ijhcs.2015.07.005

combinations of sensory feedback was also made possible by comparison with the physical, real-world realization of such stylus-surface interaction.

2. Related literature

2.1. Forces for on-screen textures

It has been shown that forces are dominant over geometric features to convey information about surface profiles through active touch (Robles-De-La-Torre and Hayward, 2001). Based on this evidence, attempts have been made to substitute lateral forces by visual vibrations of the mouse cursor and by vibratory feedback at the mouse manipulation point (Hachisu et al., 2011). The frequency of these vibrations would mirror the changes in the speed of the cursor, as they are introduced in the pseudo-haptic paradigm proposed by Lécuyer (2009). This kind of substitution, however, is not trivially transferable to surface-based interactions such as those with touchscreens, since it relies on dynamic changes of the control/display ratio of the input device. Local and dynamic image deformations were also proposed to convey a sensation of stiffness (Argelaguet et al., 2013), and it was shown that they can render several levels of apparent stiffness in manipulations through pointing devices. The effectiveness of these techniques in touchscreens and tablet-based interactions has not been ascertained yet.

In order to overcome the difficulties of using sensory illusions in more direct manipulations, such as those found in tablets, some researchers have proposed to stretch a rubber membrane over a frame on top of the touchscreen (Lefebvre and Pusch, 2012). This increases the perceived sense of physicality in the continuous deformation of virtual objects. In this case, the control/display ratio is used to alter the perceived level of resistance of the virtual object, by controlling the extent to which finger movement is translated into object deformation.

Bau et al. (2010) proposed TeslaTouch, a tactile feedback for touch interfaces based on electrovibration at the bare finger tip.

Harrison and Hudson (2012) demonstrated how shear can expand the range of possible interactions at the touchscreen, and how it can be used to implement a variable control/display ratio, without sacrificing any screen real estate. What they proposed is equivalent to having an isometric pointing stick at the point of touch. Their experimental apparatus was built by mounting a capacitive touchscreen on top of a LCD display. Operating between the display and touchscreen were two analog joysticks. Shear-sensitive touchscreens may be suitable for pseudo-haptic feedback enhancement for texture exploration.

McDonald and Kuchenbecker (2013) proposed a haptic simulation model for tool-mediated texture interaction, that is surface texture exploration mediated by a handheld stylus provided with sensors and a vibrotactile actuator. Their measurements show that lateral and axial accelerations at the probe form trains of complex pulses, each corresponding to a contact event between the tip of the tool and a ridge in the texture grating. In their setup, a dynamic model is used for impacts, and forces are transferred from the normal to the transversal plane via friction.

2.2. Sound out of texture exploration

In sound synthesis, several models exist that describe the contact phenomena occurring at the interface between an object and a surface. Friction is one such phenomenon based on stick-slip commutation (Avanzini et al., 2005). Other salient phenomena such as rolling are rendered by patterns of impacts (Rath and Rocchesso, 2005). In those studies and models, surfaces are often specified as one-dimensional height profiles, either sampled or generated algorithmically.

A flexible sound synthesizer for scratching, rubbing, and rolling sounds has been developed by Conan et al. (2013, 2014): sound generation is based on a dynamic impact model, and impacts are distributed in time and controlled in amplitude according to stochastic models of scratching, rubbing, and rolling. Another synthesis engine is the Sound Design Toolkit (Delle Monache et al., 2010), which offers a set of physics-based sound models organized according to an ecological taxonomy of everyday sounds.

A remarkable work that uses the exploration of physical textures for sound-generation purposes is that of Merrill et al. (2008). They proposed to use physical textures as affordances for brushing, scraping, striking, etc., and these gestural actions could be exploited for continuous playback and modification of prerecorded audio samples.

Only a few studies have investigated if and how texture sounds can affect motor behavior. Castiello et al. (2010) showed that the sound of fingers on different material textures affects movement duration in a reaching-to-grasp task, with sounds that are congruent with the visual appearance producing shorter movement durations. Moreover, their experiments provided evidence that the contact sound is used by both the planning and the on-line control systems at the neural level. In an experiment aimed at revealing how sound may affect materiality and behavior in the use of touch screens, Tajadura-Jiménez et al. (2014) sensed finger gestures of free exploration and linear displacement to drive synthesized textural sounds of controllable nature and frequency content. They found very small effects of sound quality on movement speed and finger pressure, for blindfolded subjects.

2.3. Trajectory-based interactions

Stylus-mediated exploration of a surface can be seen as a trajectory-based task (Accot and Zhai, 1997). The steering-law model, as derived by Accot and Zhai, was proposed to predict the performance of different devices when used for steering constrained paths on a surface (Accot and Zhai, 1999; Kulikov et al., 2005). The typical goal for those tasks, however, is quite different from free exploration, as participants were not free to wander. Conversely, they were usually requested to perform a stroke as quickly and as accurately as possible, without crossing the boundaries of a prescribed corridor.

It has been shown that different kinds of error feedback (visual, tactile, auditory, none) have no effect on movement time (Sun et al., 2010). Conversely, the same research showed that accuracy seems to improve with tactile feedback. However, it should be noted that error feedback is not ecological, and is very different from the multisensory feedback that one would get when steering a path with a stylus on a textured surface. In the specific application context of cascading menu selection, the effect of superimposed visual force fields on selection time was measured (Ahlström, 2005). This pseudo-haptic artifice, which manipulates the pointer's movement, was shown to reduce selection time.

Sun et al. (2012) had the intuition that, when steering a path using a pen, the physical quality of the surface may play a role in the performance. They superimposed sheets of different materials on a graphic tablet and used the steering-law experimental paradigm. Although they did not observe any effect on movement time, they did find that different surfaces affected accuracy and applied force. This provides evidence that people approach the stroke differently, depending on the surface they are drawing on.

Andersen and Zhai (2008) checked how handwriting and pen gestures may be affected by different kinds of feedback (no feedback, visual, audiovisual, auditory). Audio-only (continuous sound) and no feedback had an effect in reducing the ability to control the size and the closure of shapes. They also tested different kinds of stimuli such as rhythmic patterns or variable-speed music. Although change in performance was not clearly observed, a large variability of subjective ratings of user satisfaction was reported. They found that people tend to better remember the spatial patterns rather than the auditory patterns, as if gestures would be directly reproduced from memory, and feedback would not add much modulation to this process, except where there are reference points to be crossed.

2.4. Abstract interactive objects

Many examples are found in the literature, of abstract interactive objects or artifacts that were not conceived to address users' needs, but rather to afford experimentation and to improve the knowledge and understanding of specific interaction gestalts. The construction of such devices is central in many research-through-design activities (Zimmerman et al., 2007). In haptics, an abstract interactive object based on rolling simulation was proposed by Yao and Hayward (2006). Their realization, for example, allowed to test if a person could rely on either the ball rolling rumble, or the time-to-collision cue, in a length estimation task. Examples in sonic interaction design are the Spinotron (Lemaitre et al., 2009), based on the simulation of a ratcheted wheel, the Flops (Lemaitre et al., 2012), based on pouring virtual balls out of a glass, and the Ballancer (Rath and Rocchesso, 2005), based on a rolling ball simulation. An example of artifact that integrates audio and touch for exploratory purposes is the PebbleBox (O'Modhrain and Essl, 2013).

3. Exploring textures across modalities

Two-dimensional textures can be observed visually and acquired as pictures, or they can be experienced with touch through scanning processes. Exploration with the bare finger gives a spatial, intensive measure of roughness. Tool-mediated exploration along a trajectory (indirect touch) produces what is essentially a multidimensional signal in the time variable only, carrying information about surface roughness, hardness, and friction. Indirect touch often produces an audible signal that carries the same kind of information through sound (Klatzky and Lederman, 2010). On the other hand, any sound signal can be interpreted as a surface profile that may be appreciated with the other senses.

In this perspective, we designed a tool named Sketch-a-Scratch, that allows us to specify textures in one or two dimensions with different means, and to move seamlessly from vision to touch to audition (Delle Monache et al., 2015):

Image → sound/vibration: An image is scanned along a line, and luminance values converted into a one-variable surface roughness profile. This can be explored by scraping, rubbing, or rolling (Fig. 1), and the instantaneous force and displacement of vibrating surfaces are rendered by means of a vibrotactile actuator or a loudspeaker.

Vibration ↔ sound: A physical texture is scanned using a probe, and a piezo sensor is used to capture the resulting vibrations. Alternatively, any sound, especially if inherently textural, can be used as a surface profile to be experienced through touch. Some notable possibilities for the specification of textures in the audio domain are the following:

> Voice: We naturally use our vocal apparatus to imitate sound textures of many kinds, including those produced by continuous contacts of an object with a surface.
>
> Synthesis: Several techniques are available to (re-)synthesize sound textures (Strobl et al., 2006).

Sound/vibration → image: Audio or vibrotactile signals (of one variable) can be used to produce an image in different ways. One trivial yet effective transformation used in our tool is the stacking of luminance-translated audio signals to produce rows of pixels. This sound-to-image transformation affords different kinds of subsequent image-based exploration of the sound material (temporal expansion, inversion, interlacing, etc.).

Texture-exploration actions can be described by microscopic contact events occurring between the probe and the surface, which can be simulated by impact and friction models (Papetti et al., 2011; Avanzini et al., 2005). While Sketch-a-Scratch affords exploration by scraping, rubbing or rolling, for the sake of this investigation only point-wise micro-impacts were considered. When the full-fledged tool is used, the dynamic nature of the impact and friction models allows one to seamlessly morph between the different kinds of surface exploration, thus opening to performative utilization.

In addition to displaying visual textures on its screen, Sketch-a-Scratch implements local image deformations that may be used as a visual pseudo-haptic effect. The image is locally deformed at the point of interaction as if the stylus was exerting superficial vertical and lateral forces.

3.1. Impact model

Sketch-a-Scratch uses an impact model that describes two colliding bodies: a point-mass (exciter) and a resonating object. The contact force f_i is a function of the object compression x and

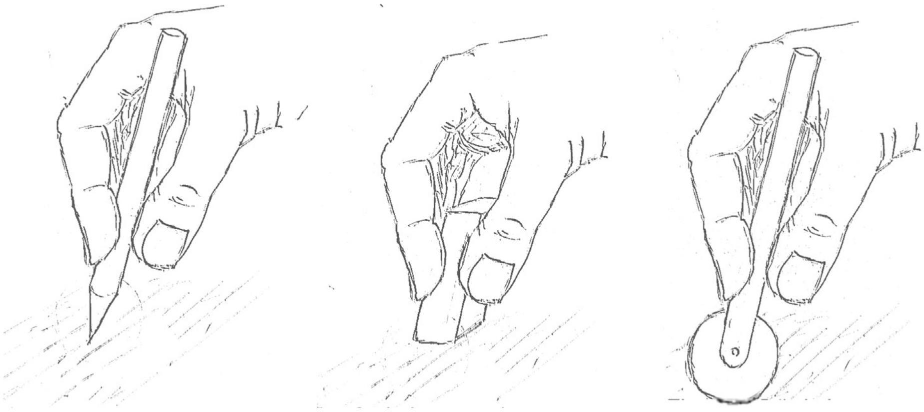

Fig. 1. Scraping, rubbing, and rolling.

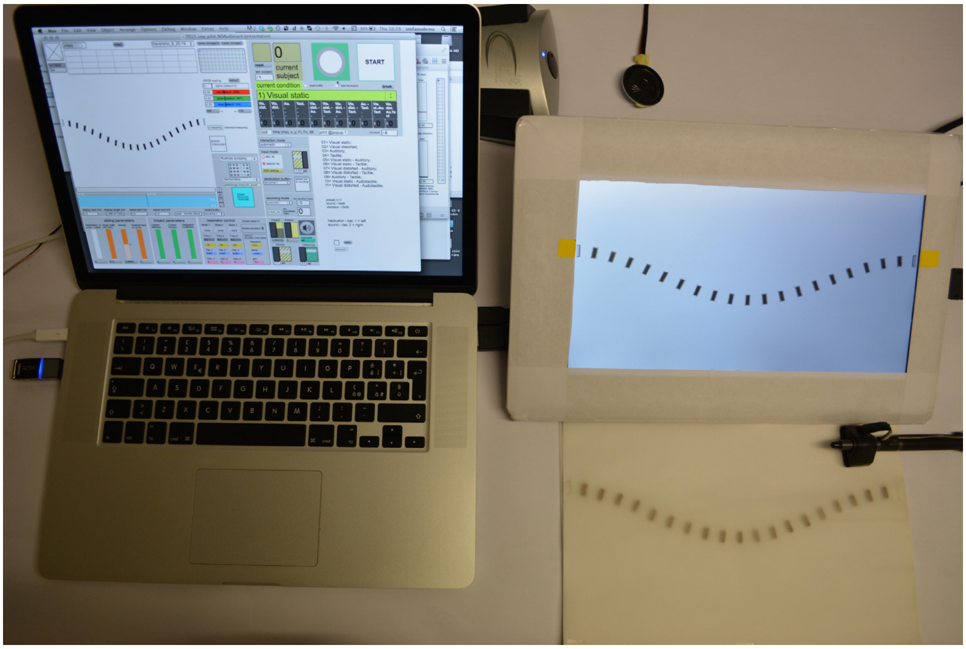

Fig. 2. Experimental apparatus for Sketch-a-Scratch. On the left: MacBook Pro running the Max 6 application. On the right, from top to bottom: T-Amp amplifier with mylar-cone speaker, Wacom Cintiq tablet, stylus with vibrotactile transducer, physical realization of the path used in the experiment.

compression velocity $\dot{x}$:

$$f_i(x,\dot{x}) = \begin{cases} -kx^{\alpha} - \lambda x^{\alpha}\dot{x}, & x > 0 \\ 0, & x \le 0 \end{cases} \quad (1)$$

where k accounts for the object stiffness, λ represents the force dissipation, and α describes the local geometry around the contact surface. When $x \le 0$ the two bodies are not in contact.

In the current implementation, a surface profile modulates the relative displacement offset between the exciter (stylus) and the resonating object (texture). The normal force applied to the stylus is also used to modulate the impact force calculated by the model.

The impact model produces vibratory signals that can be output as sound, as well as used to drive a vibration transducer, rendering respectively the aural and vibrotactile outcome of texture exploration. Although not used in the current realization, the model dynamics also produce forces which could be rendered through a haptic device. Similarly to what done by McDonald and Kuchenbecker (2013), in our experimental apparatus the stylus is actuated by means of a vibrotactile transducer driven by the low-frequency components of the synthesized audio output.

4. The tool and its use

Sketch-a-Scratch is based on a 13.3 in Wacom Cintiq graphic tablet, which offers a high resolution screen (1920 × 1080 pixels) and a stylus. A TactileLabs Haptuator Mark II vibrotactile transducer was attached to the stylus (see Fig. 2, notice that the "eraser tip" is used). A mylar-cone dynamic speaker (Pro Signal ABS-209-RC, diameter: 45 mm, frequency response: 500–5500 Hz) was taped to the back of the tablet and wired to one of the two channels of a Sonic Impact T-Amp amplifier, the other channel being connected to the vibrotactile transducer. In this way, sound and vibration were consistently produced at the locus of action.

On the software side, Sketch-a-Scratch is an application for Max 6.[1] The graphical user interface shown in Fig. 3 allows one to load images, record audio tracks, and turn them into surface profiles, moving seamlessly from one domain to the other. The surface profiles can be explored with virtual probes of different characteristics, thus simulating scraping, rubbing, or rolling. Exploration can be either automatic by acting on the GUI (passive), or manually driven by the stylus (active).

The visual representation of textures displayed by the graphic tablet can be locally distorted to mimic the deformation of a virtual membrane being pushed by the stylus.

The micro-impact synthesizer is outlined by the green box in Fig. 3. Impacts are described in terms of stiffness, sharpness, dissipation, and resonances. The vertical penetration of a virtual probe sets the threshold level of the roughness profile above which contact signals are produced, and is controlled by the pressure applied by the stylus.

Extensive demonstrations (Delle Monache et al., 2015) and performances with Sketch-a-Scratch let us collect several user comments and expressions of interest. First-person reports confirmed that the addition of sound and vibration can alter the feeling of the surface being explored, as well as the perceived shape of the probe (or pencil, or brush). The overall experience is enriched, and activities such as drawing are described as more engaging. Some illustrators recalled the rich sensory experience of drawing with different pens and pencils on various paper materials, and how they miss it when drawing on tablets. They showed interest in possible applications of Sketch-a-Scratch to simulate different tips and surfaces for drawing purposes.

5. Experiment

Although anecdotal comments of casual users provided useful confirmation to the design of Sketch-a-Scratch, it is important to have objective measurements of how the design assumptions are reflected in actual use. In particular, a crucial open question is: Can sound or vibration rendering actually affect the action, substituting for lateral forces that are not produced at the smooth surface of the tablet? To investigate this research question, we designed a

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[1] cycling74.com

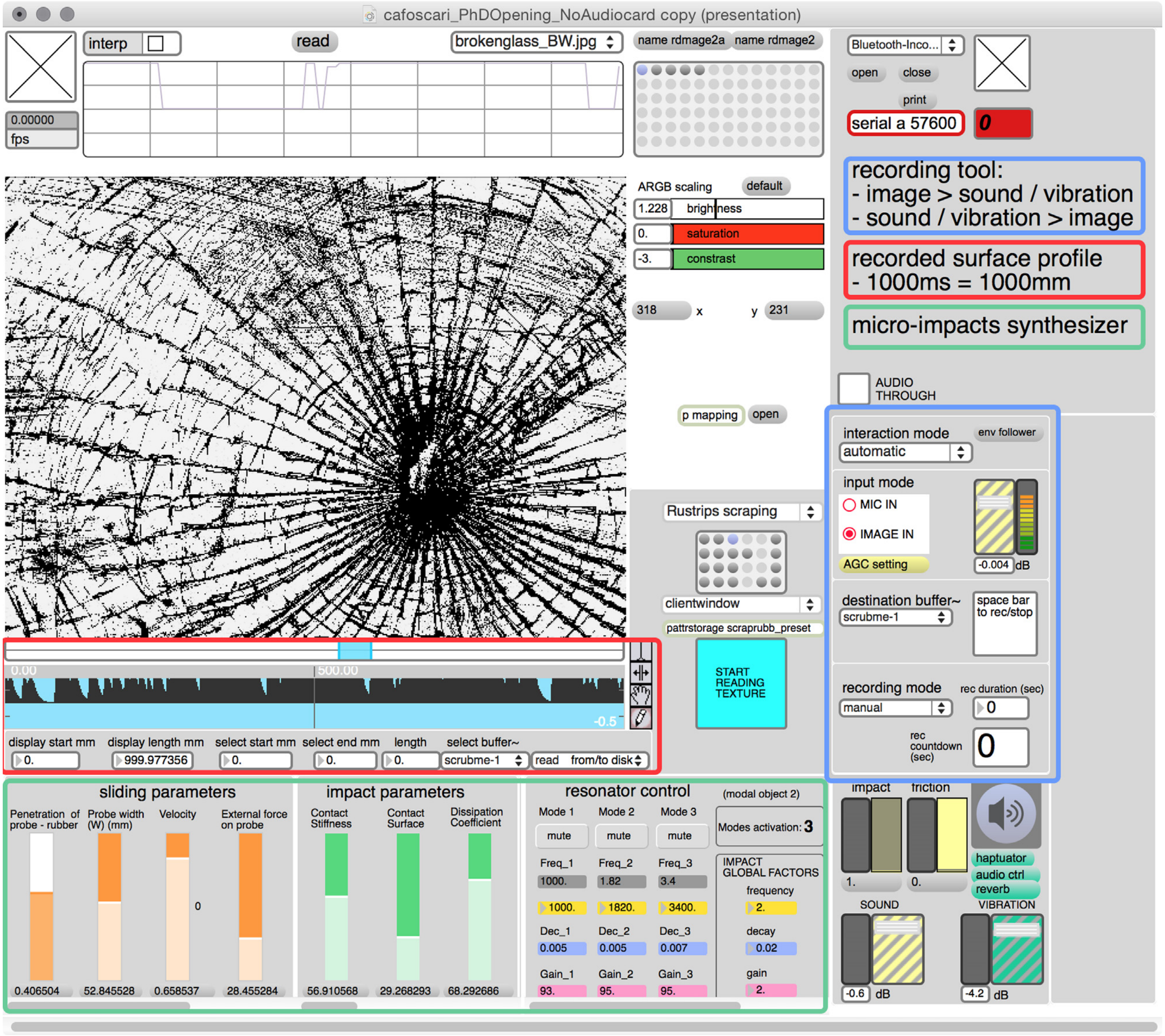


Fig. 3. GUI for Sketch a Scratch.

controlled experiment in which Sketch-a-Scratch is used as an abstract interactive object. The experimental task is that of steering a path within a prescribed corridor, under different feedback conditions.

Although the task is similar to what is usually done to derive the parameters of the steering-law, we are not interested in extracting an index of difficulty or other measures of performance for the given apparatus. Instead, we aim to verify if and how the different combinations of feedback modalities affect the time and uncertainty of execution, as well as the applied force.

The suggested task clearly differs from the free or performative exploration of a surface texture. However, if we can measure systematic modifications or modulations of action in such constrained conditions, we can reasonably infer that even larger modifications will occur in free or performative exploration. Support for such a generalization comes from the observation, often made in HCI research, that the expressive intentionality of a gesture directs perception towards the sensory information that becomes *ready-to-hand* (Svanæs, 2013).

The design of the experiment and the experimental procedure is described in this section. The results are described in Section 6. Section 7 describes a post-experiment, where measurements were taken on a concrete physical realization of the same virtual texture.

5.1. Apparatus and participants

All the components of the experimental apparatus (Sketch-a-Scratch) are illustrated in Fig. 2.

The Wacom Cintiq tablet displayed the path that the participants were requested to trace. The path was made of rectangular (9 × 4 mm) bars arranged along a cosinusoidal shape (horizontal extension = 291 mm, vertical extension = 46 mm). The length and width of the path were chosen after checking the literature (Sun et al., 2010) and informal testing, in such a way that movement times in the range 2–3 s would be most likely. In the steering-law studies, the experimental paths are usually either rectilinear or circular (Accot and Zhai, 1999; Sun et al., 2010, 2012), and different combinations of length and width are provided as experimental factors. Conversely, we were interested in having different combinations of feedback modalities as a factor, and to see how they may affect the exploration of textures that exhibit variation along one dominant direction (such as those, for example, derived from vocal signals). We avoided the use of a simple rectilinear path, because we suspected that participants may internalize the movement of a rectilinear stroke, and trigger it without using multisensory feedback but proprioception. The cosinusoidal shape is somewhat harder to internalize and, therefore, participants are more likely to take advantage of all sensory feedback that becomes available. Two yellow markers (visible in Fig. 2) were attached to the tablet frame to indicate the starting and ending positions.

The impact model was set to simulate impacts with small metal bars. The luminance values of the displayed path were converted into a corresponding surface profile, whose exploration resulted in contact sounds (at about 51 dB(A)) and vibration. Audio or audio-tactile feedback was produced when the stylus encountered the bars along the cosinusoidal path, irrespective of whether the path was visually displayed.

During the task execution, the apparatus recorded the following data to separate text files for each trial: elapsed time (in ms), stylus position as x and y screen coordinates, normal force, tilt, lateral acceleration along the x-axis. Normal force, tilt and position of the stylus were read directly from the Wacom driver. The data were sampled at 200 Hz, while their resolution varied with the different variables: e.g., the coordinates x and y have pixel resolution (1920×1080), and the normal force has 11-bit resolution (2048 levels).

Fourteen volunteers (seven male, seven female, age ranging from 20 to 55, with an average of 33.9 years and standard deviation of 10 years) participated in the experiment. All the participants reported normal hearing, and normal or corrected to normal sight. They performed the test using their preferred hand (three left-handed, eleven right-handed), and all of them chose to perform the task from left to right. The experiment was conducted in an office environment, with normal lighting conditions and background noise not exceeding 45 dB(A).

5.2. Method and task

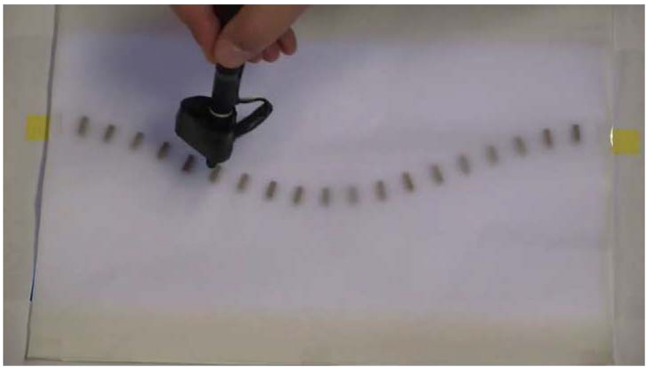
The experiment was a 10×11 repeated measures design with ten trials and eleven feedback conditions. The conditions were:

1. Visual static
2. Visual dynamic
3. Auditory
4. Vibratory
5. Visual static + auditory
6. Visual static + vibratory
7. Visual dynamic + auditory
8. Visual dynamic + vibratory
9. Auditory + vibratory
10. Visual static + auditory + vibratory
11. Visual dynamic + auditory + vibratory

The sequence of 110 trials was randomized for each participant, except for the very first trial, which was always performed in condition 1, so as to provide an initial visual reference. Notice that in conditions 3, 4, 9 the path was not visually available. In conditions 2, 7, and 11, the displayed bars were dynamically distorted as the stylus passed over them (see the accompanying video). In conditions 4, 6, and 8, white noise (60 dB(A)) was added in order to mask any auditory cue that might be conveyed by the haptuator. Video S1

5.2.1. Briefing

Before the test, each participant was briefed and exposed to each of the 11 conditions, and then let free to explore them. The task was described as that of tracing the path as fast as possible without leaving the corridor, in a single stroke. It was explained that, in order to stay within the prescribed path, the participant could exploit all the available sensory cues (visual, vibratory, auditory) that were available at the moment.



Video S1. Sketch-a-Scratch as a tool for multisensory exploration of virtual surface textures: Experimental setup and examples of path steering under different feedback conditions.

5.2.2. Execution

Afterwards, the experimenter started the randomized sequence of trials, whose progression was automatized. A bell sound before each new trial gave a start signal to the participant, who had at most 8 s to steer the stylus through the path. A random time interval, ranging from 2 s to 4 s was added before prompting the next trial.

5.2.3. Debriefing

After the test, the participant was debriefed and exposed to a physical realization of the textured path, made of paper and wood (Fig. 2, bottom right). This realization has exactly the same shape and size of the image displayed on screen, but the bars are thin (1 mm) wooden rectangular pieces glued over a paper sheet, and a second sheet of tracing paper is overlaid, so that a pen-based exploration of the path would induce surface deformations. Comments about the traversing experience on the tablet under different feedback conditions, as well as on the physical version of the path, were collected.

6. Results

6.1. Time

As one might expect, the gestures performed without visual feedback took longer than the others. Fig. 4 reports the mean gesture time (across fourteen participants and ten trials) for each condition.

A two-way repeated measures ANOVA was run, with repetition trial and feedback condition as within-participants factors (MacKenzie, 2013). The participants got slightly faster with practice (trial 10 had a mean execution time 12% shorter than trial 1), and this small learning effect was marginally significant ($F_{9,117} = 2.23,\ p < 0.05$). The gesture time was significantly dependent on feedback condition ($F_{10,130} = 10.43,\ p < 0.0001$). The trial × condition interaction effect was not significant ($F_{90,1170} = 1.09,\ p > 0.05$).

Upon closer inspection, the task execution times of individual participants revealed two different attitudes: on the one end there are participants whose gesture execution time was not affected by the feedback modality, and on the other end there are those whose execution time was significantly affected by the feedback modality. Fig. 5 reports the distributions of execution times of two

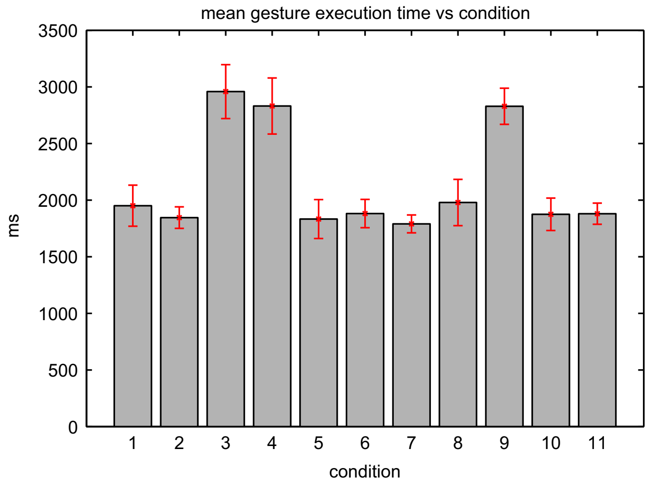


Fig. 4. Mean gesture time for the eleven conditions, over fourteen participants and ten trials per condition, with error bars of one standard deviation showing the variability between trials, across subjects.

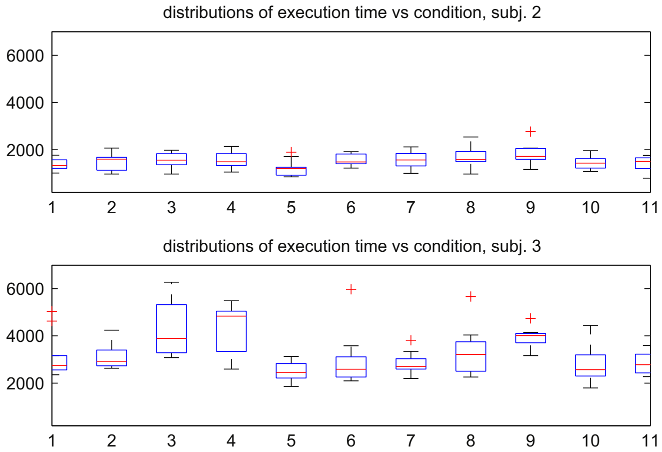


Fig. 5. Gesture execution time vs. condition, for two participants.

participants, one per each of these two classes, where participant 2 (top) was as fast in non-visual as in visual conditions.

The two classes of participants were automatically discriminated by performing a one-way ANOVA on the execution times of each participant. Those five participants showing a *p*-value larger than 0.01 were excluded from further analysis, as their regularity across different conditions suggested that they did not perform expressively and under effect of the feedback modality. By focusing on the participants who exhibited some sensitivity (in gesture time) we could more effectively look for further effects on trajectory, force and tilt.

6.2. *Trajectory*

The time variability of the trajectories $x(t)$ along the x-coordinate was checked for the nine participants whose execution time resulted affected by condition. All the trajectories were normalized, in all trials and all conditions, with respect to time, so that their duration would be the same as that of the longest one. For that, we used a sample-and-hold expansive transformation of $x(t)$. In this way, it was possible to compute a median trajectory for each participant in each condition, and an inter-quartile range (*iqr*) trajectory across all the ten trials of any given condition.

6.2.1. *Variability*

The L2-norm of the array containing the *iqr* trajectory was taken as a measure of variability of a participant in a given condition. By running a one-way ANOVA on the variability of all participants, no significant effect of condition could be measured ($F_{10,88} = 1.48,\ p > .05$). This variability, however, should not be taken as a measure of accuracy, as it is often done when deriving the parameters of the steering law. In fact, there could be a systematic deviation of trajectories under certain conditions, which per-condition variability does not capture. We stress that in this analysis we considered only the horizontal component of motion, as we were interested in one-dimensional explorations of textures.

6.2.2. *Systematic deviation*

The existence of systematic deviations from a reference trajectory was tested by computing the median, for each condition, of the differences of trial trajectories from the reference (median trajectory in condition 1). The one-way ANOVA performed on the L2-norms of these ten (one per remaining conditions) median differences did reveal a significant effect ($F_{9,80} = 5.96,\ p < .0001$). A multicomparison revealed that systematic deviations existed for the three non-visual conditions 3, 4, and 9, all the deviations in the other conditions being not significantly different from each other.

In summary, the trajectory analysis shows that non-visual movements were both slower and different in their temporal unfolding, as compared to all other movements that rely on a visible path.

6.3. *Force*

The effect of condition on the normal force exerted with the stylus was studied by computing median and *iqr* curves for force $F(t)$, for each participant in each condition. We could not measure an effect on the median exerted force ($F_{10,88} = 0.07$ ns), nor on its variability ($F_{10,88} = 0.63$ ns).

The lateral force was deduced from the lateral acceleration recorded by the apparatus. Effect of condition was found on the median lateral force ($F_{10,88} = 2.93,\ p < 0.005$), but not on its variability (*iqr*, $F_{10,88} = 0.6$ ns). This just confirms the result of gesture execution time, with non-visual condition being performed more slowly (and with smaller accelerations).

6.4. *Tilt*

Neither the median ($F_{10,88} = 0$ ns) nor the variability (*iqr*, $F_{10,88} = 0.48$ ns) of pen tilt data was significantly affected by condition.

7. Further measurements on physical steering

In order to gain better understanding on how the multisensory texture exploration of everyday physical surfaces differs from the on-screen experience of textures, we performed a follow-up measurement session. For this purpose, over three months after the experiment documented in Section 5, we recalled the nine participants who were previously selected as the most sensitive to the various feedback conditions (see Section 6.1). These nine participants were asked to perform ten traversing trials on the physical paper-and-wood realization of the path, already used in the experiment debriefing and described in Section 5.2.3. Such thin realization was overlaid on the Wacom Cintiq graphic tablet, in such a way that the tablet was still able to record position, tilt and force of the pen.

A new set of all-physical measurements added a twelfth condition to our set of data, labeled as the “physical condition”.

7.1. Time

As far as completion time is concerned, Fig. 6 shows the mean performance of the nine selected subjects in the eleven conditions of the experiment of Section 5, together with their mean completion time in this second session with the physical realization (condition 12). As compared to Fig. 6, the columns of Fig. 4 are all shorter, as the discarded “insensitive subjects” were also faster in their gestures, thus contributing to lowering the overall means. More importantly, the mean completion time in the physical condition is the lowest of all conditions, being as small as 1623 ms, and all other conditions requiring at least 2171 ms on average, for these nine participants. A two-way repeated measures ANOVA confirmed that the gesture time was significantly dependent on feedback condition ($F_{11,88} = 15.36,\ p < 0.0001$). A multiple comparison confirmed that the mean completion times in conditions 3, 4 and 9 (non-visual) are significantly larger than all the others, and that the mean completion time in condition 12 (physical) is significantly lower than all the others. Mean completion times in conditions 3, 4, and 9 are not significantly different from each other, and mean times in conditions 1, 2, 5, 6, 7, 8, 10, and 11 are not significantly different from each other.

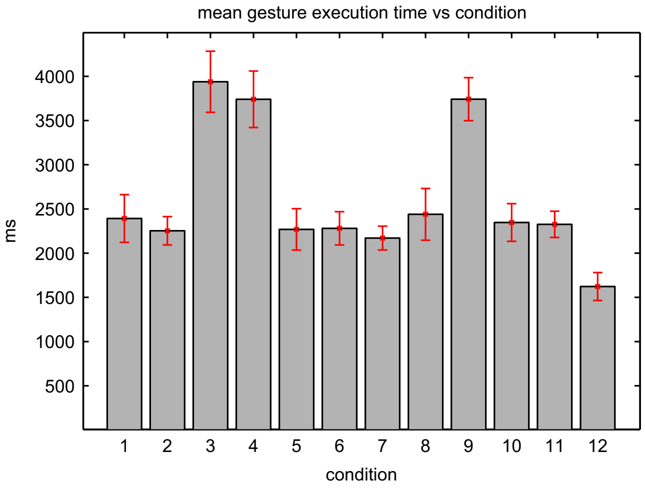


Fig. 6. Mean gesture time for the twelve conditions, over nine participants and ten trials per condition, with error bars of one standard deviation showing the variability between trials, across subjects.

7.2. Trajectory

By repeating on the twelve conditions the analysis of Section 6.2.2 aimed at revealing systematic deviations from the reference median trajectory of condition 1, we found a significant effect ($F_{10,88} = 5.37,\ p < 0.0001$). Apart from the deviations that we already found for the three non-visual conditions, the trajectory for the physical condition was also found to be markedly different.

7.3. Force

The force measured through the tablet is, on average, lower in the physical condition (mean of the L2-norm of median force trajectory is 16.1) as compared to all other conditions (which give mean values between 22.78 and 25.67). Due to the large variability of forces, however, such difference still does not reach significance ($F_{11,96} = 0.64$ ns).

By looking at the trajectories of individual participants, it is clear that some participants did perform their traversing gesture differently in the physical condition. For example, Fig. 7 shows the median force trajectories, as a function of horizontal displacement, in all twelve conditions, for participant 14. While in all other cases the trajectories have similar shapes, in condition 12 the behavior is much more complex. A clearer picture of what happens emerges by performing the autocorrelation of these twelve median force trajectories, whose results are depicted in Fig. 8. While in conditions 1–11 the autocorrelation functions are monotonically decreasing, in condition 12 the autocorrelation function shows peaks, and the lag corresponding to the first peak may be related to the periodic distribution of bars in the path. Similar oscillations in the autocorrelation function were found for participant 6, although much smaller in amplitude, and for participant 5, although much wider in lag. In general, for most participants the force trajectory (and its autocorrelation) in the physical condition was qualitatively different from all other conditions.

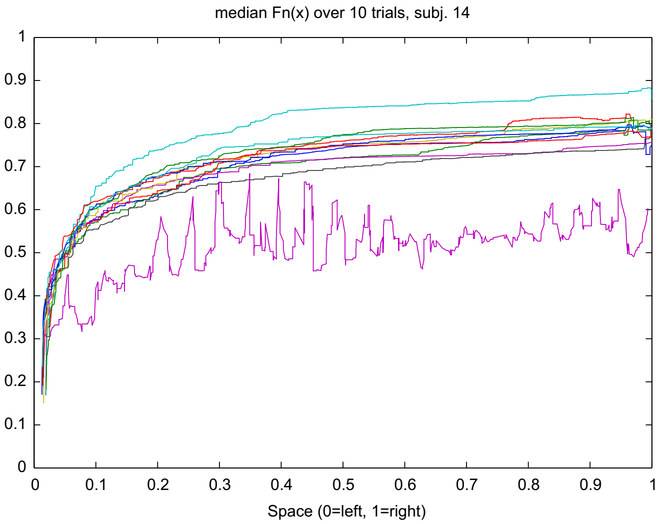


Fig. 7. Median force trajectories in each condition for subject 14. The force trajectory for condition 12 is clearly different from the others.

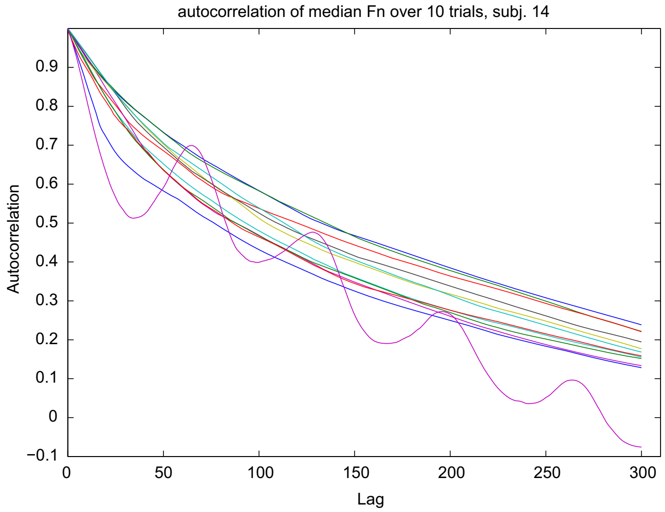


Fig. 8. Autocorrelation of median force trajectories in each condition for subject 14. The oscillatory autocorrelation function corresponds to condition 12.

8. Discussion

Having designed an abstract interactive object that affords multisensory exploration of surface textures, we used this device in a steering task, to see if and how users modify their behavior when traversing a one-dimensional texture under different feedback conditions.

We saw that physics-based auditory and vibratory feedback are equally effective in making the task possible, but they induce a cautious behavior, with participants being about 50% slower than in presence of visual information about the path (Fig. 4). Moreover, in non-visual conditions the $x(t)$ trajectories turned out to be markedly different, thus highlighting a different quality of gesture. Conversely, when the path was visually displayed, neither local image deformations (similar to those in Argelaguet et al., 2013) nor auditory/vibratory feedback induced any apparent changes in traversing behavior. The fact that such effects could not be measured in a subset of "sensitive subjects" reinforces the counterargument against the effectiveness of multisensory pseudo-haptics for texture exploration.

In summary, the experiment showed that vibratory and/or acoustic feedback can effectively support steering in non-visual conditions, but these sensory stimulations do not have measurable effect when they are complementary to visual stimuli. Our initial assumption, that lateral forces can be substituted by visual, auditory or vibratory stimuli in a pen-based interaction on a screen, has found little support in measures of performance in the proposed steering task. Indeed, that lateral forces due to differently elastic surfaces have some effect (on force and accuracy) in steering tasks was already shown (Sun et al., 2012). Therefore, our experiment shows that such lateral forces are not easily substituted by multisensory feedback, and that the rendering of haptic quality of drawing or scraping on different surfaces is still a difficult issue with tablets. This seems to be in contrast with successful examples of pseudo-haptics (Argelaguet et al., 2013; Hachisu et al., 2011; Mensvoort et al., 2010; Lécuyer, 2009). However, those examples of visual substitution have been validated through psychophysical measurement of perceptual thresholds and scales, and not by measuring performance in continuous interactions. Lécuyer (2009) admits that pseudo-haptic feedback "could correspond to the learning of a systematic association of sensorimotor displacement and visual feedback" and that "researchers are still undecided as to the nature and to the level of consciousness of the observed phenomenon". Our experiment indicates that the impression of lateral forces as conveyed through visual, auditory, or vibratory feedback is not a deep and unavoidable sensory illusion.

When comparing this work with other research that showed how texture sounds can affect motor behavior (Castiello et al., 2010), it should be considered that, differently from those experiments, here the sound (and vibratory) feedback signals have always been congruent with the visual stimulus. It is possible that, if playing with incongruent sound feedback, significant behavioral differences would have been registered. This was indeed observed in design exercises exploiting contradictory sonic feedback (Rocchesso et al., 2009).

In the debriefing, most of the participants confirmed that the task requires more caution when no visual clue is given, and that in visual conditions the other forms of feedback are not very important to perform the task. However, when asked to compare the experimental apparatus under condition 11 (all kinds of feedback in place) with the physical (paper and wood) realization, they largely agreed that the simulation effectively mimics the multisensory feedback found in reality. Some participants commented on the different nature and strength of the forces experienced with the physical realization, which were not quite reproduced with vibratory feedback.

By making a separate set of measures with the physical realization in the same experimental setup, we could ascertain that the traversing gestures are significantly faster when moving the pen on a physical texture, as compared to the texture simulation. Both the trajectories and the force profiles were shown to differ markedly from the virtual realization. In particular, complex oscillatory force profiles could only be detected in gestures that traced the physical path. These observations shed light on the intrinsic limitations of multisensory rendering of textures on flat screens.

Similarly to what happened with the Ballancer (Rath and Rocchesso, 2005), Sketch-a-Scratch has been instrumental to investigate continuous multisensory interaction with a virtual object. In the former case such virtual object was a rolling ball, in the latter it is a surface texture. Performance could be measured in both cases through a specific task, and in both cases the abstract interactive object could be directly compared with a physical concrete realization.

9. Conclusion

We presented Sketch-a-Scratch, an abstract interactive apparatus that can be used to investigate multisensory stylus-based interactions. In particular, exploration of surface textures is the target playground of Sketch-a-Scratch, whose expressive qualities and responsiveness make it also suitable for performative activities.

The proposed device was used to better understand how multisensory feedback affects gestural actions, and how far we can go with the physics-based simulation of visual, auditory, and vibratory feedback, as compared with interactions with physical textures. A thorough understanding of these phenomena would have important implications for the design of tools for creative activities such as painting or drawing. The results so far obtained show that pseudo-haptic visual, auditory, or vibratory feedback have little behavioral effect on trajectory-based tasks. Such results pose a counterargument against the effectiveness of pseudo-haptics as deep and unavoidable sensory illusions, at least for touch screens. This does does not rule out a subjective perceptual appreciation of multisensory feedback, which is often reported.

Further research is needed to stress the potential of sound and vibration to improve the experience and effectiveness of painting and drawing, when these activities are performed on interactive surfaces.

Acknowledgments

The authors D.R. and S.D.M. are pursuing this research as part of the project SkAT-VG and acknowledge the financial support of the Future and Emerging Technologies (FET) programme within the Seventh Framework Programme for Research of the European Commission, under FET-Open Grant number 618067. The author S.P. performed this work as part of the project AHMI, funded by the Swiss National Science Foundation (SNSF), Grant number 150107.

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