FRICTION SOUNDS FOR SENSORY SUBSTITUTION

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ABSTRACT

This paper explores the use of a physics-based sound model of continuous contact for auditory display in interactive settings. An audio-visual interactive display is developed in which the sound model is controlled by the user's gestures. The display is used to investigate to what extent audition can substitute for haptic feedback in conveying perception of inertial properties of a manipulated object. In a first experiment the audio-visual display is controlled through a standard pointing device (a marble mouse, or trackball). A second experiment uses a tangible object and a computer vision system that tracks the object motion. Early results suggest that the perception of effort is a cross-modal phenomenon in which auditory feedback plays a relevant role.

1. INTRODUCTION

The use of multimodality in human-computer interfaces is motivated by our daily interaction with the world. In everyday life humans communicate and interact using multiple channels which are interdependent and complementary. Especially in tasks that present a direct manipulation interaction (e.g., icon dragging), typical visual feedback techniques tend to give the impression that manipulation is happening on a surrogate object rather than a real one. In order to provide *substance* to the manipulated objects, physical reality must be mimicked more closely. In particular real objects tend to resist to motion due to their inertia, to friction with contacting surfaces, and so on.

Many kinds of haptic devices with force feedback have been proposed and manufactured as a direct solution to this kind of requirement. However, there are many practical cases where it is desirable to substitute other modalities for haptic feedback. One possible reason is that haptic devices are in most cases cumbersome and expensive, and another is that they provide a strictly personal display (e.g., a user cannot share a sensation of effort with an audience). A number of alternatives have therefore been proposed. Approaches based on purely visual feedback have been demonstrated to be effective in some cases. Cartoon animation techniques applied to widget components and graphical object manipulation do enhance the interaction [1]. Force-feedback has also been visually simulated via cursor displacement [2] and pseudo-haptic feedback [3].

However, in many applications the visual display does not appear to be the best choice as a replacement of kinesthetic feedback. Touch and vision represent different priorities [4], with touch being more effective in conveying information about "intensive" properties (material, weight, texture, and so on) and vision emphasizing properties related to geometry and space (size, shape). Moreover, the auditory system tends to dominate in judgments of temporal events, and intensive properties strongly affect the temporal behavior of objects in motion, thus producing audible effects at different time scales. According to the ecological approach, many properties of physical objects and events can be recovered on the basis of auditory information alone (see [5, chapter 1] for an annotated bibliography of studies on "everyday listening").

In light of this remarks, audition appears to be an ideal candidate modality to support *illusion of substance* [1] in direct manipulation of virtual objects, and indeed Massimino and Sheridan [6] have shown that audition is an effective *sensory substitute* for some typical manipulation tasks.

This paper investigates the role of continuous contact sounds in displaying resistance to motion of manipulated objects and in modulating the perception of effort experienced by the user. The auditory feedback is obtained using a recently developed physical model of friction [5, chapter 8]. Physically-based sound models are particularly suited for interactive sonification settings, since gesture-based control is easily mapped into physical parameters of the model (e.g., normal force and sliding velocity). Two experiments have been designed, in which the friction model has been used together with an interactive audio-visual display and a tangible interface.

A related study on audio-visual displays is reported in [7], where the authors focus on impulsive contact (i.e. collision between two objects). One notable result is that causality judgments ("Is the second object set to motion because of collision with the first one?") are increased when auditory (a clack) and/or visual (a blink) information marks the onset of the target motion, but there is no significant difference in performance between the two modalities. In other words the increase of causal interpretation is not a genuine cross-modal effect. In this paper we follow a similar experimental approach, although in an interactive setting and with a focus on continuous rather than impulsive contact.

A second related study, which investigates relative contributions of tactile and auditory information to judgments of surface roughness, is reported in [8]. Although psychophysical tests reveal that touch dominates over audition in texture perception, they also suggest that sound plays a more relevant role when using a probe than in the case of direct contact with bare fingers. In this paper we follow [8] for the analysis of experimental results about magnitude estimates and modality effects. As already mentioned, however, the focus is on resistance to motion and perceived effort rather than texture.

Section 2 provides a brief overview of the physical friction model used in the simulations. Section 3 describes the design procedure that led to the development of an interactive audio-visual friction display. Section 4 reports upon three experiments that make use of the interactive display. Results are discussed in section 5.

2. THE SOUND OF FRICTION

We developed a sound model based on a detailed physical description of the frictional interaction between two facing surfaces. The model is derived from [9] and is described in detail in [5, chapter 8]. This model departs significantly from other physically-based approaches typically used in sound synthesis applications. The main difference is that the model is dynamic, i.e. the relationship between the sliding velocity v and the friction force f is represented through a differential equation rather than a static mapping. As a consequence, the model is able to account for more realistic acoustic transients during non-stationary interaction.

Assuming that friction results from a large number of microscopic elastic bonds (called "bristles" in [9]), the v-to-f relationship is expressed as:

$$f(z,\dot{z},v,w) = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 v + \sigma_3 w, \qquad (1)$$

where z is the average bristle deflection. The coefficient σ_0 is the bristle stiffness, σ_1 is the bristle damping, and the term $\sigma_2 v$ accounts for linear viscous friction. A fourth component $\sigma_3 w(t)$ relates to surface roughness, w being modeled as fractal noise. This component is needed in order to simulate scraping and sliding effects. The main distinguishing feature of the model is that an additional non-linear first-order differential equation is introduced to describe the average bristle deflection as a function of the sliding velocity. As a consequence, equation (1) is no longer a static v-to-f mapping.

Since many "knobs" are available in the model, a phenomenological description of its parameters has been provided in [5, chapter 8], that can serve as a starting point for the sound designer. In particular, it was found that certain parameters affect overall sound features such as pitch and bandwidth, while other parameters are more related to transient effects.

The friction model has been applied to several examples of acoustic systems with frictional induced vibrations. Among the possible applications, one is the simulation of bowed string musical instruments: a first study in this direction is documented in [10]. Besides musical systems, the model has been applied to the simulation of a variety of complex everyday sounds generated by frictional interactions, which comprise a rolling/braking wheel, a rubbed glass, and a squeaky swinging door, all described in detail in [5, chapter 8]. Audio-visual interactive applications have been generated, where the user controls the external forces acting on a virtual object in the scene through a standard mouse, and the audio (displacement) signals are used to drive both the graphics renderer and the audio feedback. This approach allows for a high degree of interactivity and demonstrates that a single physical synthesis engine can be used to drive both graphics and audio rendering. One main consequence is that the two modalities are highly consistent and synchronized on a fine scale.

3. AN INTERACTIVE DISPLAY FOR THE PERCEPTION OF FRICTION

The friction model has been implemented as a plugin to the open source real-time synthesis environment `pd` (Pure Data).[1] The audio-visual displays described in the remainder of this section have been implemented as `pd` patches with the aid of the OpenGL-based external graphical library `gem`.[2]

3.1. An exploratory workbench

A 2D interactive animation was designed, which depicts a block sliding on a surface (see figure 1). The animation is intentionally composed of stylized graphical objects, similar to the sketches typically used in psychology for visual experiments (see, e.g., [11]). This serves the purpose of demonstrating the importance of audio in conveying information when visual cues are ambiguous or very subtle. Au-

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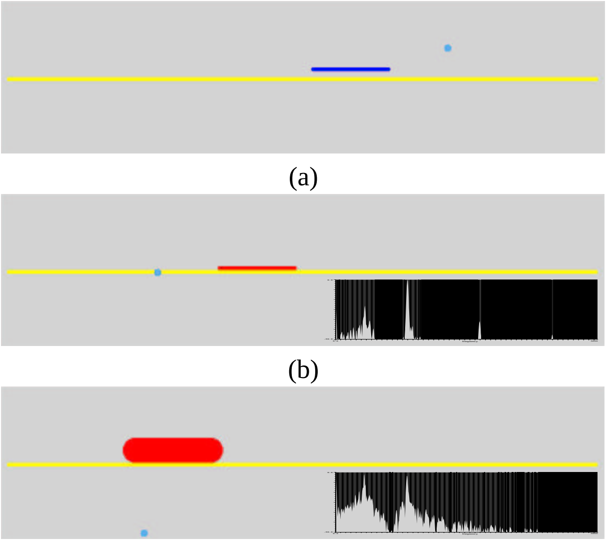
[1] http://www.pure-data.org

[2] http://gem.iem.at/


(a)

(b)

(c)

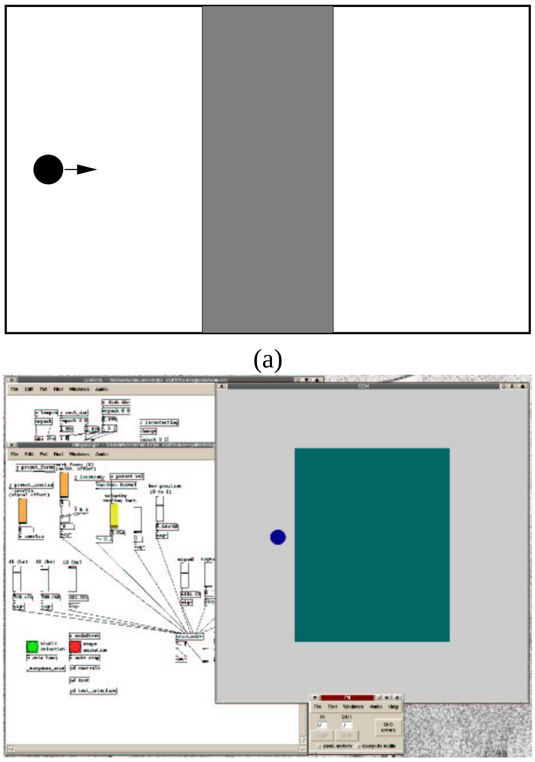
Figure 1: *A 2D animation of a block moving on a surface. Audio feedback from the friction model elicits perception of effort. The blue dot indicates the position of the "handle" (dragged by the mouse) which pulls the block. Spectra of two audio frames are overlaid to the corresponding image frames.*

dio feedback from the animation was obtained using the physical friction model described in section 2.

Users interact with the object by dragging a handle (the blue dot depicted figure 1) with the mouse. The instantaneous tangential and normal forces that act on the block are constructed as linear elastic forces, proportional to the x and y distances between the handle and the center of gravity of the block. In other words the interaction metaphor is that of pulling the block with a rubber band or a spring.

Depending on the direction of the normal force, the block can be either suspended over the surface, as in figure 1(a), or in contact with it, as in figure 1(b,c). As the normal force is increased in the negative y direction, the effort required to move the block is increased as well. This is rendered graphically by changing the block color from blue to red and scaling its vertical dimension. Audio feedback obtained through the friction model changes dramatically and in a physically consistent way depending on changes in the normal force, ranging from noisy friction to stick-slip motion, up to chaotic behavior when the normal force reaches extremely high values. The increase of complexity when augmenting the force values is clearly noticeable in the overlaid spectra of figures 1(b,c).

Despite the effectiveness of the auditory display, subjects in informal tests reported difficulties in interacting with the display of figure 1. In particular, the meaning of the "handle" and its influence on the object behavior was not easily understood. These observations led to a substantial redesign of the display


(a)

(b)

Figure 2: *(a) The 2d visual experimental setup developed by Minguzzi to test the "braking effect" (drawing based on [12]); (b) the interactive display after the redesign.*

3.2. Redesign

The main idea for the redesign of the interactive display came from previous psychophysical studies. In particular, a notable example of visual perception of friction and effort is found in the "braking effect" studied in the early sixties by Levelt and, a few years later, by Minguzzi (see e.g., [12, pp. 300–301]). His 2D visual experimental setup comprises a disk which moves with constant velocity until it crosses a colored strip (see figure 2(a)). When the disk enters the colored strip, its speed is suddenly and drastically reduced (by a factor 8 or so), and its motion continues at constant speed. The velocity recovers completely at the exit from the strip. Perceptual experiments have shown that subjects tend to describe the situation as the disk being blocked by the colored strip, which is then perceived as a viscous surface.

The redesigned interactive display, reproduced in figure 2(b), has strong similarities with the above described setup. Users interact with the display by dragging the disk with a pointing device (object manipulation is implemented accordingly to typical dragging operations: pointer displacement in conjunction with left button selection). In this way the sliding object is controlled in position and velocity by the user, and the unintuitive "rubbed band" mediation used in the preliminary design is removed.

Friction only occurs within the colored area, and is again rendered auditorily using the physical friction model described in section 2. Visual rendering is inspired by the above mentioned "braking effect". As already mentioned, in Minguzzi's original experiments the disk velocity exhibits an abrupt slow-down while crossing the colored strip. This way of displaying resistance to motion is unpractical in a context of manipulation via a pointing device, as the dragged object would accumulate a constantly increasing delay behind the pointer. One could increase the Control/Display (C:D) ratio so that larger actions on the device are needed to keep the apparent motion of the pointer uniform. This strategy proved to be successful to render bumps and holes in 2-D interfaces [13], but it has two major drawbacks for our purposes: (i) being non physical, it is expected to increase the sensation of interactions mediated by a device, (ii) it is hardly usable in a tangible computing context (see the design of experiment 2 below), where there is a tight coupling between pointer and pointing device. Therefore, we decided to manipulate visual delays, using the the following threaded algorithm:

```
while (true) {
  pointer_position = pointer.read();
  sleep(a_few_milliseconds);
  if (timer != 0) approach.stop();
  timer = delay[n];
  approach.start(pointer_position,timer);
}
```

where `approach` is a separate thread that decrements a timer initially set to a delay corresponding to a given level `n` of resistance. This timer is re-initialized every time a new pointer position is read.

Using this algorithm results in a disk motion which is a low-passed version of the pointer motion, thus producing the desired visual inertia effect.

4. EXPERIMENTS

Three different experiments were designed to test the effectiveness of friction sounds in conveying information about perceived resistance to motion of a manipulated object.

The first experiment is based on the audio-visual setup described above and on a within-subjects design in which participants are presented with three interaction modalities (audition only, vision only, audition+vision). The experiment served as a prestudy that helped to validate the design of the audio-visual stimuli.

In the subsequent experiments the procedure was varied in two different ways. In one case the design was changed, and a between-subjects design was adopted in order to minimize practice and carryover effects. In the second case a different interface was used, in which subjects manipulate a real object and the auditory feedback is controlled trough a computer vision system that extracts kinematic parameters.

4.1. Experiment 1

4.1.1. Participants and stimuli

Six subjects (between 25 and 67 years old) participated in experiment 1. All participants reported normal hearing and sight, and normal motoric capabilities in their hands. All of them were naive as to the purposes and hypotheses of the test, and all of them volunteered.

The interactive audio-visual display described in section 3.2 (see figure 2(b)) was used to synthesize the stimuli.

4.1.2. Procedure and design

Auditory stimuli were obtained using five levels for the normal force between the disk and the plane it is being rubbed on. Similarly, visual stimuli were obtained using five values for the delay of the disk motion with respect to the pointer (see Table 1). The visual delay was chosen to cover a range that ensures elicitation of a relation of causality between the pointer and the disk, as found in the launching experiments by Michotte [14]. Recently, Guski and Troje [7] found that causality is still attributed when the "slave" object is moved with a delay up to about 180 milliseconds. For delays larger than that, the subjects may experience two problems:

- the disk motion appears to be loosely related to the control actions;
- disk and pointer can temporally get far from each other, thus forcing the locus of attention to jump back and forth from where the action is and where it produces its effects. Such jumps of the locus of attention are generally considered to be a bad thing in visual interfaces [15].

A within-subjects design was used for this experiment. The presets of table 1 were arranged in three modalities (audition only, vision only, audition+vision), therefore totaling 15 stimuli. Each stimulus was presented three times to the subject, in random order. Auditory stimuli were presented monophonically via headphones. The isometric pointing device used to implement interaction was a Logitech marble mouse (trackball).

Level n.	Normal force (N) (auditory)	Delay (ms) (visual)
1	0.01	20
2	0.03	60
3	0.1	100
4	0.4	140
5	1.1	180

Table 1: *Audio-visual preset values used for the stimuli*

The subjects were allowed to interact with each stimulus as long as desired (typically $\sim$ 10 to 20 s). For each stimulus they were asked the question "Based on visual and auditory cues, rate how much the disk is resisting to motion." The numeric answer scale comprised 11 steps from 0 to 10. Before beginning the actual experiment the subjects were presented with 6 demonstration trials, 2 from each of the three modalities.

The choice of the phrase "resistance to motion" in the test question is motivated by the fact that we wanted the subjects to be as free as possible in interpreting the display. For this reason more specific references to physical reality (e.g., "viscosity," "damping," etc.) were not used. Also, there was no reference to "effort", since this concept refers to the subject rather than the manipulated object.

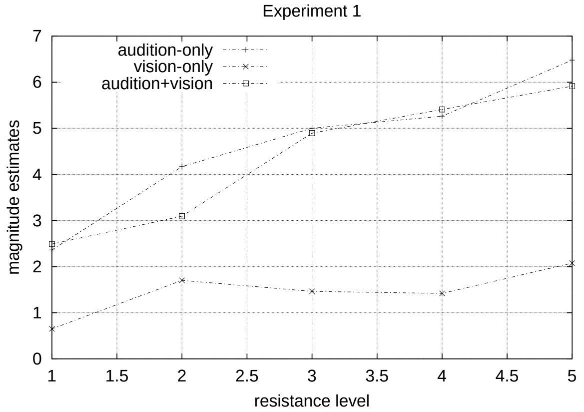
4.1.3. Results

None of the subjects reported difficulties in interacting with the display. No recordings of the interactions were taken. However from informal observation they appeared to use different interaction techniques: as an example, two subjects were particularly interested in exploring the strip boundaries, while other concentrated on the interior. The velocity ranges also appeared to be varying depending on the user.

Magnitude estimates were extracted using the following procedure.

- For each subject, estimates were averaged across stimulus repetitions.
- To compensate for differences in individual numerical scales, the averaged estimates for each subject were normalized by dividing each score by the individual participant mean and multiplying by the grand mean (across participants).

Results are shown in figure 3. It can be noticed that on average subjects identified the increase in resistance to motion with good accuracy. In particular, the magnitude estimates in the audition-only and audition+vision conditions are strictly monotonic functions, while this is not the case for the vision-only condition.



Modality	*Standard deviation*				
aud. only	1.58150	2.58870	2.58180	2.53770	2.99260
vis. only	0.73707	1.72145	2.09156	2.25198	2.58703
aud + vis	1.23233	0.71568	1.62341	1.55291	1.70713

Figure 3: *Results from experiment 1: normalized magnitude estimates (and standard deviations) as a function of the resistance levels (see table 1).*

Figure 3 also shows that the mean magnitude estimates are higher in the audition-only condition than in the vision-only condition. Moreover, the judgments are distributed on a broader range. In particular, subject 6 attached a 0.00 score to all the stimuli of the vision-only condition, and when interviewed after the test confirmed that she hardly noticed any varying visual cues. The only exception to auditory dominance is subject 2, where conversely a clear visual dominance was noticed. None of the subjects was ambiguous in this respect. In all cases, there is strong dominance of one modality.

The highest mean magnitude estimates and the broadest range of judgments are found in the audition+vision condition. This result shows that the presence of bi-modal feedback provided the most reliable cues.

Despite the limited number of participants, these results provide experimental validation of the effectiveness of the audio-visual stimuli adopted. Therefore the same preset values (see table 1) were used also in the subsequent experiments.

4.2. Experiment 2

4.2.1. Participants and stimuli

Sixteen subjects (between 28 and 67 years old) participated in experiment 2. All participants reported normal hearing and sight, and normal motoric capabilities in their hands. All of them were naive as to the purposes and hypotheses of the test, and all of them volunteered.

As in experiment 1, the interactive audio-visual display described in section 3.2 (see figure 2(b)) was used to synthesize the stimuli.

4.2.2. Procedure and design

As already discussed above, subjects involved in the first experiment chose a “dominating” modality: specifically all but one of the subjects chose to concentrate mostly on the auditory cues and considered the visual ones to be less significant.

In order to avoid this effect, we chose a between-subject design for the second experiment. The presets of table 1 were again arranged in three modalities (audition only, vision only, audition+vision), but this time the participants were divided into three subgroups and each subgroup was presented with only one modality. For each modality, the five stimuli were presented four times to the subjects, in random order.

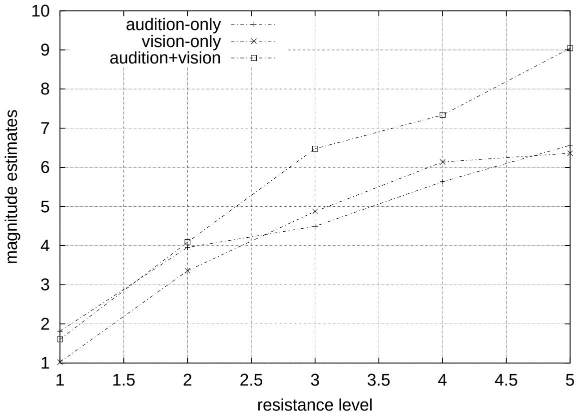
As in experiment 1, the auditory stimuli were presented monophonically through headphones, and a Logitech marble mouse (trackball) was used. The subjects were allowed to interact with each stimulus as long as desired. Before beginning the actual experiment the subjects were presented with 5 demonstration trials. The subjects were given the same instructions and were asked the same question as in experiment 1.

4.2.3. Results

Magnitude estimates were analyzed using a similar procedure as in experiment 1 (i.e., responses were processed by averaging across repetitions and normalizing across participants). In order to be consistent with the between-subjects design, however, in this case the normalization was performed separately for each of the three subgroups. Results are shown in figure 4.

On average participants again identified the increase in resistance to motion with good accuracy. However the results differ notably from experiment 1. Specifically it can be noticed that visual cues were found to be very reliable in this case, and in fact were identified more reliably than the auditory ones, as shown by the standard deviations reported in figure 4. This result confirms and complements the findings from the first experiment: when subjects were provided with both auditory and visual feedback (as in experiment 1) they tended on average to neglect the latter in favor of the former; however when they were presented with only one modality then the visual feedback became extremely effective.

As in experiment 1, the highest mean magnitude estimates and the broadest range of judgments are found in the audition+vision condition.



Modality	*Standard deviation*				
aud. only	0.72784	0.68891	1.45486	0.79769	1.35084
vis. only	0.43074	0.55212	0.65316	0.44835	0.57261
aud + vis	0.33461	1.28389	0.73740	0.33292	1.33563

Figure 4: *Results from experiment 2: normalized magnitude estimates (and standard deviations) as a function of the resistance levels.*

4.3. Experiment 3

4.3.1. Participants and stimuli

Twenty subjects (between 20 and 55 years old) participated in experiment 3. All reported normal hearing and sight, and normal motoric capabilities in their hands. All of them were computer scientists, and naive as to the purposes and hypotheses of the test. All of them volunteered.

In this third experiment we used a tangible interface as shown in figure 5. After experimenting with different possibilities, we chose an orange squeeze ball, for its comfortable grasp and for its material which did not provide any significant real auditory feedback when in contact with a hard surface. In order to be consistent with the previous experiment, the tangible object was not varied, instead we experimented with visual and auditory feedback.

Using a tangible interface allows for the removal of the pointing-device mediation and provides the user with the feeling of actually moving the object rendered on the screen. The interaction metaphor that underlies experiment 3 is therefore slightly different from that of experiment 1 and 2, where the object is dragged by the pointer.

We used the same implementation of the friction model as in experiment 1 and 2. In this case, the setup was realized in the Max/MSP and Jitter environment.[3] The center position of the tangible object was tracked in real-time, using the Lucas Kanade algorithm [16]. This position signal was used to extract the velocity parameter of the friction physical model.

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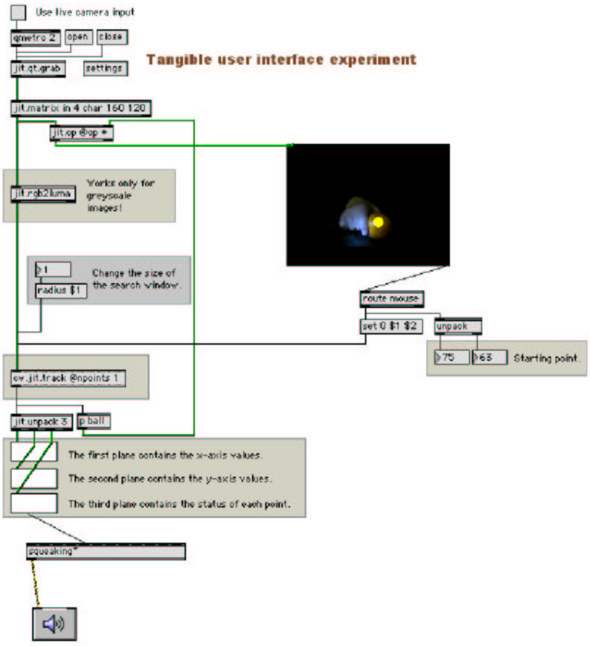
[3] http://www.cycling74.com



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The first plane contains the x-axis values.

The second plane contains the y-axis values.

The third plane contains the status of each point.

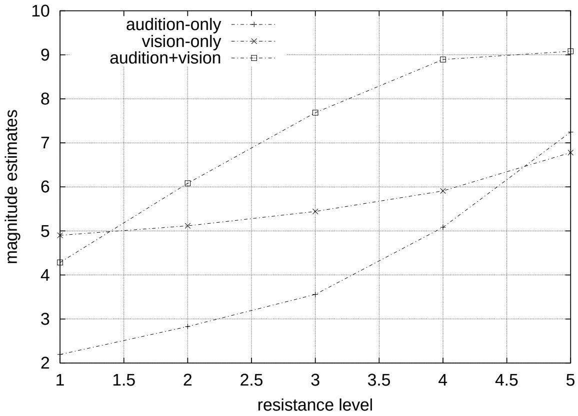
Figure 5: *The Max/MSP that realizes the tangible user interface used in experiment 3. The snapshot reproduces a camera frame, a user's hand and the orange squeeze ball can be recognized. The dot on the ball represents the center of the interface which is tracked in real-time.*

4.3.2. Procedure and design

As before, auditory stimuli were obtained using five levels for the normal force between the disk and the plane where it is being rubbed on (see table 1).

The user was able to move the tactile interface vertically along a hard wood surface of about 30 cm. By using a web-camera, the tangible interface was displayed in Jitter, and its center position tracked in real-time. In order to be consistent with the previous experiments, we introduced a delay in the visual display, with the values given in table 1. Users were asked to look at the monitor and not at the physical interface; in the monitor the delayed object was displayed, as was the case with the animation of the previous experiment.

The experiments were conducted in a quiet room, where only the facilitator and one subject at the time were present. The sound was delivered through headphones, and the visual display was shown on a 17" screen. The relatively large visual display was chosen to increase the sense of presence and immersion in the visual reproduction, so that the subjects could concentrate on the visual display shown on screen rather than looking at their own hand moving the tangible interface.



Modality	*Standard deviation*				
aud. only	0.57917	0.71063	1.07293	1.47344	1.37486
vis. only	1.59829	1.35221	1.02455	0.96279	1.13388
aud + vis	1.59928	0.83242	0.59893	0.92856	0.89794

Figure 6: *Results from experiment 3: normalized magnitude estimates (and standard deviations) as a function of the resistance levels.*

A within-subjects design was used, as in experiment 1. The total number and arrangement of the stimuli was the same as in experiment 1 (5x3 design). The subjects were given the same instructions and were asked the same question as in experiment 1.

4.3.3. Results

Magnitude estimates were analyzed using the same procedure as in experiment 1 (i.e., average across repetitions and normalization across participants). Results are shown in figure 6. It can be noticed that also in this case subjects identified the increase in resistance to motion with good accuracy. In particular, the magnitude estimates in all the three conditions are strictly monotonic functions.

Figure 6 shows that, similarly to experiment 2, also in experiment 3 there is no clear dominance of one modality. Magnitude estimates are on average slightly higher in the vision-only condition than in the audition-only condition, but the judgments are distributed on a broader range in the audition-only condition, suggesting that levels of "auditory resistance" were perceived more clearly. These results, when compared with those from experiment 1, seem to suggest that the use of a tangible interface in conjunction with the visual display may emphasize the effect of visual cues.

As in the previous experiments, the highest mean magnitude estimates and the broadest range of judgments are found in the audition+vision condition.

5. DISCUSSION

The findings from the three experiments described in the last section seem to confirm the effectiveness of substituting the physically-based sound model for haptic feedback. Specifically, the perceived resistance to motion is found to depend monotonically on the physical parameter which is varied in the auditory stimuli (i.e., the normal force between the manipulated object and the underlying surface).

Magnitude estimates by the subjects of experiment 1 provide clear indication that auditory cues dominate over visual cues when a within-subjects design is used. This indication is complemented by the results from experiment 2, that shows that visual cues are more clearly perceived when a between-subjects design is used. Results from experiment 3 suggest that the use of a tangible interface in conjunction with the visual display may emphasize the effect of visual cues, although further analysis would be needed in order to assess to what extent the different underlying interaction metaphor influences the subject responses.

In the current setup the tactile modality is not modified. However, the possibility to use tangible interfaces as in experiment 2 allows a large number of different situations to be tested. As an example, the cross-correlation of the three senses or of the tactile and auditive senses can be explored by varying the objects that the user is manipulating or the surfaces in which such objects are moving. These experiments can provide further indications on the role of auditory feedback in the perception of size and weight of objects.

6. ACKNOWLEDGMENT

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