Visual and Haptic Perception of Object Elasticity in a Virtual Squeezing Event

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ABSTRACT

Numerous studies have been performed on the human perception of object's weight, elasticity or viscosity. Most of them were however based on discrimination tasks, and used or simulated very simple objects with linear elasticity. In the experiment presented, we asked participants to make judgements on the elasticity of a deformable virtual object from haptic and visual information. We found that observers could make judgements on elasticity in an orderly way, and that all of the different stiffness values were correctly discriminated except the two lowest ones. It was found too that visual information, when available, modified the movements parameters, such as movement amplitude and mean manipulation speed, but did not help improving the results of the task.

Keywords: elasticity, stiffness, deformable object, haptic information, visual feedback

1 INTRODUCTION

Elasticity is defined as the ability of an object or of a piece of material to resume its normal shape spontaneously after deformation. When talking about deformable objects, such as a spring, the term stiffness is used, that is, the physical parameter defining the relation between a deformation and the force applied on the surface of the object that leads to this deformation. Compliance is defined as the inverse of stiffness and is sometimes used instead.

When talking about human perception, we will later use the term "elasticity", while we will use the term "stiffness" when we will talk about the physical parameter defining the rigidity of an object.

The elasticity of an object is one of its fundamental properties, from a perceptual point of view. With a habituation technique Walker, Owsley, Megaw-Nyce, Gibson and Bahrick [13] found that already at young age (80–126 days old), elasticity can be perceived and that it can be discriminated from a moving object that is not deformed. Warren, Kim and Husney [14] studied visual and auditory perception of the elasticity of bouncing balls and how it could be used for regulation of the bouncing. The main conclusions were that observers can accurately perceive the elasticity of a bouncing object and can use that information to control their actions. These studies suggest that perception of elasticity is a basic experience.

It should also be noted that elasticity can only be perceived over time, that is, it cannot be detected in static situations. A dynamic situation is needed where the object changes in some way, for instance, when handled by people. This property can be perceived via touch, kinaesthesia, vision, and even by audition.

Katz and Stephenson [5, 6] investigated the relation between weight and elasticity. In the experimental tasks, participants had to compare elastic forces to weight forces. Results showed that participants always overestimated elastic forces compared to weight forces, suggesting that dynamics of elasticity and of gravity are not perceived similarly.

Observers' ability to detect thresholds for related perceptual parameters, such as force, stiffness and compliance has been experimentally studied.

Pang, Tan & Durlach [9] used a 1-DoF haptic device to simulate constant forces, and the observers' task was to discriminate between two alternative levels of forces (a reference level and an increased level). The results were JNDs of about 7 %, roughly constant over 2.5 to 10.0 N. It should be noted that these results were obtained in a dynamic situation, where the observer was actively squeezing the virtual object. Similar JNDs were obtained by Jones [3] in related experiments where static forces were compared in a contralateral limbmatching procedure on participants arms. The range of forces tested in this experiment was 15 to 85 % of the maximum voluntary contraction (from 169 to 482 N).

JNDs for stiffness perception are usually found to be greater. Jones and Hunter [4] had participants comparing the stiffness of simulated springs using a contralateral limbmatching procedure. Participants adjusted the stiffness of a motor connected to one (matching) arm until it was perceived to be the same as that connected to the other (reference) arm. Their results showed an average JND of 23 % for stiffness. The magnitude of the reference stiffness ranged from 0 to 6260 N/m and reference viscosity values ranged from 2 Ns/m to 1024 Ns/m in their experiments.

Tan et al. [11, 12] have shown that the discrimination of compliance was strongly affected when the pushing distance was randomly modified during the experiment. The JND was of about 6 % for force discrimination and 8 % for compliance discrimination using a fixed-displacement paradigm, while it dropped respectively to 14 % and 22 % using a roving-displacement paradigm. The authors have shown that compliance perception was based either on work or terminal force information.

In sum, these experiments demonstrate that observers can discriminate between different degrees of force and elasticity, and it was suggested that stiffness (and consequently compliance) discrimination was mainly based on terminal force information.

Differences between the kinesthetic and the visual perception of elasticity have been observed in several works. Tan et al. [12] presented a measure of the kinesthetic perception of absolute rigidity. It was reported that when participants, eyes closed, reached a point where the deformable object could be felt rigid, the displacement caused by the probing was visually detectable by an external observer. This suggests that human kinesthetic and visual perception of rigidity can differ.

Srinivasan, Beauregard and Brock [10] presented the impact of visual information over kinesthetic information in a comparison of

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two springs with different stiffness. It was shown that when visual information was different or even contradictory to the kinesthetic information, visual information prevailed over the kinesthetic information. This suggests that visual information can strongly influence human perception of stiffness, and even dominate contradictory haptic information.

Lecuyer et al. [7, 8] used an isometric gesture interface to simulate the stiffness of a spring. In these experiments, the virtual stiffness was calculated on the basis of the deformation visually represented as a function of the force applied on the isometric device. Here again, visual information blurred haptic information, as participants reported different stiffnesses while the mechanical stiffness of the device always remained the same.

As suggested in this introduction, literature presents an interesting knowledge about the human perception of elementary properties of materials such as elasticity or mass. However, all of these studies were mainly based on very simple experimental cases, such as the use or the simulation of a spring, and did not show if observers could order these properties. Consequently, the aims of the present experiment were the following:

1. To study to what extent observers via haptics alone can pick up the information about the elasticity of an object provided when it is squeezed through a tunnel by the observer, furthermore when the relation between the elastic force and the movement produced by the observer is non linear, and consequently more complex than the simple case of the deformation of a spring.
2. To study the relation between the judgements of elasticity, parameters of the force interaction and movements used by the observers when they squeezed the object through the tunnel.
3. To study to what extent visual information improves the judgements when it is added to the haptic information.
4. To evaluate in which ways the movement parameters of the task are modified in presence or absence of visual feedback.

2 Theoretical model and apparatus

2.1 General description of the model

The model we implemented aimed at simulating a deformable paste with which the participant could interact through a haptic device. We used a particle-based physical modelling system [1], which allows to represent various properties of the matter (elasticity, plasticity, viscosity, etc.), different states of the matter (solid, liquid, gaseous, powder, etc.) or natural interactions between several material objects in a very general way. Using this modelling system, the models of objects are represented by a network of interconnected elements of two types: particle (punctual material) elements, and non-material interaction elements.

The task was to evaluate the stiffness of the paste, by moving it through two obstacles that formed a narrow "tunnel", and the model was designed so that the movements performed by the observer would be restrained as much as possible along one axis.

Different components constituted our model (figure 1):

1. A piece of soft material (further called the "paste"): this is the object whose stiffness will be tested in the experiment.
2. The tunnel, constituted by two fixed obstacles, which interact only with the paste. The obstacles are arranged so that the paste object will be squeezed as it passes through the tunnel.
3. The element representing the external interaction from the haptic device: the manipulation point.
4. The box containing the paste.

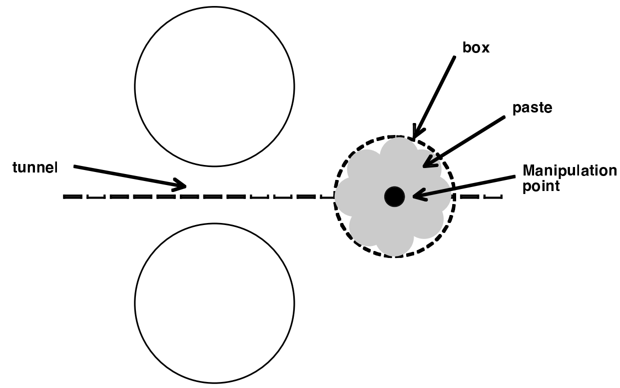

Figure 1: Schematic representation of the model designed for the experiment

2.2 The "paste" object

We have chosen to model the paste object by a network of 20 interconnected particle elements. To keep a homogeneous and isotropic representation of the paste object, all the particle elements were connected one to each of the others by interaction elements with equal non-null rest lengths, which implemented linear visco-elastic interactions. The total weight of the particle elements composing the paste object was chosen so that the inertia forces during manipulation would be low compared to the visco-elastic interaction forces.

In order to simulate various rigidities of the paste object, seven different values were successively used for the stiffness parameter of the interaction elements connecting the particle elements. These values are summarised in table 1. In the same table are indicated, for each stiffness value, the force needed to deform the paste sufficiently so that it could slip through the tunnel.

Particle elements were not by themselves deformable. Consequently, in our visual representation of the paste object, the shape of the individual representations of the particle elements did not change over the simulation, and it was only the changing distance between the particle elements that gave the impression of a deformable object (figure 2). Each of the particle elements inside the paste object was represented by non-shadowed plain circles, which diameter was enlarged sufficiently so that the paste looked like a completely filled shape.

Table 1: Relationship between the stiffness parameter of the interaction interaction elements of the paste object and maximum interaction force

Stiffness parameter	Stiffness of the interaction elements [N/mm]	Maximum interaction force [N]
K_1	0.003	0.45
K_2	0.007	0.63
K_3	0.014	0.95
K_4	0.031	1.64
K_5	0.067	3.10
K_6	0.145	5.59
K_7	0.315	8.87

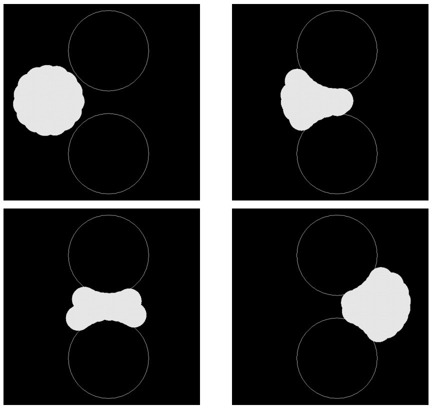

Figure 2: Snapshots from the visual scene: the paste object is passing through the tunnel from left to right (low stiffness case)

2.3 The tunnel

To simulate the squeezing of the paste, we chose to have the paste moving through a tunnel. The tunnel was modelled by two spatially fixed material points and connected to each of the particle elements of the paste object by buffer interaction elements. Therefore, the paste could freely move if the distance was greater than the distance threshold; otherwise, a visco-elastic interaction was set up, preventing the paste from getting closer to the obstacles.

We have said previously that the paste object was implemented as a linearly deformable object. However, due to the particular geometrical configuration used, the relation between the movement produced by the observer and the resulting interaction force was not linear.

The spatial bounds of the obstacles (that is, the distance from the paste at which the visco-elastic interaction was set up) were graphically represented on the screen by white empty circles.

2.4 Manipulation of the paste: the box

In order to let the observer interact with the simulated scene, we have chosen to enclose the paste inside a circular virtual box, whose position could be controlled through the haptic device, but which was not represented on the visual scene. Its diameter was set a little smaller than the diameter of the paste at its equilibrium state, so that the box and the paste would always stay in contact, and that no collision could be felt during manipulation. Forces applied by the paste on the box were applied to the user through the haptic device, and at the same time, forces applied by the user to the haptic device were applied to the paste object. The manipulation paradigm thus obtained by the addition of the manipulation box remained transparent from the user point of view, thus giving the feeling to the user that he/she was directly controlling the movements of the paste without any intermediary object. Neither during the pilot experiment nor during the final experiment did participants complain about the lack of controllability or realism of the manipulation situation.

To avoid participants to be spatially lost in the haptic only condition, we added an elastic guiding with a high stiffness (1 N/mm) but very low viscosity along the horizontal axis. That way, forces were applied orthogonally to the axis of the requested movements as the participant manipulated out of the manipulation axis.

2.5 The haptic device

We used a haptic device [2] with a 3-DoF stick (no rotational movements). The stick used was 6 cm long, with a 1 cm solid sphere fixed at its extremity (figure 3). Table 2 summarizes the functional characteristics of the device. Movements along the vertical axis were blocked inside the model by a very stiff visco-elasctic interaction, and the translational and contralateral axis in the gesture workspace respectively corresponded to the horizontal and vertical axis in the visual representation on the computer screen.

Table 2: Functional characteristics of the ERGOS device

Size of workspace	60 x 60 x 25 mm	
Max force exerted at peak	Horizontal axes ($X\&Y$)	150 N
	Vertical axis (Z)	600 N
Max continuous force	Horizontal axes ($X\&Y$)	15 N
	Vertical axis (Z)	60 N

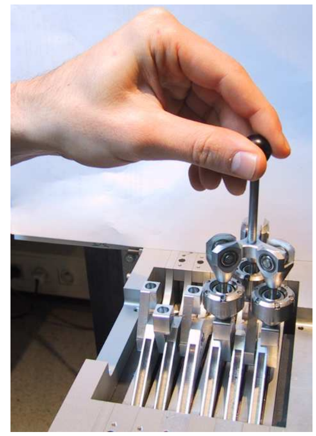

Figure 3: Picture of the haptic device used for the experiment

The computation of the model and the communication between the simulator and the haptic device were run at 3 kHz, the visualization output of the model was performed at 50 Hz, and the dynamics of all the trials of the experiment were recorded at 3 kHz for further analysis.

3 METHOD

3.1 Participants

Twelve persons participated in the experiment, eight men and four women, from 22 to 36 years old (mean 27 yrs). All of them were right handed and nobody had neuromotor or visual impairments. All were naïve to the details of the experiment and its hypotheses.

3.2 Choice of stimulus situations

In order to get a suitable range of stimulus situations, a pilot experiment was carried out with 6 participants (3 men and 3 women) in a wide range of situations. The results of the pilot experiment suggested that some of the situations with low stiffness could not be discriminated and that in the situation with the highest stiffness some participants could not squeeze the paste through the narrow corridor because it was too stiff; furthermore, the simulation was sometimes unstable in the highest stiffness case. These situations were eliminated and the parameters chosen for the main experiment are described in Table 1.

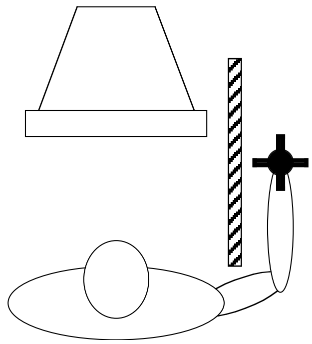

Figure 4: Schematic representation of the experimental situation

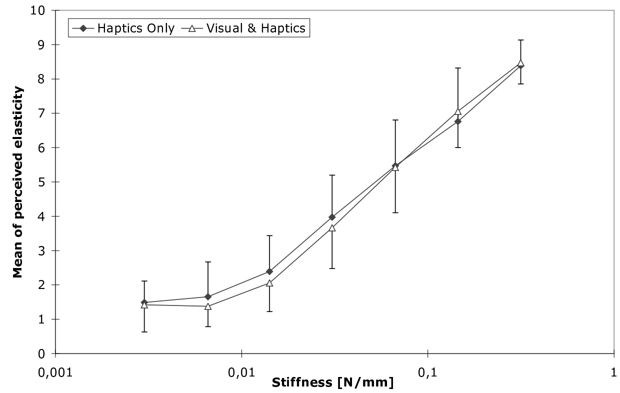

Figure 5: Means and standard deviations for the perceived elasticity, as a function of the presented stiffness

3.3 Design

Two experimental conditions were investigated: (1) Haptics only and (2) Vision and haptics. Each of the conditions was presented twice, and all participants ran the complete experiment. The four conditions contained the same seven stimuli (see table 1) and were given in ABBA/BAAB series, each order for half of participants. The stimuli within each experimental condition were presented in random orders, half of them the reverse of the other half.

3.4 Procedure

Participants were seated in a darkened room to the left side of the haptic device, about 60 cm in front of a 21" video screen. Participants were instructed to grasp the stick using three fingers as when holding a pen (figure 3), the elbow reposing on the table, leaving the wrist free to move. A large wooden board was fixed between the participant and the haptic device, in order to prevent the participant from looking at his/her hand. In the haptic-only experimental condition, participants were blindfolded.

The participants were first instructed about their task: to judge the elasticity of the paste, by moving it through the tunnel with the haptic device. The manipulation situation was presented, especially the elastic guiding along the horizontal axis, and the participants were instructed not to use high manipulation speeds (such as shaking movements) in order to lower the effects of viscosity. The participants were told to judge the elasticity for each stimulus situation by giving a numerical value from 1 to 9 (one decimal allowed). No time constraints were imposed, but the participants were instructed to answer as spontaneously as possible, and not to elaborate notation strategies, for example by considering the values they had given before.

After these instructions, a stimulus situation was presented in order to give the participants an experience of the manipulation, and to verify that they had clearly understood the task. At the beginning of each series, two reference stimuli were presented in the experimental conditions of the current series. First the lowest stiffness value was presented, then the highest stiffness value. Participants were instructed that these stimuli corresponded to the values 1 and 9, respectively in the judgement scale. The total length of the experiment did not exceed 20 minutes.

4 Results

4.1 Perceived stiffness

One of the main results of this experiment consists in the judgement of the elasticity given by the participant during the experiment. ANOVAs did not show any significant effect from the repeated measurements in the two experimental conditions. Figure 5 plots the mean results of the subjective judgements for the two experimental conditions, without differentiating the repeated measurements. An ANOVA demonstrated the highly significant effect of the stiffness stimulus on the perceived elasticity ($F_{(6,66)} = 299.409$, $p < .001$), but no significant effects of the experimental situations Haptics only and Vision and Haptics ($F_{(1,11)} = .204$, $p = .660$) or of the interaction ($F_{(6,66)} = 2.021$, $p > .05$). Post hoc t-tests demonstrated significant differences between all values of the stiffness parameter in all cases except between the two lowest values K_1 and K_2 with p–values far below 0.001.

The first observation is that the observers well managed to perceive the information about elasticity available in the stimulus situation described in terms of the maximum interaction force.

4.2 Number of passages

To get an indicator of the difficulty of the task, we recorded the number of passages through the obstacles for each trial (figure 6). The mean number of passages was between 10 and 15 and the standard deviations were about 10 for all the stiffness values in the two experimental conditions. No significant effects were found from the experimental conditions ($F_{(6,66)} = .59$, $p = .813$), but significant effects were found from the stiffness parameter ($F_{(6,66)} = 3.322$, $p < .01$). Post hoc t-tests demonstrated no significant differences for the values of Haptics only condition, but significant differences were found for the Vision and Haptics condition, between K_1 and K_7 and between K_7 and each of K_2, K_3 and K_4 ($p < .05$). No significant interaction effects were found ($F_{(6,66)}$, $p = .633$).

4.3 Maximum amplitude and manipulation speed

For each trial, the maximum amplitude of the movements performed was recorded. Means and standard deviations measured of this parameter are given in figure 7. Significant effects were found for the stiffness parameter ($F_{(6,66)} = 10.215$, $p < .001$), and for the experimental conditions ($F_{(1,11)} = 85.131$, $p < .001$). Using post hoc t-tests it was found that about half of the pairs of values for the stiffness parameter were significantly different ($p < .05$). Therefore, one can observe a strong difference between the two experimental conditions: the amplitude of movements is about twice as large in the haptics only condition. The interaction between the stiffness parameter and the experimental conditions was highly significant ($F_{(6,66)} = 10.631$, $p < .001$).

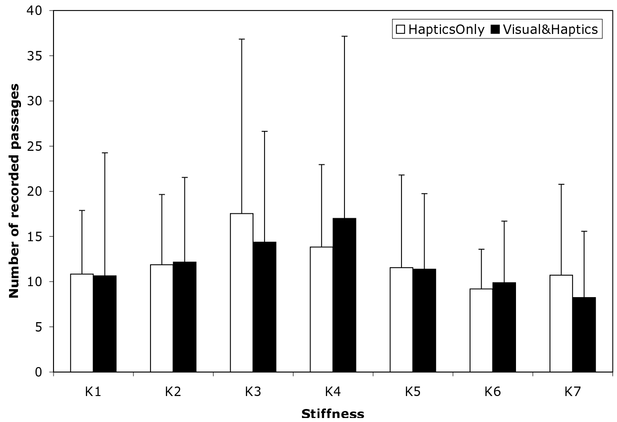

Figure 6: Means and standard deviations of number of passages through the tunnel for each stiffness stimulus

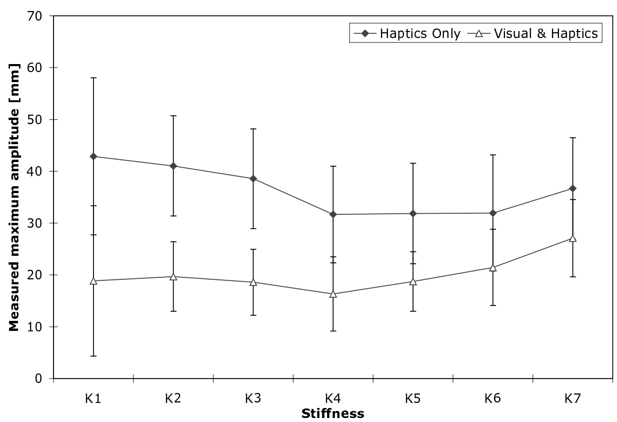

Figure 7: Means and standard deviations measured for the amplitude of the movements performed

The manipulation speed at free movement is represented on figure 8. It represents the means of the manipulation speed when there was no contact between the paste and the obstacles. As for the amplitude measurements, significant effects were found from the stiffness parameter ($F_{(6,66)} = 34.255$, $p < .001$), and from the experimental conditions ($F_{(1,11)} = 56.218$, $p < .001$). Also the interaction was highly significant ($F_{(6,66)} = 17.888$, $p < .001$). Post hoc t-tests demonstrated significant differences between K_6 and K_7 on one side and nearly all of the other values of the stiffness parameter.

One can observe in figure 7 that the movement amplitudes were about twice as large in the haptics only experimental condition as in the visual and haptics condition. The difference between the two experimental conditions decreased as the stiffness increased, but it was still very significant for the highest stiffness (K_7). We measured that the size of the manipulation workspace where there is a contact between the paste and the tunnel was [-7.5 mm; +7.5 mm] along the manipulation axis, that is, a moving range of 15 mm. The movement amplitudes in the visual and haptics condition were generally found around 20 mm, which is just above the manipulation space where the paste and the tunnel are in contact. Conversely, the movement amplitudes in the haptics only condition were much greater, generally around 40 mm, indicating that the participants extended much more their movements out of the useful workspace. This suggests that visual feedback constituted an important information to

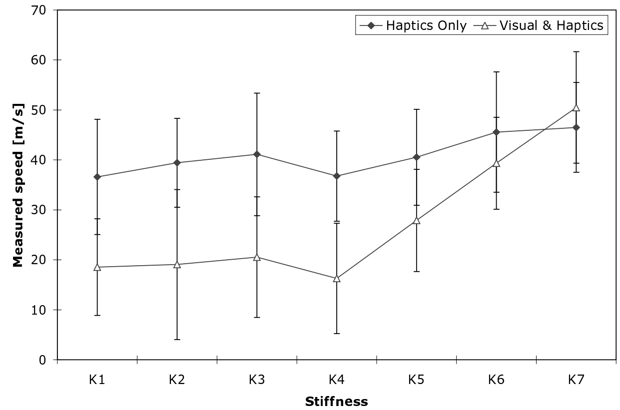

Figure 8: Means and standard deviation measured for the speed at free movement

help the participants keeping close to the useful workspace of the manipulation.

A very similar observation can be made for the manipulation speeds depicted on figure 8, where the manipulation speeds measured were found to be twice as large in the haptics only condition as in the visual and haptics condition. The stiffness parameter did not have any effect on the manipulation speed for low values (from K_1 to K_4), but it clearly appears on figure 8 that it had an effect for higher values in the Haptics and Visual condition, whereas it didn't in the Haptics only condition. This can be explained by the behavior of the model itself: the paste is expulsed out of the tunnel after having reached the middle of the obstacles. Furthermore, the stiffer the paste, the larger the forces expulsing the paste out of the tunnel. Thus, the minimum manipulation speed at the end of the tunnel is constrained by the forces from this expulsion effect. This expulsion effect did not have such a strong effect in the haptics only condition, however, mainly because the manipulation speeds and the movements amplitudes were already greater than the minimum speeds and amplitudes constrained by the expulsion effect.

On the other hand, the decrease in amplitude from stiffness K_1 to K_4 in the haptic only condition can be explained by the fact that the haptic stimuli were larger when the stiffness of the paste increased, thus providing a better haptic feedback of the scene to the observer, and minimising the extra movement around the useful workspace.

5 Discussion

The main result of this experiment is that the participants managed well to perceive different degrees of elasticity of the paste on the basis of the available stimulus parameters. They were given the two extreme stimulus situations at the beginning of each experiment series, and they managed to order intermediate elasticity values with precision. It is interesting to note too that there are not much of individual differences in the shape of the perceived elasticity function. These results are consistent with other results found in literature, which show that observers can discriminate correctly objects with different elasticities. Here we furthermore show that observers can order different elasticities.

We found that the perceptual judgement on the paste elasticity was the same in the haptics only condition and in the visual and haptics condition. This indicates that visual information did not help improving the task, and is furthermore consistent with spontaneous comments made by some participants, who reported that they did not take into account the visual information, except for keeping track of the position of the paste in the scene (that is, to stay in the useful workspace of the simulation). However, it is interesting to note that the movement parameters of the manipulation task were clearly modified with visual feedback: (1) the amplitude of movements decreased, indicating that the movements were restricted to the space where there could be a contact between the tunnel and the paste, and (2) the manipulation speed decreased. A potential explanation of the increase of manipulation speed in absence of visual feedback is that the participants moved faster in order to increase the amount of haptic information.

We can compare our results to those found by Srinivasan et al. [10] and Lecuyer et al. [7, 8], who reported that visual information could overcome haptic feedback in some situations. In these studies, however, the experimental apparatus presented contradictory stimuli for the haptic and visual senses, forcing a choice between one of the two senses to fulfil the task. In the present experiment, coherent representations for the haptic and visual scenes were used, since they were generated by the same model. The good realism of the simulation was spontaneously mentioned by some participants during the post-experiment interview, and moreover, none of them complained about the lack of believability of the simulation. Only one of the participants (among twelve) revealed during the interview that he had used visual information to judge of the elasticity, with particular attention to the visual dynamics of the paste; his results were however not significantly better than those of the other participants.

As an indicator of the difficulty of the task, we measured the number of passages through the tunnel before the participants gave their response. The major tendency that can be seen in figure 6 is an increase of the number of passages for the intermediary values of stiffness. Indeed, participants reported during the interview following the experiment that the high stiffness values were found easy to discriminate, and that the low stiffness could not be discriminated, but on the contrary that intermediary stiffness values were more difficult to evaluate because they were placed at the middle of the notation scale (that is, they couldn't be perceived either as low stiffness values or as high stiffness values). This was confirmed by t-tests, showing significant differences between the intermediary stiffness values and the others in the Haptics only condition.

Analysis of the number of passages revealed that no significant effects were found from the experimental conditions parameter. We assume that this point is correlated to the fact that the results obtained were similar in the two experimental conditions: participants did not experience more difficulty in the haptics only experimental condition, and thus did not need more passages through the obstacles to fulfil the task.

6 Conclusion

The aim of this experiment was to study how an observer could judge the elasticity of a deformable object from haptic and visual information only. Like most of our interactions with objects of everyday life, this experiment implemented a non linear relation between the movements performed by the observer and the resulting interaction forces.

The results have shown that observers well managed to judge on elasticity in an orderly way, without having learned about the task before the experiment, and the perceptual scale was found to be similar among participants. This experiment tends to indicate that elasticity is a perceptual scale that can be ordered, unlike for example timbre concerning audition, or colour concerning vision. Another strong result was that visual information did not help the observers improving their evaluation of elasticity, although it strongly modified the movement parameters, such as the movement amplitude or the mean movement speed.

In similar experiments [7, 8, 10] it was demonstrated a visual dominance over haptic information in similar tasks, which is contrary to our results. We assume that these opposite results are due to the fact that the consistency between the visual and the haptic information was deliberately modified and somehow avoided in these experiments, thus forcing one of the visual and haptic senses to prevail over the other one to evaluate the elasticity of the simulated object. On the contrary, in our experiment, the consistency between the visual and the haptic simulation was satisfied by the use of a unique model for the whole simulation, thus conferring to the simulation a strong feeling of believability, as naturally mentioned by the participants during the post-experiment interview.

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