



Research report

Effects of visual–haptic asynchronies and loading–unloading movements on compliance perception

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ABSTRACT

Spring compliance is perceived by combining the sensed force exerted by the spring with the displacement caused by the action (sensed through vision and proprioception). We investigated the effect of delay of visual and force information with respect to proprioception to understand how visual–haptic perception of compliance is achieved. First, we confirm an earlier result that force delay increases perceived compliance. Furthermore, we find that perceived compliance decreases with a delay in the visual information. These effects of delay on perceived compliance would not be present if the perceptual system would utilize all force–displacement information available during the interaction. Both delays generate a bias in compliance which is opposite in the loading and unloading phases of the interaction. To explain these findings, we propose that information during the loading phase of the spring displacement is weighted more than information obtained during unloading. We confirm this hypothesis by showing that sensitivity to compliance during loading movements is much higher than during unloading movements. Moreover, we show that visual and proprioceptive information about the hand position are used for compliance perception depending on the sensitivity to compliance. Finally, by analyzing participants' movements we show that these two factors (loading/unloading and reliability) account for the change in perceived compliance due to visual and force delays.

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1. Introduction

Springs are compliant objects with rigid surfaces that when displaced from their rest states produce a force F proportional to their displacement D . This relation is called Hooke's law and it is usually expressed as

$$F = kD, \quad (1)$$

where k is defined as the spring stiffness. Spring compliance C is instead defined as the inverse of the spring stiffness k . In compliance form, Eq. (1) becomes

$$C = \frac{D}{F}. \quad (2)$$

Eq. (2) shows that in order to perceptually estimate spring compliance C , sensory information about the amount of displacement D and force F need to be obtained by the sense organs [8]. Position

information is redundantly provided by visual and proprioceptive sensory modalities and force information is obtained through the haptic sense [20]. Psychophysical research has demonstrated that during visual and haptic manipulation both modalities can influence perceived compliance [21,22]. It has been proposed that in situations where redundant information is obtained through different sensory modalities, the unimodal estimates are integrated in a statistically optimal fashion, the combined percept is a weighted average of the unimodal estimates, and weights are inversely proportional to the noise of the unisensory estimates [3]. Similarly, there are indications that this scheme might apply also to visual and haptic perception of compliance [9]. In this study we will adopt the same point of view to investigate how the perceptual system obtains an estimate of compliance in the presence of visual–haptic delays.

Delay during visual–haptic manipulation of a compliant object can either influence force information or visual information. In both cases, delay is relative to the action performed and to the proprioceptive information about the hand position. Delay invalidates Hooke's law, as the linear relationship between force and displacement described is not true any more. Values of force are related to values of displacement at different instants in time, so that Eq. (1) becomes $F(t_A) = kD(t_B)$ where $t_B = t_A + \Delta t$. Delay in the force with respect to the proprioceptively sensed displacement is obtained

Abbreviations: AR, augmented reality; HMD, head-mounted display; JND, just noticeable difference; PSE, point of subjective equality; 2IFC/3IFC, 2/3 intervals forced-choice.

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Nomenclature

Symbols

D	spring displacement from rest state
D_P	spring displacement sensed proprioceptively
D_V	spring displacement sensed visually
F	force generated by the spring
k	spring stiffness
C	spring compliance
w_x	weight of information x in a weighted average

with a positive value of Δt . Delay in the visual information about displacement (still relatively to proprioception) is obtained with a negative value of Δt . Here we will introduce both kinds of delays – on force and on visual information – and test how this non-linearity affects perceived compliance.

Delay in a force-feedback system (like in haptic virtual reality or telemanipulation environments) can impair the stability of the system [7]. For this reason, delayed haptic rendering of virtual objects with respect to proprioception has received much attention recently [16,17,14]. For example, Ohnishi and Mochizuki [15] showed that there is a systematic dependency of perceived compliance on the delay between the amount of displacement of a virtual spring and the force generated by the simulated spring. In [17] it is shown that when force trails spring displacement, virtual objects are perceived to be softer; when force leads displacement (e.g. by means of a Kalman predictor) objects are instead perceived to be harder.

These studies, however, considered only haptic information about compliance; vision was precluded or made uninformative about spring displacement by limiting the type of visual information provided (i.e. [17]). In our work, we examine compliance perception during visual-haptic interactions, where both visual and proprioceptive sense modality convey information about spring displacement. Vision (or the lack thereof during haptic exploration) can have a strong effect on the perception of compliance (i.e. [13]) and could therefore prevent any effect of delay during visual-haptic manipulation. In order to be able to introduce delays in visual-haptic object manipulation, we employed a specialized augmented reality (AR) system [5]. The setup allows visual-haptic interaction with virtual objects – in this study a spring – and at the same time allows participants to view their real hands instead of a virtual representation. Our reasoning is that the effect that visual information might have on perception increases if participants view their own hand embedded in the real environment and also information about the position of the whole arm rather than only of the fingertip (as shown in [19]).

In the rest of the paper we report the results of four psychophysical experiments and one simulation. We show that delay in the visual information about the interaction decreases perceived compliance making virtual springs to appear stiffer (Experiment 1) and this effect depends on the amount of delay (Experiment 2). Based on the opposite effects of visual and force delays on perceived compliance, we propose a model of visual-haptic compliance perception which main hypothesis is an uneven weighting of compliance information obtained (a) during loading-unloading movements and (b) through visual-haptic sense modalities. Weighting of information should depend on the relative sensitivity to compliance differences. We confirm that there is a higher sensitivity to compliance differences during loading movements than during unloading (Experiment 3). We also demonstrate that the relative weight of visual-haptic information depends on the degradation of visual and proprioceptive information (Experiment 4). We show that uneven weighting of loading-unloading and visual-haptic information can

explain the effect of visual and force delay by running a simulation of the hypothesized model of perceived compliance on the force and position data recorded in Experiment 1. From this simulation we find that the value of weights that fit the data are very close to the values for loading-unloading obtained in Experiment 3 which favor loading information.

2. Experiment 1: effect of visual and force delays

Setups allowing human-machine interaction in telepresence, virtual reality, and augmented reality are frequently affected by delays in both force and visual feedback channels. First, we study the effect of such delays on the perception of object compliance. It has been shown that delay in the elastic force exerted by a spring increases its perceived compliance [7], i.e., decreases its perceived stiffness. Since compliance is related to both position and force information, we hypothesize that a delay in the visual information concerning the amount of displacement could have similar effects. For this, participants judged perceived object compliance in four conditions where we modify the delay of visual and/or force information: *no delay*, *force delay*, *visual+force delay*, and *visual delay*.

2.1. Materials and methods

Fourteen participants (seven males, seven females, 19–38 years) took part in the experiment. Eleven participants had never used a haptic interface before and all were naive to the purpose of the experiment. They all reported normal or corrected-to-normal vision and no haptic or somatosensory disorders. All were right-handed.

2.1.1. Setup

The augmented reality (AR) setup employed in this study is shown in Fig. 1 and described in detail in [5]. Visual information was provided using a stereoscopic head-mounted display (HMD) (Trivisio, 3scope) and two cameras (dragonfly2 firewireA, point grey). The video captured by the cameras was visible on the HMD with the possibility of superimposing virtual objects. Visual occlusion of virtual objects was determined through blue color keying. The HMD and the cameras had identical field of view (40°) and resolution of 800×600 @ 60 Hz, yielding appropriate depth perception. An external infrared tracking system (NDI OPTOTRAK 3020) was used to track the HMD position (accuracy 0.2 mm) and orientation to generate the appropriate view of the virtual objects. The HMD was supported by a flexible arm; this allowed only small head movements, but it increased user comfort during the experiment.

The HMD setup was a video-see-through system; it showed the visual signal recorded by the cameras. Unavoidable latency in the visual presentation was introduced due to the processing of graphic information. We measured the visual latency of the setup using photodiodes to be 66 ms. This value is the estimate of the end-to-end visual latency for the whole AR system at hand. Notice that below we refer to this unavoidable asynchrony of the setup with the term “intrinsic latency”, while the

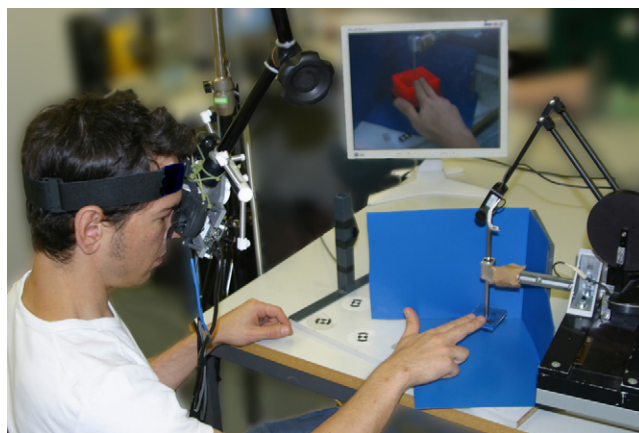


Fig. 1. Augmented reality setup employed for the presentation of the stimuli. The subject interacts with the virtual springs through contact with the horizontal plate mounted on the haptic device. The monitor (absent during the experiment) shows the monocular view visible on the HMD where the virtual spring is added to the scene and visually placed under the subject's finger.

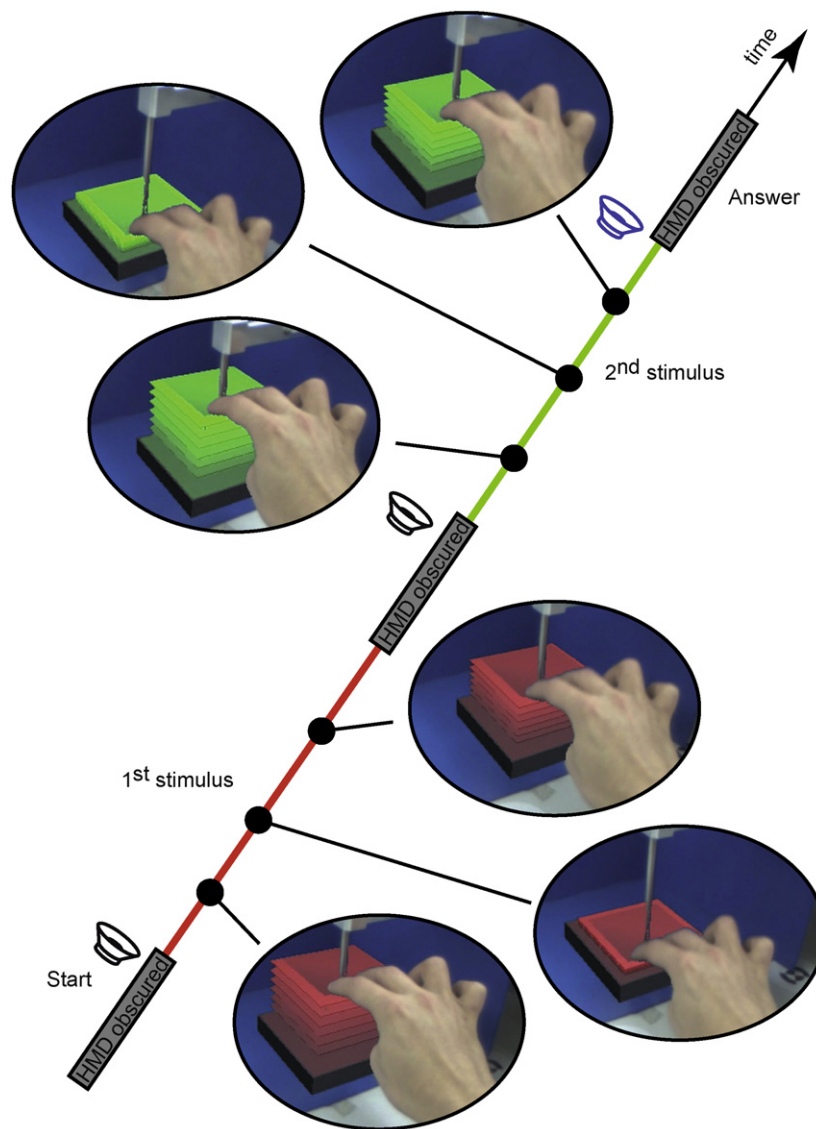


Fig. 2. Timeline of one trial in Experiment 1.

term “delay” will be reserved to indicate additional, artificial latencies introduced through experimental manipulations.

Haptic interaction was realized using a commercial force-feedback device (PHANTOM 1.5, Sensable). The device was controlled with a Real Time Linux system via custom drivers. All data (tracking, simulation, image display, and force feedback) were tightly synchronized within 1 ms by a hardware trigger mechanism. Haptic stimuli simulated the “spring-cells” employed by Srinivasan and Lamotte [20]. Haptic interaction was performed with two fingers pressing downwards and the virtual spring-cell was arranged on the table. Participants touched a horizontal plate with rigid surfaces, which simulated the top surface of the spring-cell. The plate was mounted on a vertical rod held by a guide rail, which restricted motion along the vertical direction. The rod was attached to the haptic device; rendering an offset force compensated the weight of the assembly.

2.1.2. Procedure

The experiment was conducted using a 2-Interval Forced-Choice (2IFC) paradigm. Each trial consisted of a pair of virtual elastic springs presented sequentially to the participant in random order: one spring being the standard and the other being the comparison (Fig. 2). The simulated compliance of the standard stimulus (which could appear either in the first or the second interval) had a constant value of 33.3 mm/N. The standard stimulus varied across trials with regard to visual and/or force delay. The comparison stimulus was simulated without any additional artificial delay and the simulated compliance varied across trials. This value was randomly selected from a set of ten with the method of constant stimuli: 27.0, 28.2, 29.4, 30.8, 32.3, 34.5, 36.4, 38.5, 40.8, and 43.5 mm/N. Each comparison stimulus was presented ten times.

The visual stimuli were virtual springs that were displayed as cuboids 80 mm high (when completely unloaded) and 100 mm × 100 mm square base at a fixed position with respect to the environment. The sides were displayed having 6 pleats (like the bellows of an accordion). The color of the springs could be varied so that the first stimulus in the trial was red and the second was green. At the bottom of the spring there was a non-deformable base of a dark color that was 20 mm high, with a footprint of 120 mm × 120 mm. The base was displayed visually as rigid, while for haptic feedback it was rendered as a deformable continuation of the spring. Participants could see the virtual spring resting on the base, their hand, and the surrounding environment through the HMD (Fig. 2).

Participants successively interacted with each of the two stimuli in a trial in order to compare perceived compliance between intervals. An acoustic signal indicated when to start. Participants did one single movement with their right hand aiming to reach the base of the spring and back to the fully unloaded state. The movement was performed with a stretched arm, in a steady movement downwards (loading the spring) and upwards (unloading the spring) without any break at the bottom. When the spring was fully unloaded again, the HMD screen turned black for 500 ms. Thereafter, the second spring was presented, marked by a change in spring color and a second acoustic signal. When both springs had been presented and the exploration was completed, the screen turned black again and a third acoustic signal with a different pitch indicated that participants should report which of the two springs seemed harder by pressing one of two answer buttons with their feet. The next trial began 500 ms after an answer was given.

Four conditions were tested, in which the standard stimulus was varied: *no delay*, *force delay*, *visual delay*, and *visual + force delay*. Note that in all these conditions (including the *no delay* condition) the intrinsic end-to-end visual latency of 66 ms

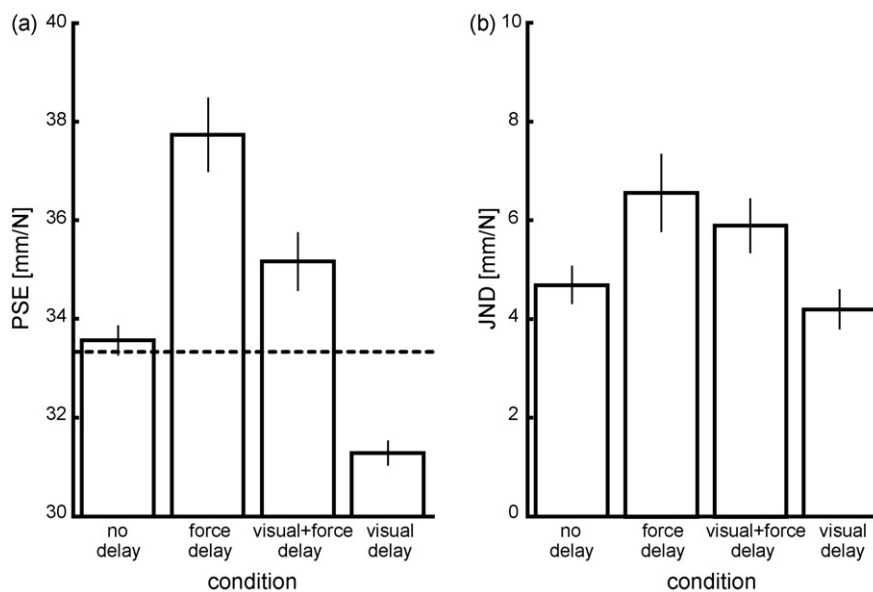


Fig. 3. Values of (a) PSE and (b) JND obtained in Experiment 1. Error bars represent the standard error of the mean across participants.

was still present; however, there was virtually no latency in the haptic rendering. For the *visual delay* condition, the rendering was shifted by three frames, thus adding a further delay of 100 ms to the latency of 66 ms. For the *force delay* condition, haptic rendering of the resistive force generated by the standard stimuli was shifted by 20 ms. It should be noted that the amount of force delay is slightly smaller than the ones employed in other related investigations [15–17]. The value was selected according to the results of a pilot experiment (see Appendix A).

Before the actual experiment, participants underwent a training phase. First, they were introduced to the procedure, stimulus sequence, and task, while feedback about the correct answer was given. Thereafter, a preparatory test was performed, only involving the ten comparison stimuli and a standard of 40.0 mm/N with no delay. Each combination was randomly presented five times, resulting in 50 standard-comparison pairs. These data served as a pretest to examine the accuracy of participants' responses, to verify that the task had been fully understood, and to possibly exclude subjects with very low haptic sensitivity. After this, the actual experiment was performed.

Each test-reference pair was randomly presented ten times, resulting in 400 trials, which were separated into four blocks. Each block of 100 trials took approximately 10 min with a 5 min break in between to reduce stress and fatigue. Including instruction and training, the approximate experiment duration was about 2 h. Answers, movement trajectory, and forces generated by the device during the trials were stored for later analysis.

2.1.3. Data analysis

The data from training and experiment were analyzed separately for each participant. The proportion of standard stimuli reported to be softer than the comparison stimuli at each simulated value of compliance was fitted with a cumulative Gaussian function using PSIGNFIT [30]. From the psychometric functions we determined the point of subjective equality (PSE) as the simulated compliance corresponding to a proportion of 0.5 and the just noticeable differences (JND) as the difference in simulated compliance between the proportion of 0.5 and 0.84. The PSE is the value of compliance for the unconditioned comparison stimulus that is perceived to be equal to the compliance of a standard stimulus manipulated in the different conditions. The JND is the minimal difference in compliance that could reliably be detected between standard and comparison stimuli (84% of the times).

2.2. Results

One participant had a JND in the training session that exceeded 16.7 mm/N (50% of the simulated compliance of the standard). Another participant reported during the experiment of having misunderstood the task, considering the color of the stimulus while judging compliance. Thus, these two datasets had to be excluded from the analysis. Furthermore, a third participant decided to stop the experiment after 320 of the 400 trials due to sensation of nausea. The partial data collected with this last subject was sufficient for the correct fit of the psychometric function, so results – which are in line with the ones obtained by every other subject – were

included in the results reported. The data collected from 12 participants in the four experimental conditions (*no delay*, *visual delay*, *force delay*, and *force + visual delay*) are analyzed below.

The effect of force and visual delay was present for every participant, namely perceived compliance increased with force delay and decreased with visual delay, with an average change in perceived compliance of $13.3 \pm 2.4\%$ (s.e.m.) in the *force delay* condition and of $6.1 \pm 0.8\%$ in the *visual delay* condition (Fig. 3). Force delay and visual delay had a significant effect on perceived compliance (two-way repeated-measures ANOVA on PSE: force delay, $F(1,11) = 31.5$, $p < 0.001$; visual delay, $F(1,11) = 54.5$, $p < 0.001$; interaction $F(1,11) = 0.14$, $p = 0.71$).

The standard stimulus in the *force delay* condition was perceived more compliant and in the *visual delay* condition it was perceived to be less compliant with respect to the actual simulated value (one-sample *t*-test on PSE against 33.3 mm/N: force delay $t(11) = 5.69$, $p < 0.001$; visual delay $t(11) = 8.20$, $p < 0.001$). The *force + visual delay* condition is perceived in between the *visual delay* and *force delay* conditions, not different from the *no delay* condition, but different than simulated (Bonferroni corrected paired-sample *t*-test on PSE of *visual + force delay* against: *visual delay* $t(11) = 4.95$, $p < 0.005$; *force delay* $t(11) = 4.46$, $p < 0.005$; *no delay* $t(11) = 2.62$, $p = 0.071$; one-sample *t*-test against 33.3 mm/N: $t(11) = 3.05$, $p < 0.05$).

Mean JND across participant and conditions was 5.33 ± 0.56 mm/N with higher values for the conditions containing force delay (Fig. 3). Force delay worsens the ability to discriminate compliance, while visual delay does not have a significant influence (two-way repeated-measures ANOVA on JND: force delay, $F(1,11) = 22.7$, $p = 0.002$; visual delay, $F(1,11) = 3.37$, $p = 0.09$; interaction, $F(1,11) = 0.05$, $p = 0.82$). The values of JND obtained in this experiment correspond to a Weber fraction of 16.0%.

2.3. Discussion

In line with previous results, we find that asynchronies between spring displacement and elastic force generated by the spring result in a change of perceived compliance. For example, in [17] the elastic force was either an instantaneous function of the amount of displacement, or it was delayed by 30 or 60 ms after the displacement, or it led the displacement by 50 ms (by means of a Kalman predictor). The delayed force created the same perceptual change found in our experiment. This earlier result, however, was obtained

by either precluding the visual inspection of the spring [17] or by not displaying the amount of spring displacement and the hand position [16]. In our work, we extend these findings by showing that the effect of force delay on compliance is present when visual information about the amount of spring displacement is provided. Moreover, the magnitude of the effect as measured from the PSEs is about 13% of the simulated compliance with a delay of 20 ms, which is higher than the 4% obtained by Ohnishi and Mochizuki [15] with the same delay. It is not clear whether the difference in effect size can be due to the presence of visual information during interaction or to the way the interaction is performed, as the effect of delay depends on the movement velocity.

More importantly, perceived compliance decreases when the visual information about the interaction is delayed relatively to the movement performed by the participant. This result is opposite to what was found with force delay, as it makes the surface appear harder. In [22] it is hypothesized that the effect of visual distortions on perceived compliance is asymmetric, as humans are more susceptible to the illusion that a stiff surface appears more compliant much more than a compliant surface appearing stiffer. Accordingly, we find that visual delay has a smaller effect on perceived compliance (about 6%), especially considering the different amount of delay in the two conditions (20 ms vs. 100 ms). Moreover, the effects of visual and force delay appear to be additive, so that if both delays are present, there is a (partial) compensation of the two effects.

The general sensitivity to compliance differences obtained greatly depends on the task and apparatus employed. In this setup, we obtained a Weber fraction comparable to other investigations. For example, Jones and Hunter [8] found a Weber fraction for stiffness of 23%, Tan et al. [23] found values as low as 8%, while Ohnishi and Mochizuki [15] found much higher values ranging 30–40%. Adding force delay seems to decrease the accuracy with which compliance can be discriminated, increasing the Weber fraction, especially for delays exceeding 30 ms [15]. The addition of visual delay, instead, does not have a significant effect on the sensitivity to discriminate compliance. However, it has to be kept in mind that the condition containing no additional visual delay still has an intrinsic visual latency of 66 ms, which is likely degrading performance compared to an interaction without delayed visual information.

2.3.1. Effect of delay on force and displacement

An open point is the effect of the delays employed in this experiment on force and position information. Direct interaction with a real spring does not involve the delays normally present in augmented reality or telemanipulation environments. As described at the beginning of the paper, Eq. (2) defines the value of compliance for an interaction with a spring that does not involve delay. This value can be calculated with visual (D_V) and proprioceptive (D_P) information about spring displacement relatively to the rest state. This value is equal for both types of sensory information and is described by Hooke's law written as $C = D_P/F = D_V/F$. In other words, the measured values of spring displacement and simulated force plotted in a displacement vs. force space follows a linear relationship. Fig. 4a shows haptic-only data recorded from the interaction with virtual springs in the AR setup that (since it has no latency in the force-feedback channel) makes it equivalent to interaction with real springs. The steepness of the line in this space represents the compliance of the spring, with steeper lines indicating harder springs.

When vision is precluded and the only estimate of compliance can be done through the haptic sense, force delay causes the sensed force to be $F(t_N) = kD(t_{N-1})$, changing the value of D_P/F over time. The force is lower than the one generated by a real spring during loading movements and higher during unloading (Fig. 4b). This makes D_P/F

higher during the loading phase of the movement (which would correspond to softer springs) and lower during the unloading phase (harder springs).

The situation is not very different when visual information is present. Force delay modifies the value of both D_P/F and D_V/F over time. These values are lower than simulated during loading and higher during unloading movements.

On the other hand, when visual information about the displacement of the spring is delayed (visual delay), the viewed position of the hand is influenced so that $D_V(t_N) = D_V(t_{N-1})$. This creates an inconsistency between the amount of displacement sensed proprioceptively and visually (Fig. 5c). For loading movements, this means that the spring appears visually to be less displaced than what is specified proprioceptively. For unloading movements, instead, the spring is visually more displaced. As a consequence, while D_P/F is unchanged and constant over the course of the interaction and equal to the simulated value of compliance, the value of D_V/F varies over time; it is lower than the simulated compliance during the loading phase (which would correspond to harder springs) and it becomes higher than the simulated compliance during the unloading (softer springs).

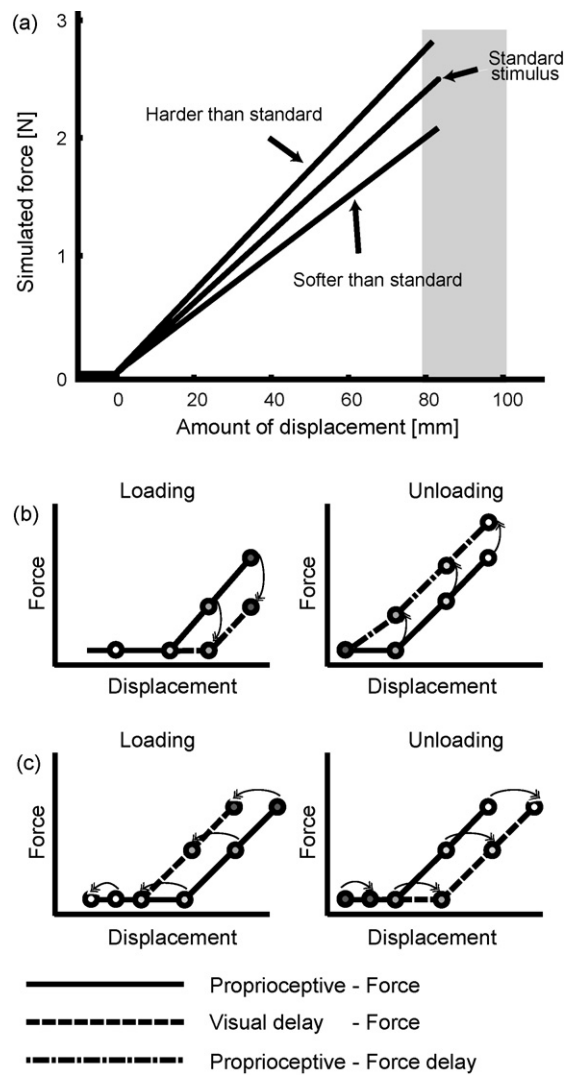


Fig. 4. (a) Data recorded during haptic-only interaction with three springs and plotted in displacement vs. force space. The grey area represents the visually inaccessible base. (b) Effect of force delay on the recorded values of displacement and compliance during loading and unloading movements. (c) Effect of visual delay.

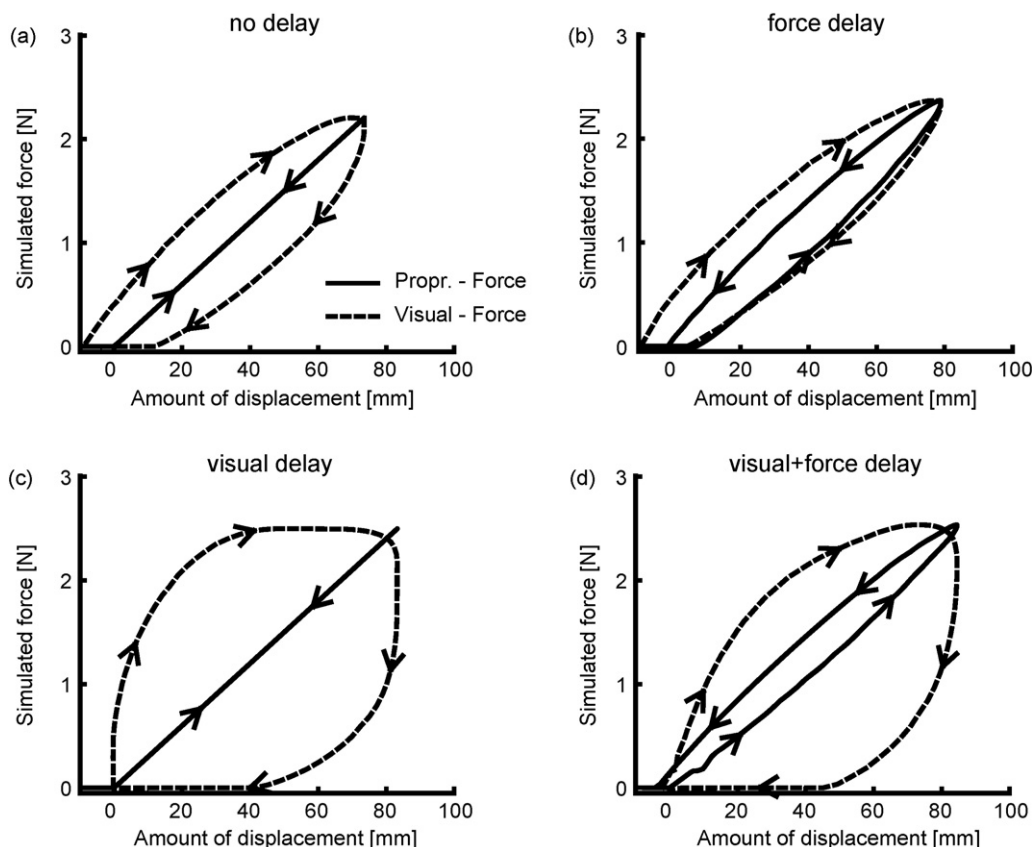


Fig. 5. Data recorded during typical interactions in the four conditions of Experiment 1 plotted in the *displacement vs. force* space: (a) *no delay* condition, (b) *force delay* condition, (c) *visual delay* condition, and (d) *visual + force delay* condition. The arrows indicate the temporal sequence of the recordings.

The magnitude of the discrepancies created by the force and visual delay depends on the amount of delay and the movement velocity. The higher the visual delay and velocity are, the greater is the discrepancy in the two phases of the movement. To visualize this effect, it is possible to plot in the displacement vs. force space the values of force and displacement (proprioceptive and visual) at each instant in the interaction with a standard stimulus as in Fig. 5. In the AR setup utilized in this study, even in the *no delay* condition (Fig. 5a) there is an intrinsic visual latency (66 ms). The curve that describes the proprioceptive–force interaction with the spring does not deviate from the line that a real spring with compliance equal to the standard stimulus would have. Instead, the curve describing the visual–force interaction deviates from the one of the real spring. In the loading phase the curve is above the line, it crosses over near the maximum force/maximum displacement point (the lowermost point reached by the hand of the participant during the movement), and then the curve lies below the real spring line for the unloading phase. When visual information is additionally delayed by 100 ms, this deviation becomes much more accentuated (data recorded during one interaction with a standard stimulus is visible in Fig. 5b). Fig. 5c and d shows instead the effect of force delay in conjunction with the intrinsic latency and with the added delay to the standard stimuli during one interaction. In these two figures it is possible to see that the effect of visual delay on the visual–force curve is opposite to the effect of force delay on the proprioceptive–force curve. During loading movements, the proprioceptive–force curve with force delay is on the lower side of the line representing simulated non-delayed compliance; the curve due to visual delay is on the higher side of the line. The curves have opposite evolution over time, clockwise for visual–force information, counterclockwise for proprioceptive–force.

The curves for visual–force and proprioceptive–force information in Fig. 5 show that there is a difference in the two phases of the movement depending on the type and amount of delay. For force delay, it has been shown that the amount of delay influences linearly perceived compliance of springs [15]. In the next experiment we will test whether the visual delay added to the intrinsic latency has a similar, but opposite effect on perceived compliance.

3. Experiment 2: different visual delays

Delay in the force and visual information influences the shape of the curves in displacement vs. force space. The deviation from the non-delayed straight line depends on the amount of delay. Similarly, Ohnishi and Mochizuki [15] showed that the perceived compliance of objects gradually decreases with increasing force delay. Here we want to investigate whether the change generated by visual delay has a similar effect on perceived compliance. Namely, that the effect of visual delay described in Experiment 1 is linearly dependent on the amount of delay in the visual information.

3.1. Method

Eight participants (five males, three females, 21–29 years) took part in the experiment. Five participants had never used a haptic interface before and three were experienced users of AR setups. Two experienced participants were informed of the research goal, the other participants were naïve to the purpose of the experiment. They all reported normal or corrected-to-normal vision and no haptic or somatosensory disorders. All were right-handed.

The apparatus and experimental procedure were identical to Experiment 1. Four conditions were tested, where the visual delay of the standard stimulus was varied (0, 66, 133, and 200 ms) and that of the comparison was kept at 0 ms. Note that this

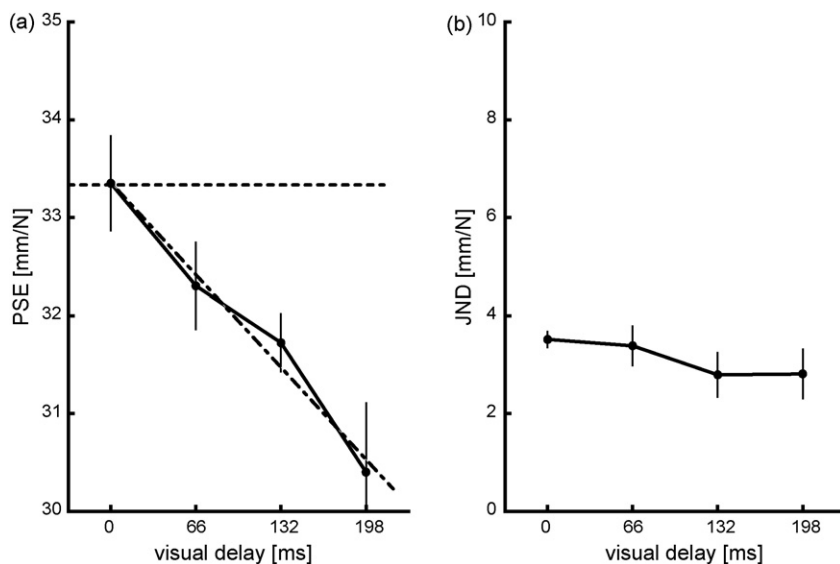


Fig. 6. Values of (a) PSE and (b) JND obtained in Experiment 2. The dashed line is the outcome of the linear regression analysis performed on the PSE data.

delay was in addition to the intrinsic end-to-end visual latency of 66 ms. No stimuli contained force delay.

3.2. Results

Fig. 6 indicates average PSE and JND across participants for the different visual delays. In the range tested, the perceived compliance decreases linearly with visual delay. For every 100 ms of visual delay there is a reduction in perceived compliance of 1.22 mm/N (95% c.i. 0.62–1.83 mm/N) as indicated by the linear regression analysis represented as a dotted line in Fig. 6a ($r^2 = 0.36$, $p < 0.001$). There is an overall significant change of perceived compliance with different visual delays (one-way repeated-measures ANOVA on PSE: $F(3,31) = 6.27$, $p < 0.005$). The values of JND do not change significantly with delay (one-way repeated-measures ANOVA on JND: $F(3,31) = 1.59$, $p = 0.22$). In this regard, there is no clear difference in the pattern of JND values obtained with the naïve and expert participants, apart from an obvious overall difference in sensitivity.

3.3. Discussion

The results confirmed that perceived compliance increases when visual information is presented with a delay. The effect of visual delay on compliance is comparable to what was found in Experiment 1 for similar values of delay. Similarly to what happens with force delay [15], the change in perceived compliance is linearly dependent on the magnitude of visual delay.

Visual delay modifies the position of the hand sensed visually with respect to the one sensed proprioceptively. Higher delays create a larger spatial discrepancy between the proprioceptive and the visual positions of the hand. As shown in Figs. 4 and 5, delay has an influence on the visual–force curve, while leaving the proprioceptive–force curve unperturbed. In the loading phase of the movement the visual–force curve lies above the non-delayed line, while in the unloading phase the curve lies below. The two deviations depend on the movement velocity, but are opposite in direction.

3.3.1. Information over the whole interaction

Here we will analyze how the information summarized in the visual–force curve in force vs. disparity space relates to the perception of compliance. The deviation of the curve caused by delay is

likely related to the change in perceived compliance and therefore this should be the case even for the information gathered with vision. According to different findings, in fact, visual information is utilized in visual–haptic perception of material properties [9,13,21,22]. In general, compliance could be sensed either by processing force and position information [17], the change in force and change in position [11], or measurements like the work performed [24]. In all these cases, visual information could provide an estimate of the amount of spring displacement over time. The final estimate of compliance would be affected by the visually sensed displacement. But notice that the effect of *visual delay* on the amount of seen displacement is opposite during loading and unloading movements. The change in position is proportional to the velocity, which has opposite sign during the two phases. During loading the seen displacement is lower and during unloading it is higher. In normal circumstances this would correspond to a harder spring during loading movements and a softer spring during unloading. It seems unlikely that an estimate on compliance based on the information obtained during the whole interaction could produce a change in overall compliance, as the effects during loading and unloading balance each other out. To create a decrease in perceived compliance due to visual delay when both loading and unloading movements are performed, the influence of visual information should be more prominent for loading movements. Namely, the only explanation for the pattern of response is if information about compliance in the unloading phase of the movement is underweighted in the formation of a final estimate of compliance (as the information in unloading phase with visual delay specifies a softer spring than simulated).

Similarly, in the presence of *force delays*, the information during loading specifies a softer spring, while the information during unloading specifies a spring that is harder than the simulated one. Here we find that force delay cause an increase in perceived compliance, which would mean that the final estimate of compliance is primarily based on the information acquired during loading.

In the next experiment we will test whether this imbalance is also present in the different sensitivity to compliance differences during the two movements. If this is the case, we would expect that participants would use the information for which they are more sensitive to, which should be the one collected during loading movements. This would suggest a perceptual mechanism responsible for the effect of delay on compliance.

4. Experiment 3: loading and unloading

During the manipulation of a spring-like object, the perceptual system collects information about spring displacement and the force exerted. Although it has been hypothesized that the most relevant sources of information about spring compliance are the peak force during maximum displacement and work [23,24], there is also evidence that other sources of information can affect perceived compliance [1,4]. It has been shown, for example, that increasing the number of sampling movements can increase the sensitivity to compliance [12]. Accordingly, Nisky et al. [14] modeled the increase in the information gathered at each moment following a statistically optimal strategy. It is likely that the perceptual system integrates all different sources of information into one single – more reliable – compliance percept even when they originate in different moments in time.

Here we reason that while making exploratory movements to address the compliance of an object there is a natural subdivision of the interaction into a loading and an unloading stage. During the loading part of the exploration, participants have to exert a force on the spring to create the displacement. During the unloading stage, on the other hand, the exerted force is decreased and the elastic force generated by the spring displaces the finger towards the rest state. We hypothesize that the two parts of the exploration might lead to differently reliable information about compliance, where the elastic force in the loading phase is potentially sensed with higher accuracy than in the unloading phase. If this is the case, we expect participants to be more sensitive to differences in compliance between two springs while performing loading movements than when they perform unloading movements.

4.1. Method

Six participants (two males, four females, 22–44 years) took part in the experiment. Four participants had never used a haptic interface and two were experienced users of AR setups. All participants except one were naïve to the purpose of the experiment. They all reported normal or corrected-to-normal vision and no haptic or somatosensory disorders. All were right-handed.

The apparatus was similar to Experiment 1, except that a mask precluded direct visual contact. Three conditions were tested in different blocks: *loading*, where participants displaced the spring from the fully extended to fully displaced; *unloading*, where participants first touched the fully displaced spring and then released it till its full extension; *loading + unloading*, where participants performed both movements in sequence, including a brief stop when the spring was fully displaced. See Fig. 7 for details. All conditions were explained and all movements required were trained before each block of trials. Participants could train until they felt confident they memorized the sequence of movements and they could perform the judgments correctly.

In the loading condition, participants performed the movement to explore the compliance of the springs by loading the spring starting from the fully extended state. When they heard an acoustic signal, they compressed the spring with their hand from the unloaded state of 100 mm to a compressed one of about 25 mm. An “end stopper” was rendered at the bottom of the spring (see bottom of Fig. 7 for details). It consisted of a linear force gradient ramping to 6 N in 5 mm to prevent the participant from colliding with the table and to reduce the effect of terminal force information [24]. When participants reached the end stopper, the force exerted by the spring was switched off. Subjects then retracted their hand moving it away from the horizontal plate mounted on the haptic device. After 1000 ms the device repositioned autonomously to the fully extended state and the next spring was presented. Participants then contacted the plate again and waited for a second acoustic signal indicating to start the compression of the second spring. The second compression was done about 2500 ms after the force of the first spring was turned off.

In the unloading condition, participants found the plate mounted at the end of the haptic device lying on the table. They positioned their hand on the plate whereafter a force ramped up over the course of 1000 ms. While the force increased, participants moved their hands upwards until they noticed a force discontinuity representing the border of the “end stopper” force field, about 25 mm from the table. At this maximal spring compression, participants continuously applied a steady force downwards against the device to hold a position close to the virtual end stopper. After a signal, participants moved upwards to allow the spring to fully extend while evaluating the stiffness of the spring. After that, the plate repositioned autonomously to the start position on the table. The next stimulus was the presented about 1500 ms later, resulting in 2500 ms between two unloading movements.

In the loading + unloading condition, the interaction started from the fully extended spring. Participants first compressed the spring to 25 mm where they experienced the characteristic force increase of the end stopper, briefly paused, and moved back to the original position. To make this condition comparable to the loading and unloading conditions, subjects were required to move their hand away from the horizontal plate between stimuli. An acoustic signal indicated when the next spring was presented (about 2500 ms after the unloading movement was completed). Answers were again given via foot pedals. Proportions of responses were fitted with a psychometric function to obtain an estimate of JND, while PSE was fixed at the simulated compliance of the standard stimulus.

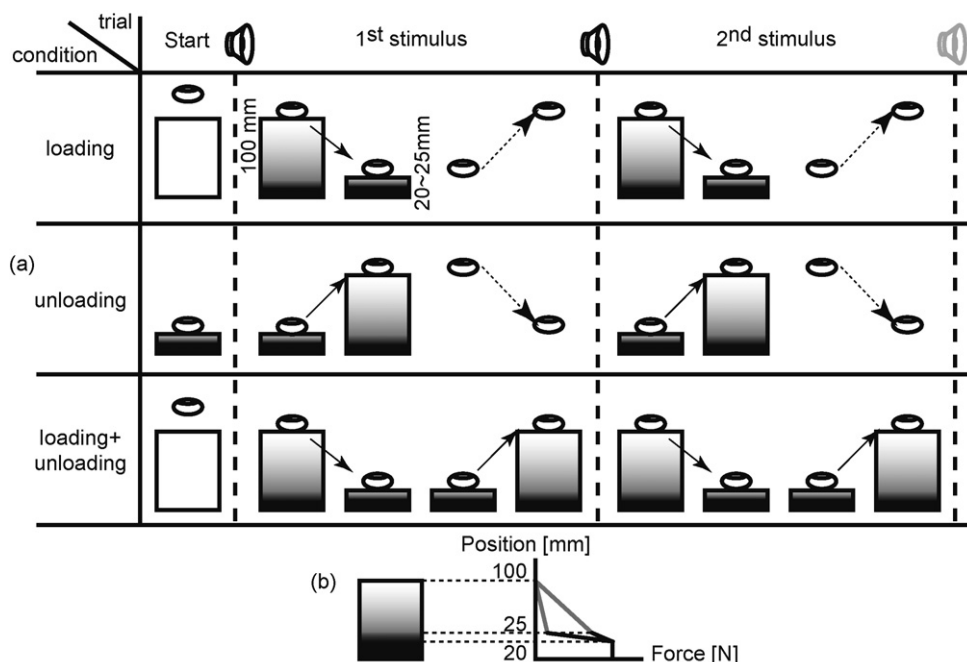


Fig. 7. (a) Timeline of an experimental trial in the three conditions tested in Experiment 3. (b) Force values generated by the haptic device to simulate the virtual spring and the end stopper employed in Experiment 3.

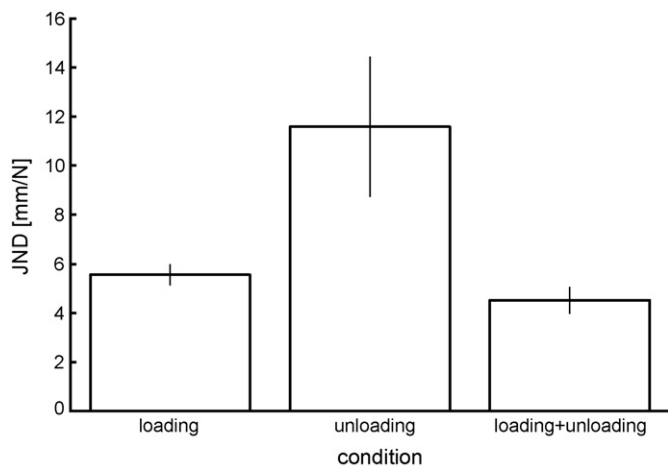


Fig. 8. Values of JND obtained in Experiment 3.

4.2. Results

Fig. 8 depicts the values of JND obtained in the three conditions. Sensitivity to compliance differences is lowest in the *unloading* condition. The JND in the *unloading* condition is 11.59 ± 3.15 mm/N (which corresponds to 34.8% of the simulated standard compliance) while in the other two conditions the JND was comparable to the values obtained before. In the *loading* condition JND was 5.59 ± 0.57 mm/N (16.8% of the standard compliance). The *loading+unloading* condition exhibited the highest sensitivity to compliance with a JND of 4.58 ± 0.58 mm/N (13.8% of the standard compliance). Performance in the discrimination of compliance significantly differed in the three conditions (one-way repeated-measures ANOVA on JND: $F(2,17)=6.28$, $p < 0.05$). The *loading+unloading* condition led to higher sensitivity than either the *loading* or the *unloading* condition for all but one participant and thus the average JND in the *loading+unloading* condition was lower than the *loading* and the *unloading* condition (paired-sample *t*-test, $t(5)=2.11$, $p < 0.05$; $t(5)=2.38$, $p < 0.05$).

4.3. Discussion

Perceived compliance while performing spring displacement can be thought of as the sum of two separate movements, a loading and an unloading movement. These two movements can both provide information about the compliance of the spring and so they might be used together to make a final judgment about the spring compliance. If this is the case, the interactions performed in the *loading+unloading* condition tested here can be thought of as the combination of the two sequential sources of information about compliance (the two phases of the motion), which are equivalent to the movement performed in the *loading* and in the *unloading* conditions.

According to theories stating that multisensory integration is similar to maximum-likelihood integration and therefore statistically optimal [3], the performance in a task with redundant information is well described by a weighted average of the individual sources, where the weights are assigned according to the relative precision of the estimates made from each of the source. If this scheme is applied to the *loading+unloading* condition, the two sequential sources of information about compliance can be combined into a unified estimate of compliance to increase sensitivity. The integration should happen according to the relative reliability r

of the two estimates, which is defined as the inverse of the variance and in this experiment can be calculated from the JND according to

$$r = \frac{1}{2JND^2}. \quad (3)$$

If the two estimates are affected by independent sources of noise, to obtain optimal performance the weight of the information about compliance acquired during the loading phase should be

$$w_{loading} = \frac{r_{loading}}{r_{loading} + r_{unloading}} \quad (4)$$

while the weight assigned to the information gathered during unloading should be $w_{unloading} = 1 - w_{loading}$ (see [2]). Using Eq. (4), we can thus estimate the weight that should be given to the information acquired during loading and unloading phases in the *loading+unloading* condition that would give optimal performance. The average value across observers is $w_{loading} = 0.78 \pm 0.06$.

Optimal integration of the information obtained in the two phases of movement does not only entail that the JND in the *loading+unloading* condition should be lower than in the other two conditions; the increase in sensitivity should happen so that all the available information about compliance is exploited. Optimal integration of redundant but independent sources is reflected in a value of reliability that can be calculated according to

$$r_{loading+unloading} = r_{loading} + r_{unloading} \quad (5)$$

(see [2]). The optimal value of reliability can be converted back to predict the optimal value of $JND_{loading+unloading}$ using Eq. (3), which gives the value of 4.73 ± 0.36 mm/N across observers. This value is very similar to the JND obtained experimentally which is 4.58 ± 0.58 mm/N (paired-sample *t*-test on predicted against actual JND, $t(5)=0.39$, $p=0.71$). The similarity of the experimental value to the maximum JND that can be obtained indicates that perceived compliance is obtained through a weighted average of information obtained in the two phases of motion and that the weights assigned are close to optimal.

Overall, the results of this experiment indicate that sensitivity to compliance is different in the two phases of the movement, that during combined loading–unloading movements the sensitivity increases, and that a close to optimal weighting of information accounts for this improvement. In the next section, we will test whether this difference in sensitivity can explain the change in perceived compliance due to force and visual delays that was encountered in Experiment 1.

5. Integration model

In this section we analyze the force and position data collected in Experiment 1 to address whether the difference in sensitivity during loading and unloading movements can predict the subject responses. We simulate a model that estimates compliance based on the force estimate F , the proprioceptive estimate of the amount of spring displacement D_p , and the visual estimate of the amount of spring displacement D_v . The model performs a bimodal estimate of compliance by weighting the visual and proprioceptive information about displacement. The estimate is performed independently on the loading and unloading phases of the movement and the two estimates are weighted.

We simulate the same four conditions utilized above: *no delay*, *visual delay*, *force delay*, and *visual+force delay*. The estimates for the standard and comparison stimuli are compared to obtain a set of responses from the model. Psychometric functions are fitted to the proportion of times the comparison is estimated to be harder than the standard. The PSE values obtained by applying the model to the data are compared to the ones obtained by each of the participants.

We test the hypothesis that the estimate of compliance obtained during the loading phase of the movement is weighted more than the information available during unloading, according to the higher reliability of information acquired during the loading phase found in Experiment 3. This hypothesis is alternative to the null hypothesis that the weights are equal for the loading and unloading movement phases.

5.1. Simulation details

Force and displacement data recorded for each participant in the four conditions in Experiment 1 were used in the simulation. Data were downsampled at 100 Hz and trimmed to exclude extension of the spring beyond the rest state with zero displacement (100 mm from the table). The point of maximum displacement served as the separation between the loading and unloading phase of the movement (separately for vision and proprioception). We analyzed separately the visual–force and proprioceptive–force information during loading movements and unloading movements.

Four estimates of compliance (C_{LV} , C_{UV} , C_{LP} , C_{UP}) were computed for the standard and the comparison stimuli. In the conditions tested in this study, delay in one of the sensory information creates an inconsistency in the estimates obtained from each of these four estimates. During interaction with a compliant object, many sources of information about compliance are available (see i.e. [4,17]). Here we report two methods to compute compliance, which are based on two of these sources.

- (a) It has been shown that maximum force is used during compliance estimation [17,25]. Since in the experimental conditions employed maximum force is equal in the loading and unloading phases (and cannot explain the pattern of results due to the delays) we calculated the *average* values of displacement and force and compute an estimate of compliance according to

$$C_{mean} = \frac{\bar{D}}{\bar{F}}; \quad (6)$$

- (b) A second factor that is shown to influence compliance estimates is the work performed during interaction [24]. By calculating the absolute work done during the two phases of the movement as the area under the curves in the displacement vs. force space, we obtained estimates of compliance according to

$$C_{work} \propto \left| \sum_i \left(\frac{1}{2} \Delta F_i + F_i \right) \Delta D_i \right|^{-1}. \quad (7)$$

The four values of compliance for each of the stimuli presented to the participants were combined through a weighted average according to

$$C_{combined} = w_{loading} [w_{visual} C_{LV} + (1 - w_{visual}) C_{LP}] + (1 - w_{loading}) [w_{visual} C_{UV} + (1 - w_{visual}) C_{UP}]. \quad (8)$$

Thus, from the four estimates of compliance (C_{LV} , C_{UV} , C_{LP} , C_{UP}) we obtained a value of $C_{combined}$ for each of the presented stimuli. We then tested whether the estimated compliance $C_{combined}$ of the standard stimulus was higher than the comparison stimulus. The outcome of this test was treated as a subject response. Thus, for each of the four conditions (*no delay*, *force delay*, *visual + force delay*, and *visual delay*) the proportion of the two outcomes for each of the simulated compliances of the comparison stimulus was fitted with a psychometric function as it was done in Experiment 1.

The value of the weights ($w_{loading}$ and w_{visual}) in Eq. (8) was modified systematically from 0 to 1 in steps of 0.05. For each combination of the two weights we obtained four values of PSE and JND from the

fittings (one for each condition). We compared the PSEs obtained from the simulation with the PSEs obtained from the participants' responses in Experiment 1 by computing the sum of square (SS) differences across the four conditions. Thus we obtained a value of SS for each participant, pair of weights, and each of the two methods to compute compliance by using the following formula:

$$SS = \sum_{condition=1}^4 (PSE_{model} - PSE_{human})^2. \quad (9)$$

5.2. Simulation results

Fig. 9a and b shows the average sum of square difference between the values of PSE obtained from the model and the value of PSE obtained from the subject responses for the two methods to estimate compliance. The minimum difference between the model results and the experimental data as calculated by Eq. (9) is obtained for very similar values of weights for the two ways of computing compliance: *average* $w_{visual} = 0.24 \pm 0.05$ and $w_{loading} = 0.89 \pm 0.04$; *work* $w_{visual} = 0.08 \pm 0.02$ and $w_{loading} = 0.85 \pm 0.02$.

The smallest difference with the participant's data is obtained by the model with values of $w_{loading}$ that significantly deviate from 0.5, indicating that the loading and unloading phases are not treated equally for the final judgment of compliance (Bonferroni corrected single-sample *t*-test on $w_{loading}$ against 0.5: *average* $t(11) = 11.5$, $p < 0.001$; *work* $t(11) = 17$, $p < 0.001$). The value of $w_{loading}$ is also significantly lower than 1.0 indicating that the information about compliance obtained in the unloading phase is utilized (at least in part) in the final estimate to increase the reliability of compliance judgments (*average* $t(11) = 3.33$, $p < 0.05$; *work* $t(11) = 7.00$, $p < 0.001$).

The small value of w_{visual} indicates that visual information about the amount of spring displacement is used but it is weighted only slightly with respect to proprioceptive information. However, the fact that visual information is utilized in the final estimate of compliance is evidenced by values of w_{visual} higher than 0.0 (*average* $t(11) = 5.08$, $p < 0.001$; *work* $t(11) = 3.22$, $p < 0.05$).

With the values of w_{visual} and $w_{loading}$ that according to Eq. (9) individually produce the smallest amount of deviation from subject responses obtained in Experiment 1, the PSEs of the simulation indicated in Fig. 9c and d are very similar to the ones obtained experimentally (*average* $r^2 = 0.79$, $p < 0.001$; *work* $r^2 = 0.53$, $p < 0.001$).

When the information about the whole interaction is considered, neither of the two methods reproduces the pattern of results obtained from participants (irrespectively of the value of w_{visual}). This is visible in Fig. 9a and b by considering the values which correspond to $w_{loading} = 0.5$. For the *average* method, for example, the PSE in the visual delay condition did not differ from the simulated value (single-sample *t*-test against 33.3 mm/N, $t(11) = 0.13$, $p = 0.90$), hence it did not reproduce the pattern of results found in Experiment 1. For the *work* method, instead, the pattern of results across conditions was even opposite to the one obtained experimentally ($r^2 = -0.58$, $p < 0.001$).

Finally, when only the information during the loading phase is considered the *average* method still achieves good performance. The similarity is however higher when the weight for loading information is lower than 1.0 (see Fig. 9a). The *work* method, on the other hand, produces considerably higher values of the sum of square difference when considering only loading information (see Fig. 9b). Even though the PSE values obtained with the *work* method for $w_{loading} = 1.0$ are correlated with experimental values ($r^2 = 0.32$, $p < 0.05$), delay exerts an exaggerated influence on compliance. As a result, the PSE in the *force delay* condition is much higher for the model than for participants (and

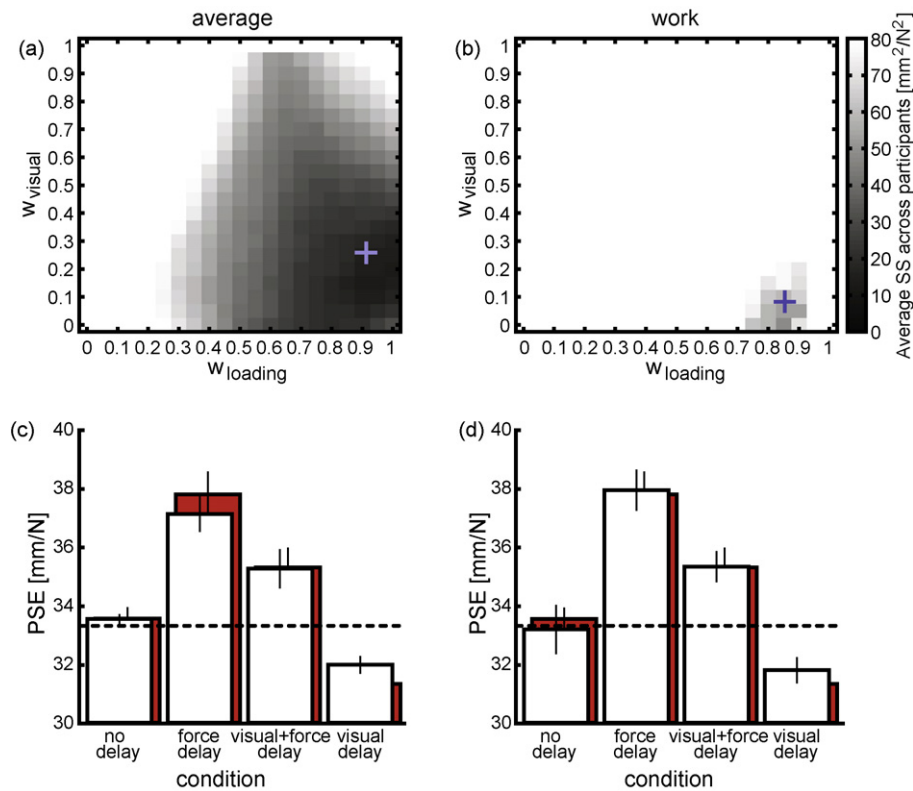


Fig. 9. (a) Average sum of square differences between the PSEs in Experiment 1 and the PSEs obtained from the simulation for different values of $w_{loading}$ and w_{visual} with the *average* method of computing compliance. The cross identifies one standard error around the average weights across observers that lead to minimum sum of square differences. (b) Sum of square differences for the *work* method. (c) Values of PSE obtained with the weights that produce the smallest sum of square difference for each participant with the *average* method. The colored bars represent the results obtained in Experiment 1. (d) Values of PSE obtained with the *work* method.

vice versa, the PSE in the *visual delay* condition is too low for the model).

5.3. Discussion

The simulation of a model for the perception of compliance based on the different utilization of the information during loading and unloading movements confirms the hypothesis that loading movements have higher weight in the final judgment. When the simulation considers the information over the whole course of interaction, it cannot account for the way humans perceive compliance, as they do not reproduce the effects of vision and force delay encountered in Experiment 1.

This finding is consistent with the relative sensitivity of judgment during loading and unloading movements shown in Experiment 3. Information during loading movements allows more precise compliance discriminations than during unloading, therefore it should be weighted more in a combined estimate of compliance. The numerical value of the weights obtained from the simulation and the optimal weights calculated in Experiment 3 should be different, however. The difference is caused by the presence of visual information in Experiment 1 and preclusion in Experiment 3. Although the presence of visual information does not increase the ability to discriminate compliance [13], the conflict between visual and proprioceptive information due to the intrinsic latency of visual information in Experiment 1 might have affected the integration of the two sources of information. It has been shown that with large crossmodal conflicts integration breaks down [6]. If this happens in Experiment 1, the already low reliability gathered during unloading movements would be very affected. The conflict would have minimal effects on loading information, as its rela-

bility is higher. As a consequence, unloading movements should have been further underweighted in Experiment 1. In Experiment 3 this conflict was not present as the interaction was only haptic and unloading movements could have been weighted more.

Our findings also demonstrate that visual information contributes at the perception of compliance. The contribution of proprioceptive information, however, is much higher than visual. One would expect that, since the spatial resolution of vision on the frontal plane in normal circumstances is higher than proprioception and haptics [28], visual information would be more weighted than proprioception. In this experiment, however, the view of the interaction is limited in precision. For example, the HMD has lower spatial and temporal resolution when compared to everyday scenarios. This difference could lower the reliability of visual information making with consequent lower weight for compliance perception. Moreover, the spatial discrepancy between the seen and felt position of the hand created by visual delay might break integration [6] and induce the perceptual system to “trust” more the proprioceptive information instead of the visual sensory modality. This would be also reflected in the results as a low visual weight.

5.3.1. Weighting of information sources

Pressman et al. [17] tested a set of similar hypotheses using a simulation, namely that compliance information is either obtained from the entire history of the interaction, during loading, or during unloading. They showed that none of the three schemes could account for the effect of force delay. The scheme based on the loading information was a very good account of the experimental data collected. However, they suggested that compliance perception is obtained primarily with maximum force and maximum displace-

ment information as this scheme conformed better on a subset of data.

It is possible that the schemes proposed by Pressman et al. [17] which used information in only from one part of the movement did not reach best results because the perceptual system uses an intermediate solution. Here we propose a model that has two differences with respect to the schemes proposed above. First, our model of compliance perception is based on a mixture of loading and unloading information, while their model considered exclusively either one phase or the other, or the entire interaction. In the simulation we find that unloading information is not completely discarded (this would happen if $w_{loading}$ was 1.0). In order to decrease the noise affecting a sensory estimate and integrate different sources of information in an optimal fashion, each source should be weighted according to its reliability. We showed that the predicted weight according to this view is similar to the one obtained in the simulation. Second, we extended the model to the case where visual information about spring displacement is present. The difference is crucial in considering the effects of delay for the integration of proprioceptive and visual information. The effect of visual delays (delays which are one order of magnitude higher than force delays) would be greatly overestimated if a weight for visual information lower than 0.5 would not be assigned.

The imbalance in the relative contribution of information during different phases of movement and for visual and haptic information are the factors responsible for the effect of force and visual delay on perceived compliance registered in Experiment 1. These two factors are sufficient to explain the pattern of experimental results collected. To confirm that the relative contribution of visual and haptic information for compliance perception depend on the relative reliability we run another test where we modify the noise affecting the visual and proprioceptive estimate of spring displacement.

6. Experiment 4: visual–haptic weight

In this experiment we test whether the relative contribution of visual and haptic information varies with the relative reliability of the two unisensory estimates. To test whether the relative weights during combination are optimally assigned to the individual estimates, the respective unimodal reliabilities would have to be known [3]. These values could then be used to calculate the predicted weight, which is verified by testing whether the combined estimate is compatible with this prediction. Unfortunately, in our case this procedure is difficult to pursue for several reasons. First, we cannot assess the reliability of visual-only perceived compliance in this experiment, as there is no unimodal visual compliance estimate as sensorial information, but just a visual position estimate. Second, we cannot quantify the magnitude of the difference at the sensorial level introduced by visual and force delay to obtain an absolute estimate of the weight given to haptic and visual information about compliance.

Although we cannot quantitatively test whether the integration of multisensory information is optimal, we can test the weighting of multisensory information qualitatively. To do this we vary the reliability of either visual or proprioceptive information and investigate whether perceived compliance changes in the direction predicted by the change in relative reliability. We use the visual + force delay condition from Experiment 1. As can be seen in Fig. 5c, this condition creates a conflict between the visual and the proprioceptive displacement information in the standard stimuli. The conflict is almost absent for the comparison stimuli (however not completely absent due to the intrinsic latency). To lower the reliability of visual information we decreased frame rate at which visual information was displayed in the HMD. This manipulation lowers the ability to determine the correct position of a moving object, including the

participant's own hand and the top part of the spring. To lower the reliability of proprioceptive information, instead, we started from the observation that precision in the estimate of vertical position decreases with the distance between the joint undergoing movement and the position of the interaction [27], mainly because of the geometric effect of the joint angles involved (kinematic transformation). For this reason, we required participants to interact with the spring only by flexing their elbow, while keeping the rest of the arm straight.

If these modifications lower the reliability of the visual and proprioceptive signals, this should affect the relative weighting and we would register a change in PSE with respect to the normal condition. With lower visual reliability the spring should be perceived to be more compliant, while with lower proprioceptive reliability the spring should be perceived to be less compliant. Moreover, the overall sensitivity to compliance should decrease with both manipulations.

6.1. Method

We tested five participants (three females and two males, aged 21–30); four were inexperienced participants and naïve to the purpose of the study and one was one of the authors. All participants reported normal or corrected-to-normal vision and no haptic or somatosensory disorders. All were right-handed.

The apparatus and experimental procedure were identical to Experiment 1 except that the visual delay of the standard stimulus (33.3 mm/N) was always 100 ms (plus 66 ms latency) and the force delay was always 10 ms. The comparison stimuli were rendered without additional delays. This situation was equivalent to the visual + force delay condition of Experiment 1, so the PSE is not expected to necessarily match 33.3 mm/N. Three conditions were tested in blocks of 60 trials each, 2 blocks for each condition in randomized order with a break in between: *normal interaction*, *visual degradation*, and *proprioceptive degradation*. In the *normal interaction* condition, the standard and comparison stimuli were compressed with a rapid loading and unloading movement, allowing participants to use hand and arm posture they preferred. In the *visual degradation* condition, the visual presentation of the image was degraded by updating visual information only every three frames instead of updating it every frame. This manipulation lowered the frame rate to 10 instead of 30 frames per second. Notice that the shift in the visual information of three frames resulted in a minimum visual delay of 100 ms. Thus, the average delay was higher in this condition than in the other two. Higher visual delay would have caused a decrease in perceived compliance, which is against the hypothesized effect due to the decrease of visual reliability. In the *proprioceptive degradation* condition, we used elastic bandages to fix a light rod to the participant's hand and forearm to limit joint movement during the interaction. Participants were required to move the arm by flexing the elbow.

6.2. Results

Results are reported in Fig. 10. Visual degradation increased the perceived compliance of the spring while a constraint in the movement decreased the perceived compliance (PSE significantly changed across conditions, one-way repeated-measures ANOVA on PSE: $F(2,14) = 16.37$, $p < 0.01$; paired-sample t -test on PSE for *normal interaction* against: *visual degradation* $t(4) = 3.98$, $p < 0.05$; *proprioceptive degradation* $t(4) = 3.63$, $p < 0.05$). Changes in perceived compliance were present for each of the participants in the expected direction. The values of JND also followed the expected trend, with decreased sensitivity with both visual and proprioceptive degradations although the effect did not reach significance (one-way repeated-measures ANOVA on JND: $F(2,14) = 3.14$, $p = 0.099$).

6.3. Discussion

The results of this experiment indicate that visual and haptic estimates of compliance are integrated according to the relative reliability of the two sensory estimates. Simple changes in the posture adopted for the exploration or in the quality of visual information can affect the weight assigned to the two modalities. When the stimulus is rendered with visual and force delays, the introduction of degradation in the visual information increases perceived

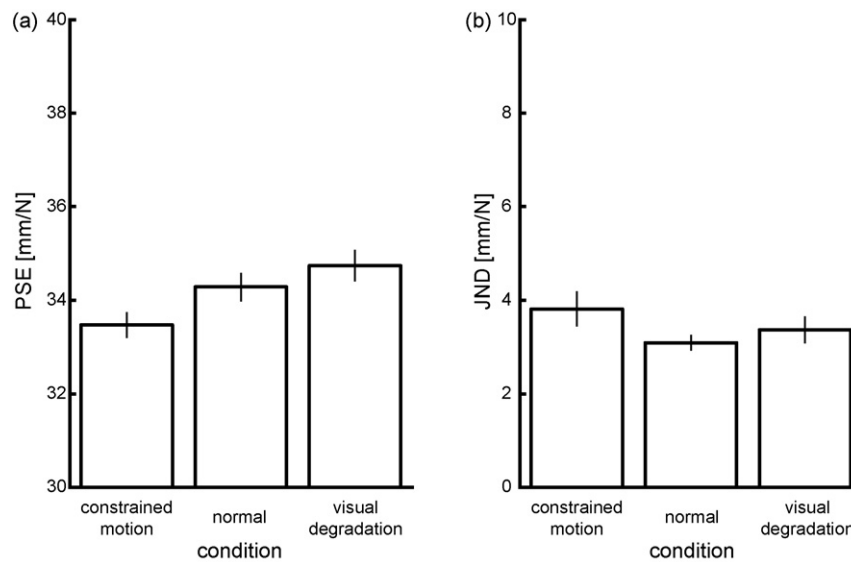


Fig. 10. Values of (a) PSE and (b) JND obtained in Experiment 4.

compliance, while constraints in the movement decrease perceived compliance. Although the magnitude of the change registered in the experiment were small (2% on average), they were present for all observers, demonstrating that the effect of visual and force delay on compliance are due to the integration of two redundant estimates.

7. General discussion

Softness of deformable objects can be perceived using different types of information [4]. For objects with deformable surfaces cues derived from contact area [1] and pressure on the finger [21] are very important in generating a percept of the material properties. But if the compliant object has rigid surfaces – like the springs used in this study – pressure distribution and skin deformation alone cannot be used to determine compliance [20]. During manipulation of springs, the information about compliance is necessarily acquired by sensing to the force produced by the spring and the amount of displacement relative to the rest state [8]. Displacement can be sensed at every instant of the interaction through vision and proprioception, while force is sensed through the haptic modality. The perceptual system would have to process these sensory estimates and combine them to obtain a final estimate of compliance.

It is not clear what is the most relevant piece of information in the sensed force and displacement information that is utilized by the perceptual system for compliance perception. Different information patterns seem to be used [10]. For example, perceived stiffness seems to be related to the terminal force [17] and the work performed during the interaction [24,25]. Others have advanced the hypothesis that the crucial information during interaction with hard materials is the amount of change in force over the change of position at the very beginning of the displacement [11]. The results of [14] also point out the relevant role of the beginning of the interaction with the compliant material in creating a perception of compliance.

Pressman et al. [17] used force delay to test how perceived compliance changed. They simulated different models of compliance perception that utilize different parts of the sensory information (cues) for the estimate of compliance. Their findings exclude models based on cues collected during the entire interaction or only the unloading movements. They propose that stiffness estimates

based on dividing the maximum force by the perceived amount of penetration offer the best fit of the data collected. Other models described the results obtained very well. For example, a model that only considered the ratio of force with displacement during the loading phase also scored very high, but not as high as the simple maximum force over displacement in some of the conditions (where the delay was present only in one of the movement phases). As shown in Fig. 9a and b we replicated this result in our simulation. Using only information during loading produces a pattern of results that resembles participants' responses, but the similarity increases by considering information gathered during unloading.

Here we extend this analysis in order to determine whether information during loading and unloading is equally utilized. We do this by analyzing the effect of visual delay on compliance perception. We reason that visually sensed and proprioceptively sensed position of the hand will influence perceived compliance, and thus introducing a conflict between the two offers a new way of looking at perceived compliance. We do this by employing an augmented reality setup rather than a visual representation of the hand using virtual reality. The reason for this is twofold. First, it has been shown that providing visual information in addition to the finger position can increase the weight given to visual information [19]. This is because explicit information about joint angles can be obtained. Second, we expect that participants will be more likely to integrate visual and proprioceptive position information if they see their own hand rather than a virtual placeholder for the finger, as the one customary employed in haptic virtual reality setups. It has been shown that beliefs about the sensory information can influence perception by favoring integration of multisensory information [18], and that previous knowledge can exert top-down influence on phenomena related to body scheme (as it is the case with the Rubber Hand Illusion [26]).

We find that delay of force information during interaction with a compliant material increases perceived compliance (induces the percept of a softer object), while delay of visual information decreases perceived compliance (induces the percept of a harder object). The symmetry of the effect of the two delays on perceived compliance (and likely also on other material properties sensed through visual–haptic interaction) could be exploited in setups providing visual and haptic information where there is an intrinsic delay in either of the two channels. For example, in telepresence scenarios involving haptic interaction, there is an unavoidable

intrinsic force delay that is due to technological limitations in the transmission and actuation of the haptic interaction. On the other hand, in virtual and augmented reality setups visual information is unavoidable affected by intrinsic delay due to the time required for tracking and rendering. The data of Experiment 1 indicates that both these types of intrinsic delays can have a significant impact on perceived material properties. However, results also indicate that it is possible to introduce an additional delay in the *other* channel (the one that is not intrinsically delayed) to compensate the perceptual effects.

Results collected in Experiments 1 and 2 cannot be explained by assuming that the subjects made use of maximal force cues alone to judge compliance in all conditions. Visual delay, for example, does not exert an effect on force, so the magnitude of maximal force is equal in both visual and haptic estimates of compliance. Nevertheless, visual delay induces a change in perceived compliance. The results are not consistent also with the exclusive use of maximal force divided by displacement cues in all conditions. As evident in Fig. 5 both visual and force delays have the same effect on the displacement corresponding to maximum force. If the perceptual system would employ this cue alone for the perception of compliance, then both types of delays would change perceived compliance in the same fashion.

Results in Experiments 1 and 2 are qualitatively compatible with the hypothesis that compliance is perceived using work cues. Work is positive for loading movements and negative for unloading. The sum of the work during loading and unloading changes with visual and force delay. This factor alone could be used as a cue for the difference in compliance across stimuli. However, to discriminate between springs in the non-delayed case, only the absolute value of work during loading and unloading has to be considered—similarly to what it has been done in the simulation. From the results of the simulation, however, it seems that compliance cannot be estimated by judging absolute work over the course of the entire interaction. To reproduce the results obtained, compliance has to be necessarily estimated both on the loading and unloading phases, but the influence of the two phases has to be uneven, with greater weight assigned to loading information. Interestingly, we find that in Experiment 3 there is a consistent imbalance in the sensitivity to compliance during these two phases of the movement. This would suggest that loading and unloading movements contribute to the creation of a compliance percept consistently with the relative reliability of the two estimates. In turn, the similarity between relative reliability and the weight assigned to the information for compliance judgments is consistent with an optimal integration scheme [3]. Moreover, in Experiment 4 we show that information reliability creates the pattern of results consistently to weights assigned to the unisensory information. The perceptual system integrates information about spring displacement coming from visual and proprioceptive sensory modalities by weighting information according to the reliability of the information. Deterioration of one or the other source of sensory information changes the weight assigned to that sensory modality in a manner again consistent with optimal accounts of perception.

The quantitative predictions made using this model are consistent with the magnitude of the effects found experimentally of force and visual delay on perceived compliance. This model is based on the idea that the goal of the perceptual system is to minimize the sensory noise. Information during the two phases of the movement is inversely weighted according to the relative sensitivity to compliance differences. One could speculate about the reasons for the difference in reliability during the two phases of motion. The first apparent difference between loading and unloading movements is the relative passivity of unloading movements, where the spring generates the force to displace the participant's hand. This difference could either lower the reliability of the pro-

prioceptive estimate or the reliability of the force estimate during unloading. If there would be a change in the proprioceptive reliability, the weighting of visual and proprioceptive information should favor proprioception during loading and vision during unloading. If there would be a change in force reliability, instead, both visual and haptic estimates of compliance would be equally affected over the course of the trial. Both possibilities are consistent with the data collected in our experiments and further investigation will be required to identify which one is correct. One possibility for addressing this issue is to decouple the amount of muscular force and hand displacement in the two phases of motion (similar to a condition used by Pressman et al. [17]) while monitoring sensorimotor information available during interaction in order to determine the reliability of proprioceptive information that the brain receives during the two phases.

In this work we have described how the effects of visual and force delay on perceived compliance are due to a different weighting of multisensory information during the course of a trial. Visual–proprioceptive and loading–unloading information is weighted differently to obtain a perceptual estimate of compliance. It seems that in all of these processes, the perceptual system integrates sensory information to perform compliance judgments by varying the weights according to the different reliability of the information. This way of doing is consistent with the view that the brain strives to diminish the detrimental effects of noise and that the mechanisms employed produce outcomes that make use of all information available reaching close to optimal performance.

Conflicts of interest

The authors declare that they have no competing financial interests.

Ethical considerations

All subjects were compensated with 30 CHF and gave their informed consent before participating. The ethics committee of ETH (Eidgenössische Technische Hochschule) has approved the experiments reported in this paper.

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Appendix A.

To determine the delay of visual and force information that was specific for the AR setup, the type of stimuli employed, and the type of movement performed by participants, we performed a pilot study.

Five naïve participants (four males, one female, 19–31 years) took part in the experiment. We measured detection thresholds for force delays and discrimination threshold under the intrinsic visual delay by asking participants to perform a 3IFC task. Three stimuli were presented sequentially, two of which were identical and one different. It was the participants' task to indicate which stimulus deviated the most from the other two (oddball). The deviation was either a visual delay (33, 66, 99, 132, 165, and 198 ms) or a force delay (5, 10, 15, 20, 25, 30, 40, and 50 ms) that could appear both in the odd or the two comparison stimuli. The value of delay corresponding to a proportion of 0.66 correct responses on the psychometric function was taken as an estimate of threshold.

For our specific setup, force delay was found to be detectable at delays of 29.6 ± 5.8 ms (s.e.m.), visual delay (in addition to the intrinsic end-to-end latency of 66 ms) was noticed at values of 109.4 ± 10.8 ms. These findings are consistent with experimental results obtained in similar setups [29]. By choosing smaller values of delay in the experiments (20 ms for force and 100 ms for visual information) the manipulation should barely be noticeable.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.brainresbull.2010.02.009.

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