The effect of force feedback delay on stiffness perception and grip force modulation during tool-mediated interaction with elastic force fields

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Running Head

Grip force modulation during stiffness discrimination task with delay

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Abstract

During interaction with objects, we form an internal representation of their mechanical properties. This representation is used for perception and for guiding actions, such as in precision grip, where grip force is modulated with the predicted load forces. In this study, we explored the relationship between grip force adjustment and perception of stiffness during interaction with linear elastic force fields. In a forced-choice paradigm, participants probed pairs of virtual force fields while grasping a force sensor that was attached to a haptic device. For each pair, they were asked which field had higher level of stiffness. In half of the pairs, the force feedback of one of the fields was delayed. Participants underestimated the stiffness of the delayed field relatively to the non-delayed, but their grip force characteristics were similar in both conditions. We analyzed the magnitude of the grip force and the lag between the grip force and the load force in the exploratory probing movements within each trial. Right before answering which force field had higher level of stiffness, both magnitude and lag were similar between delayed and non-delayed force fields. These results suggest that an accurate internal representation of environment stiffness and time delay was used for adjusting the grip force. However, this representation did not help in eliminating the bias in stiffness perception. We argue that during performance of a perceptual task that is based on proprioceptive feedback, separate neural mechanisms are responsible for perception and action-related computations in the brain.
Perception of the mechanical properties of objects is formed using information originating from different modalities, including visual and proprioceptive feedback (Ernst and Banks 2002). To understand how these modalities are combined and integrated to form perception, often a mismatch between sensory inputs is induced. One way to induce such mismatch is artificially introducing a temporal delay between sensory inputs, which may bias perception, such as in the case of perception of stiffness with force feedback delay (Di Luca et al. 2011; Nisky et al. 2010; Nisky et al. 2008; Pressman et al. 2007).

The stiffness of an elastic force field is the ratio between the force that it applies when penetrated into and the penetration distance. Since we do not possess stiffness sensors (Gurari et al. 2013; Kuschel et al. 2010), the perception of stiffness, which here we refer to as the cognitive judgment of the stiffness, is formed based on integration of position and force signals. It was shown that when the force feedback is calculated based on past probing information, the perceived stiffness of a one-sided elastic force field (i.e. resembling a compression spring) is biased (Di Luca et al. 2011; Nisky et al. 2010; Nisky et al. 2008; Pressman et al. 2007). When probing the force fields while maintaining continuous contact with them, participants underestimate the stiffness of the force field if force feedback is delayed (Nisky et al. 2008). In addition, Nisky et al. (2010) found that the extent of underestimation depends on the joint that is used for probing: perceived stiffness in the presence of delay is larger when the probing movement is pivoted around a proximal joint, such as the shoulder, compared to probing while pivoting around a distal joint, such as the wrist.

To understand how internal representation of stiffness is formed, in addition to asking participants about their subjective stiffness perception, it is also useful to explore other aspects such as their motor actions during interaction with the elastic force fields (Nisky et al. 2011; Pressman et al. 2008). One example for such motor action of interest is the adjustment of grip force that is applied on the probing tool during tool-mediated interaction with a force field. Grip force adjustment is important to maintain a firm and efficient grasping of the tool while probing, and it was documented to be modulated in accordance with load force in a predictive manner such that on one hand, the tool does not slip while encountering external forces, but on the other hand, excessive grip force is avoided (Johansson and Westling 1988; Westling and Johansson 1984). Grip force modulation was reported in various interactions with objects, including lifting of objects, where grip force is
modulated according to the anticipated weight of the object. It was shown that during repeated lifts of an object, initially, humans generate grip force based solely on a prediction resulting from the visual appearance of the object; however, at late lifts, the grip force is adjusted as sensory feedback is processed to form an internal representation of the weight of the object (Blakemore et al. 1998; Gordon et al. 1993; Quaney et al. 2005). Recently, force feedback was also shown to be important for grip force modulation during interaction with an elastic force field (Gibo et al. 2014).

Interestingly, past studies found that the grip force that participants apply during lifting is not always in agreement with their perception of weight. For example, in the well-known size-weight illusion, the weight of two identical boxes is perceived differently if there is a visual difference in their size, but after several lifts, while the perceptual illusion persists, the grip force converges to the same value regardless to the size of the box, and this value is proportional to the actual weight of the box. These results supported the idea of a gap between perception and action in the context of weight estimation (Flanagan and Beltzner 2000) adding to the overall opinion about separation between visual based perception and visual control of action (Goodale and Milner 1992; Milner and Goodale 1995).

Our study aimed to test whether such discrepancy exists between the delay-induced bias in perceived stiffness and the modulation of grip force during probing of elastic force fields. We examined the grip force that participants applied during tool-mediated probing of elastic force fields with varying levels of stiffness with and without delay in force feedback. We analyzed the applied grip force during continuous interaction with the force field while pivoting the probing movement about their wrist and shoulder joints as well as while not constraining the pivoting around specific joints (Fig. 1). Our first hypothesis was based on the predictive nature of grip force adjustment to load force. We hypothesized that during initial interaction with any unknown elastic force field, the grip force will have high magnitude to secure proper grasping while facing unexpected force. However, as stiffness representation is formed during repeated probing of the same elastic force field, the ability to predict forces is expected to become more accurate, and the grip forces are expected to decrease and be adjusted in accordance to the stiffness of the force field and the magnitude of the interaction forces. Our second hypothesis was based on the idea of decoupling between perception and action, and specifically, grip force adjustment. We hypothesized that the mechanism that adjusts grip force during interaction with elastic objects is robust to the delay-induced perceptual bias, and therefore, grip force adjustment will remain robust to
perceptual illusions. In accordance with this hypothesis, we expected to find that the
coupling between grip force and interaction forces with the elastic field is delay-
independent, and is adjusted to the nominal stiffness of the force field and the actual forces.
We expected to find this in various conditions which previously were shown to bias stiffness
judgment, including constrained probing around the wrist or shoulder joints as well as
unconstrained probing. Our findings support both these hypotheses.

Materials and Methods

Participants, apparatus, and protocol

A total of fourteen participants, all right handed (seven males and seven females, aged 22-27
years) participated in the experiment after signing an informed consent form as stipulated
by the Institutional Helsinki Committee, Ben-Gurion University, Beer Sheva, Israel. We
equipped the end-point of a haptic device (Phantom Desktop, Sensable Technologies) with a
grasp fixture with an embedded force sensor (Nano17, ATI Technologies) to record the grip
forces that were applied during the experiment. The position of the tool (as measured based
on the readouts of the haptic device encoders) was recorded at 1 KHz, and used to calculate,
in real time, a force feedback that was applied via the haptic device. Due to computation of
the applied force, a delay of 2-3 milliseconds is introduced to the force feedback. Grip force
was recorded via the force sensor at 1 KHz. Participants looked at a semi-silvered mirror
showing the projection of an LCD screen placed horizontally above it (Figs. 1A and 1B). An
opaque screen was fixed under the mirror to block the vision of the hand. The horizontal
position of the participants’ hand was displayed as a yellow square, providing them with a
visual feedback of their horizontal hand position but not the vertical displacement.

Participants were seated in front of the experimental setup, and used the thumb and index
fingers of their dominant arm to grasp the haptic device end-point, placing their index finger
on the force sensor (Fig. 1C). We instructed them to hold the device in this manner that
resembled stiffness exploration using a tool (LaMotte 2000), and explore vertically oriented
elastic force fields to determine their stiffness level (Fig. 1D). In each trial, participants were
instructed to probe two virtual force fields, represented by two distinct background colors,
blue or red, and report which one had higher level of stiffness. By pressing on a virtual green
squared button, participants could switch between the two force fields as many times as
they wished, until they were ready to answer. The time of probing was also not restricted,
and participants could perform as many probing movements as they wanted. When ready to
answer, they pressed a keyboard key that was marked with a color that corresponded to the background color of the force field that they judged to have a higher level of stiffness. By moving back and forth, participants compressed and released the virtual spring. We did not force participants to move in a specific pattern; they could move back and forth in a rhythmic or discrete manner, and choose the movement amplitude at their will. After giving their answer, the screen background turned black, and to initiate another trial, the participants were asked to press on the virtual green button.

During the probing interaction, the applied forces, $F(t)$, were proportional to the vertical displacement, $x_{\text{hand}}$, i.e. $F(t) = K \cdot (x_{\text{hand}}(t - \tau) - x_0)$, where $K$ is the stiffness of the elastic force field in [N/m], $\tau$ is the delay in [msec], and $x_0$ is the boundary of the elastic force field in [m]. To assure that the participants continuously interacted with the force field, we prevented them from accessing the boundary, by setting the boundary beyond their reachable workspace. To prevent the participants from experiencing discontinuity in forces when switching between the different force fields the virtual green button that initiates interaction with a force field was placed at $x = 0$, and the unreachable boundary location was set to $x_0 = -\frac{1.5}{K}$. Therefore, each probing movement began and finished with a force of 1.5 N, and stayed above this value for the majority of the probing movements’ extent.

In each trial, the participants were presented with two force fields, which will be referred to as Standard and Comparison. The standard force fields in all the trials had a stiffness level of $K_{\text{standard}} = 85$ N/m; in half of the trials, there was no delay between force and position, i.e. $\tau = 0$ msec, and in the other half, the applied force lagged behind the position, i.e. $\tau = 50$ msec. The comparison springs were all non-delayed, and their stiffness values, $K_{\text{comparison}}$, were chosen out of ten equally distributed stiffness levels between 40-130 N/m with jumps of 10 N/m. Since computation of force feedback adds about 2-3 msec of delay, all the virtual springs were in fact delayed. However for the comparison springs and the non-delayed standard spring, no additional delay was added and for all practical matters, we neglect the minimal 2-3 msec delay. To prevent participants from penetrating too far into the force fields and reaching the force saturation levels of the haptic device, a sound was played after a displacement of 45 mm regardless to the stiffness of the elastic field.
In Fig. 1E, a schematic representation of the experimental protocol is depicted. The experiment began with 20 practice trials in which participants compared each of the standard fields to each of the comparison fields and familiarized themselves with the system. After the training session, they completed additional 160 trials in which they performed eight comparisons between each of the two standard springs and each of the ten comparison springs. The pairs of fields at each trial were pseudorandomly predetermined, and the participants could not anticipate which force field they were about to encounter prior to the beginning of the trial. The participants never received feedback about their answers (not even in the training trials). The performance of the entire set of 180 trials took about 40 minutes.

We divided the participants into two groups: nine participants in the constrained joints group and five participants in the non-constrained joints group. Each participant in the constrained joints group performed the experiment twice on two consecutive days (Fig. 1E). In each session, the participants used either the wrist (Fig. 1A) or the shoulder (Fig. 1B) joints as a pivot for their probing movement. We used orthopedic splints to prevent participants from using their other joints during probing. The participants were randomly assigned to perform either the wrist or shoulder session first (five and four participants, respectively). In the non-constrained joints group, participants performed the experiment only once while their joints were not constrained allowing them to use whatever joints they wanted.

Data Analysis

Grip-force modulation analysis

To analyze the grip force of the participants during the probing of the force fields, we followed (Flanagan and Wing 1995), and used regression coefficients that were extracted from the grip force – load force plane regression. At a given trial, we separately examined the forces that were applied during interactions with each of the force fields, and the grip forces that the participants applied (Fig. 2A). To examine solely the forces that were generated during probing of the elastic fields while taking out possible pauses of movement, we identified the start and end of the probing motion using the velocity and position signals: temporal events in which velocity exceeded 0.005 m/s while the displacement of the tool in the vertical direction was smaller than 0.015 m (in robot coordinates) indicated the start and end of a single probing motion (black circle and star symbols in the bottom panel of Fig. 2B). We fitted a two degrees-of-freedom regression line (slope and intercept) to the trajectory in
the grip force – load force plane of the first and last probing movements (similar to (Nowak et al. 2002)) that were performed in the comparison (examples depicted in Fig. 2C and 2D) and the non-delayed standard force fields for each trial. We used the same procedure of regression line fitting for the standard delayed force fields, but with one change: since the force feedback was delayed by 50 ms, we added 50 ms to the start and end times that were identified using the velocity and position signals (an example of a delayed force field trajectory is depicted in Fig. 7A). When the slope value remains the same, the relative value of the intercept represents the average magnitude of the grip force: high intercept value represents a high grip force on average. The slope of the regression line is usually linked with the "slip ratio" of an object, i.e. the ratio between critical grip force and the load force needed to prevent object from slipping, but it also decreases with increasing velocity of the held object (Flanagan and Wing 1995). To test whether the slope of individual probing movement and the probing velocity were correlated, we calculated the average absolute velocity for each probing movement.

We did not limit the participants in the number of subsequent probing movement in each trial, and allowed them to probe freely until they reached a decision about the relative stiffness levels of the force fields within each trial. We were interested in exploring the change in grip force adjustment within a single trial as the perception of the stiffness of the elastic force fields was formed. To assess this change, we analyzed the grip force in the first probing movement of each trial, when participant did not have any prior information about the stiffness level, and in the last probing movement of each trial, when the participant has already formed her stiffness judgment. This comparison between early and late probing movements was performed for each of the 160 test trials in our experiment. Therefore, for each participant, and for each of the 160 standard and comparison force fields, we fitted 2 regression lines to the grip force – load force trajectories, and hence, 2 intercepts and 2 slopes were extracted: a pair of coefficients from the first probing movement and a pair from the last probing movement. Using these regression coefficients, we examined to what extent was the user able to predict the interaction forces and adjust the grip force to the particular stiffness level. To prevent tool slippage in face of the position-dependent elastic force field while applying efficient grip force, the instantaneous grip force must be adjusted to the instantaneous force generated by the force field (the load force). Accurate representation of the stiffness level allows for an accurate prediction of the instantaneous load force value and an appropriate adjustment of the grip force. This results in similar grip force – load force trajectories regardless to the stiffness level of the elastic force field. In this
case, the slopes and intercepts of the grip force – load force plane regression lines will not depend on the stiffness level. However, if the user cannot properly anticipate the stiffness of the elastic force field, they tend to use an excessive grip force (Gibo et al. 2014) that is similar across different stiffness levels and that is not adjusted to the load force that is applied by the elastic force field. In this case, the regression coefficients of the grip force – load force trajectory will depend on the stiffness of the elastic force field. In accordance with our hypothesis, we expect the latter to happen in the first probing movement, and the former in the last probing movement.

Analysis of the lag between grip force and load force

During probing of a non-delayed elastic force field, the force that is applied on the hand of the user is a linear function of the displacement. Since grip force is typically coupled with load force, we wished to examine whether and how this coupling changes with the introduction of delay between the force feedback and the displacement that caused it. We calculated the lags by two means: (i) calculating the lag between peaks in the grip force and load force signals, and (ii) calculating the lag for which the cross-correlation between the two signals was maximal.

Movement kinematics analysis

To test whether stiffness perception was influenced by the way participants probe the standard force fields, we analyzed different motion kinematic metrics using the hand position data recorded using the haptic device. For each trial, we estimated the following parameters (similar to (Nisky et al. 2010)) and compared the values that were calculated from the delayed and the non-delayed standard force fields:

- **Probing movement duration.** Using the identified start and end times of each probing movement (black circle and star symbols in the bottom panel of Fig. 2B), we calculated the probing time of each probing motion subjects performed.

- **Movement amplitude.** Using the reversal points (where hand velocity equals to zero), we calculated the local displacement peaks for each trial.

- **Peak absolute velocity.** For each probing movement, we examined both the pressing and the releasing of the elastic force field. For each part, we calculated the peak absolute velocity (overall two values were analyzed for each probing movement). We used the
absolute peak velocity in our analysis because the sign difference in velocity between pressing and releasing.

**Area reach deviation (ARD).** This is a metric for movement curvature. As explained above, the motion of the participants in the constrained joints group was performed using either the wrist or the shoulder joints. Such constrained motion forced the participants to a slightly curved motion. To assess the level of curvature we calculated the area between actual movements subjects performed and a straight line connecting between the start and end of each probing sub-movement. The same analysis was repeated for the movements of participants in the non-constrained joints group.

After calculating these metrics for each trial, we calculated the mean value for each participant in the unconstrained joints group. For participants in the constrained joints group we calculated the mean of each metric twice; once for each joint-pivot session.

**Perceptual response analysis**

We used the answers of the participants to calculate the probability of a subject to answer "comparison force field had higher level of stiffness" as a function of the difference between the levels of stiffness of the comparison and the standard force fields. We used the psignifit 2.5.6 toolbox (Wichmann and Hill 2001) to fit logistic psychometric curves to the probabilities, and extracted the point of subjective equality (PSE) and the just noticeable difference (JND) as described in details in (Nisky et al. 2008). The PSE indicates the stiffness difference at which the probability of the participant to answer that the comparison force field had higher level of stiffness is 0.5. This means that the PSE is the difference for which the participant could not tell which of the force fields, comparison or standard, had higher level of stiffness, and it quantifies the bias in the perceived stiffness of the standard field when compared to the comparison field. The JND quantifies the sensitivity of the subject to small differences between the stiffness levels of the two force fields. To calculate the JND, for each participant, we subtracted the stiffness difference at the 0.25 threshold value from the stiffness difference at the 0.75 threshold value and divided the result by 2.

**Statistical analysis**

For the constrained joints group, to test the effects of delay and probing joint on stiffness perception, we used two-way repeated measures ANOVA with 'delay' and 'joint' as independent categorical factors, and the PSE as a dependent variable. For the non-delayed
force fields, to test the difference in grip force value between first and last probing movement, we performed two separate three-way repeated measures ANOVA with the intercept and slope of the grip force – load force trajectory regression as the dependent variables and 'probing movement' (first or last), 'joint' (wrist or shoulder), and 'stiffness' (11 levels) as within-subject factors. To test the dependence of the grip force - load force trajectories slopes on the average velocity during initial and last probing movements, and to test the dependence of the grip force - load force trajectories slopes and intercepts on the stiffness of the elastic force field for each of the probing movements (first and last), we used repeated measures ANCOVA. For the delayed force fields, to test the effect of probing movement on the slope and intercept of grip force - load force trajectory regressions in comparison with the non-delayed force fields of the same stiffness level, we performed two separate three-way repeated measures ANOVA with the slope and intercept as the dependent variables, and with 'probing movement' (first or last), 'joint' (wrist or shoulder) and 'delay' (delay and non-delay) as within-subject factors. To test differences in movement metrics between probing motion performed in the delayed and non-delayed force fields, for the constrained joint group we conducted a two-way repeated measures ANOVAs with each movement metric as the dependent variable and 'joint' (wrist or shoulder) and 'delay' (delay and non-delay) as within-subject factors. To assess the changes in grip force – load force lag, we performed three-way repeated measures ANOVA with the lag as the dependent variable and 'probing movement' (first or last), 'joint' (wrist or shoulder) and 'field type' (comparison, standard linear and standard delay) as within-subject factors. Post hoc tests with Bonferroni correction for multiple comparisons were performed when factors had more than 2 levels. Statistical significance was determined at the 0.05 threshold in all tests.

For the unconstrained joint group, we repeated the statistical analysis in a similar manner to the constrained joint group, but without the 'joint' factor where relevant.
**Results**

*Adjustment of grip force to load force in late probing movements compared to initial probing movements*

During the first probing movement of each trial, the grip force was higher than during the last probing movement, while the force that was applied by the field remained similar. An example of one such trial of a typical subject is depicted in Figs. 2A and 2B. This difference is also evident in the grip force - load force plane trajectories and the regression lines that were fitted to these trajectories (overall $R^2$ value 0.85±0.07 for the comparison force fields) as depicted in Fig. 2C: while regression slope values are similar between the two trajectories, the intercept in the initial probing movement is higher than the intercept from the last probing. As depicted in Figure 2D, sometimes both values changed, but nevertheless, the grip force magnitude reduced between the first and last probing movements.

Overall, as depicted in Fig. 3A, the intercept decreased statistically significantly between the first and last movements ($F_{1,8}=5.52, p=0.046$), and as depicted in Fig. 3B, the slope remained unchanged ($F_{1,8}=0.313, p=0.59$). This indicates a decrease in the grip force magnitude during the final probing movement when compared to the initial probing movement. In addition, while in the first probing movement the trajectories in grip force - load force plane were different and depended on the stiffness level, during the last probing movements, these trajectories became similar across different stiffness levels. In the first probing movements, the slopes (Figs. 4A and 4B orange lines) and intercepts (Figs. 4C and 4D orange lines) of these trajectories statistically significantly depended on the level of stiffness (slope: $F_{8,81}=14.58, p<0.001$ in the shoulder condition and $F_{8,81}=5.76, p<0.001$ in the wrist condition; intercept: $F_{8,81}=8.72, p<0.001$ in the shoulder condition and $F_{8,81}=10.49, p<0.001$ in the wrist condition). In the last probing cycle, both slopes (Figs. 4A and 4B blue lines) and intercepts (Figs. 4C and 4D blue lines) did not longer depend on the stiffness level (slope: $F_{8,81}=1.78, p=0.093$ in the shoulder condition, and $F_{8,81}=1.83, p=0.082$ in the wrist condition; intercept: $F_{8,81}=1.9, p=0.071$ in the shoulder condition, and $F_{8,81}=1.94, p=0.064$ in the wrist condition).

It is likely that the probing velocity is responsible for the initial dependency between the regression parameters and the stiffness values that is reduced following a forming of an internal representation of the stiffness (Flanagan and Wing 1995). This idea is supported by an analysis of the correlation between probing velocity and slope: the correlation was
statistically significant during initial but not late probing, (initial: decrease of 0.85 in slope value for an increase of 1m/s, $p=0.03$; late: $p=0.75$).

**Biased perception of delayed force field**

Participants underestimated the stiffness of the standard force field when there was a delay between force and position. They did so more when probing with the wrist rather than with the shoulder, as indicated by a leftward shift of the psychometric function of the delayed force field in the shoulder condition, and even further leftward shift in the wrist condition, as depicted in Fig. 5A for one typical participant. This effect was observed in all the participants of our study, as evident in the averaged group data that is depicted in Fig. 5B, and is supported by a statistically significant effect of delay ($F_{1,8}=11.58$, $p=0.009$), joint ($F_{1,8}=19.325$, $p=0.002$), and their interaction ($F_{1,8}=8.465$, $p=0.02$) on the PSE that was extracted from participants’ answers. While perception was affected by the delay and the joint around which probing movements were pivoted, the discrimination sensitivity, as quantified by the just noticeable difference (JND) was not affected by these factors. This is depicted in Fig. 5C, and supported by the statistical analysis: there was no effect of delay ($F_{1,8}=3.13$, $p=0.11$), no effect of joint ($F_{1,8}=0.867$, $p=0.37$), and no effect of their interaction ($F_{1,8}=4.3$, $p=0.07$) on the JND values.

**Probing movements are similar between delayed and non-delayed force fields**

While causing a significant bias in stiffness perception, introducing delay to the force feedback did not alter the kinematics of probing movements. We tested for effects of joint, delay, and their interaction on the different kinematic metrics of probing movements: the duration of probing motion, movement amplitude, peak velocity, and movement curvature (Fig. 6). In all of these metrics, we did not observe statistically significant effects of joint (all $F_{1,8}<3.9$, $p>0.05$), delay (all $F_{1,8}<4.6$, $p>0.05$), or their interaction (all $F_{1,8}<1.2$, $p>0.05$). This indicates that delay did not affect movement kinematics in both wrist and shoulder conditions.

We analyzed the average number of probing movements that participants performed before answering, and found that they performed 3.8±1.9 (mean ± confidence interval) probing movements in the comparison force fields, 4±1.6 probing movements in the standard non-delayed force fields, and 3.8±1.3 probing movements in the standard delayed force fields. Based on Flanagan and collaborators (Flanagan et al. 2003), and on our analysis of grip force adjustment, we conclude that the number of interactions with the load force was sufficient
for the participants to adjust their grip force in accordance with it (although in other studies, it was shown that adequately scaling the grip force can be substantially longer (Danion et al. 2012; Danion et al. 2013)). Importantly, the number of probing movements was not affected by the delay in force feedback, suggesting that the stiffness discrimination task was not perceived by the participants to be more difficult due to delay.

No difference in grip force magnitudes between delayed and non-delayed force fields

During probing of elastic force fields with force feedback delay, participants reduced their grip force magnitude between the first and last probing movements similarly to the way they did during probing of non-delayed force fields. As depicted in the example in Fig. 7A, the grip force during the first probing of the force field was higher by a factor of two than the grip force during the last probing movement, while in this specific example, the load force that was applied by the elastic force field remained similar across the first and last probing movements. This assertion is also supported by the analysis of grip force - load force trajectories and the regression lines that were fitted to them. Fig. 7B shows that while the values of the slope of the regression are similar between the two trajectories, the intercept in the initial probing movement is higher than the intercept in the last probing movement.

Group analysis of the slopes and intercepts of the regression lines that were fitted to the grip force - load force trajectories of the delayed (overall $R^2$ value 0.75±0.08) and non-delayed (overall $R^2$ value 0.87±0.05) standard elastic force fields suggests that the magnitude of the applied grip force did not depend on delay. Similarly to the case of the linear elastic force fields, we found a statistically significant effect of 'probing movement' on the intercepts values ($F_{1,8}=7.067$, $p=0.029$), but not on the slope values ($F_{1,8}=4.328$, $p=0.071$). This indicates that the intercept value, representing the magnitude of the grip force, decreased in the final probing movement when compared to the initial probing movement.

For both the slope and the intercept values, as depicted in Fig. 8, we found statistically significant interaction between the 'delay' and 'probing movement' factors (slope: $F_{1,8}=11.94$, $p=0.009$; intercept: $F_{1,8}=8.79$, $p=0.018$). Post-hoc comparisons showed that this difference is caused by a difference between the delayed and non-delayed force fields at initial probing (slope: $t_8=5.4$, $p<0.001$; intercept: $t_8=2.75$, $p=0.025$), but not at the final probing (slope: $t_8=1.75$, $p=0.118$; intercept: $t_8=1.91$, $p=0.092$). These results indicate that during the last probing movement, there is no difference in the slopes and intercepts between delayed...
and non-delayed standard force fields. This is in contrast to the clear, condition-specific, perceptual effect that was observed in both of these conditions.

**Grip force - load force temporal lag**

In Fig. 9, the temporal lag for the comparison, standard non-delayed, and standard delayed force fields is depicted. In all the non-delayed elastic force fields (comparison and standard), the grip force slightly leads the load force both in both the first and last probing movements (average lead of 9.6±6 and 5.8±7 ms, respectively). This is consistent with prior similar findings and indicates the predictive nature of grip force adjustments to load force. Introducing delay breaks the coupling between hand position and load force, and causes the load force to lag hand position. Because slippage occurs due to inappropriate adjustment of grip force to load force rather than to hand position, to keep the haptic device from slipping without changing the grip force magnitude, the participants needed to adjust their grip force to the delayed load force. Therefore, because in late probing movements we did not find a difference in the magnitude of the grip force between delayed and non-delayed force fields, we expected to find a temporal shift of grip force in late probing movements.

Indeed, as shown in the example in Fig. 7A, and in the overall analysis in Fig. 9, such temporal adjustment was observed in the late probing movements. There was a statistically significant effect of the interaction between the 'field type' and 'probing movement' factors ($F_{1,8}=28.27, \ p=0.001$). Post-hoc tests revealed that the lead of the grip force increased, and was statistically significantly larger for the standard delayed force field compared to the standard non-delayed and comparison force fields at early probing movements ($t_8>32.03, \ p<0.001$ in both comparisons). In the late probing movements, this difference decreased statistically significantly (early v. late probing movements in standard delayed force fields $t_8=6.79, \ p<0.001$), and was not statistically significantly different from the last probing movements in the comparison and standard non-delayed force fields ($t_8=2.21, \ p=0.173$, and $t_8=2.26, \ p=0.161$, respectively).

We confirmed these results also using a cross-correlation analysis (we report here the temporal shift that yielded the maximal cross-correlation between the grip and load forces, and the value of the cross correlation). During the initial probing movements, the grip force led the load force for both the comparison force fields (12.7±6.3 ms, $R=0.94±0.01$) and standard non-delayed force fields (9.9±6.8 ms, $R=0.96±0.01$). For the standard delayed force field, the lead (56.1±10.4 ms, $R=0.92±0.03$) was statistically significantly larger when
compared to the comparison force fields and standard non-delayed force fields (for both
\( t_8 > 14.4 \), \( p < 0.001 \)). During the last probing movement the grip force lead of the standard
delayed force field was reduced (23.8±14.3 ms, \( R = 0.93±0.03 \)) and was not statistically
different from the comparison force fields (13.7±8.5 ms, \( R = 0.96±0.01 \)) and the non-delayed
force field (9.7±6.7 ms, \( R = 0.96±0.01 \)) (for both \( t_8 < 1.69 \), \( p > 0.38 \)).

Both these analyses suggest that participants shifted their grip force temporally, and
adjusted their grip force trajectory to the delayed load force trajectory. This is likely the
reason why they did not need to change the grip force magnitude to prevent slippage of the
haptic device.

*Biased perception, unbiased adjustment of grip force to load force, and Grip force - load force
temporal lag change observed in the unconstrained joints condition*

To validate that our observations are not a result of the un-natural constrained movement,
we conducted a control experiment in which participants interacted with the elastic force
fields using natural unconstrained probing movements. The results are very similar to what
was found in the constrained condition. For completeness, we report all the results for this
control experiment in the next four paragraphs.

The decrease in grip force magnitude and the formation of similar trajectories in the grip
force - load force plane during the last probing movement while participants interacted with
the non-delayed force fields were both reproduced in the unconstrained condition. These
are evident by statistically significant effect of 'probing movement' on the intercept values
(\( F_{1,4} = 16.98 \), \( p = 0.015 \), Fig. 10A) and lack of effect on the slope values (\( F_{1,4} = 2.163 \), \( p = 0.21 \), Fig.
10B), as well as lack of dependence of the slope and intercept values on stiffness level during
the last probing movement (slope: \( F_{4,45} = 2.27 \), \( p = 0.076 \); intercept: \( F_{4,45} = 2.34 \), \( p = 0.069 \)).

Similarly, we also found a decrease in grip force at the last probing movement during
interaction with the delayed force fields, as evident in the statistically significant effect of
'probing movement' on intercepts values (\( F_{1,4} = 139.49 \), \( p < 0.001 \)) but not on the slope values
(\( F_{1,4} = 1.349 \), \( p = 0.31 \)). In addition, we found that in the last probing movement, the grip force
magnitude was similar between the delayed and non-delayed conditions. We found no
statistically significant effect of the interaction between 'delay' and 'probing movement'
factors on the slope (\( F_{1,4} = 0.19 \), \( p = 0.68 \)) and intercept (\( F_{1,4} = 0.61 \), \( p = 0.47 \)) values. The post-hoc
comparisons showed that in the last probing movement, there was no statistically significant
difference between the slopes ($t_4=0.179$, $p=0.865$) and the intercepts ($t_4=1.81$, $p=0.143$) between the delayed and non-delayed force fields (Fig. 10C-D).

Similarly to the case in the constrained joint condition, participants underestimated the stiffness of the delayed standard force field while accurately perceiving the stiffness of the non-delayed standard force field (Fig. 10E). Average PSE for the delayed force field was -15.5±14.1 N/m (mean ± confidence interval) while for the non-delayed force field the average PSE values was -0.2±4.9 N/m. The difference in PSE was statistically significantly larger than zero (paired t-test $t_4=3.29$, $p=0.03$), and was roughly between the difference in PSE in the wrist and shoulder conditions. We did not observe any difference in JND values ($t_4=1.4$, $p=0.23$, Fig 10F), or movement metrics (all $t_4<1.3$, $p>0.2$, Fig 10G), suggesting that the discrimination ability and movement kinematics did not change between the two force fields and thus cannot be responsible for the bias in stiffness perception.

The temporal analysis of the grip force trajectories also yielded consistent results between the constrained and unconstrained conditions (Fig. 10H). There was a statistically significant effect of the interaction between the 'field type' and 'probing movement' factors ($F_{2,8}=189.2$, $p<0.001$). Post-hoc tests revealed that the lead of the grip force over the load force during first but not last probing of the delayed standard force field was statistically significantly larger compared to the standard non-delayed and comparison force fields (first: both $t_4>16.1$, $p<0.001$; last: $t_4=2.54$, $p=0.191$, and $t_4=1.67$, $p=0.51$, respectively). Lag analysis using cross-correlation showed similar trend. The lag value during initial interaction with the delayed force field (-54.3±8.3 ms, $R=0.84±0.07$) was larger compared to the values in the comparison (-4.2±8.6 ms, $R=0.88±0.04$) and standard force fields (-6.1±6.5 ms, $R=0.89±0.04$), but was reduced in the final interaction (delayed force field lag -7.3±1.7 ms, $R=0.89±0.07$; comparison lag -2.79±2.6 ms, $R=0.88±0.06$; standard force fields lag -4.26.3±1.51 ms, $R=0.9±0.05$).
Discussion

We explored the modulation of grip force during interaction with elastic force fields with and without force feedback delay. Based on an analysis of participants’ grip force and their verbal response, we argue that there is a gap between the representation of stiffness that is used to adjust grip force and the representation that is used to form perception. The different representations of stiffness provide compelling evidence for the existence of two separate neural processes that yield stiffness representation based on information that originated from a single sensory modality.

We confirmed that during modulation of grip force in repeated interaction with an elastic force field in our experimental setup, the magnitude of the grip force in the late probing movements was lower than during initial exposure to the force field, and was adjusted in accordance with the stiffness of the force field. The initially excessive grip force is likely related to the participants’ initial uncertainty about the expected stiffness of the elastic force field at their first encounter with it. As the representation of the stiffness was formed, the grip force was adjusted to the load force, and hence reduced. In prior studies that examined the linear relation between grip force and load force, intentional excessive grip force was associated with high intercept and small slope values when participants were instructed to keep an elevated level of grip force (Flanagan and Wing 1995). In our experiment, excessive grip force is only associated with increased intercept value. This difference may be due to the non-conscious process that underlies grip force generation in our study compared to the conscious effort of participants to generate specific grip force in (Flanagan and Wing 1995).

The adjustment of grip force magnitude at the late probing movement was similar in delayed and non-delayed force fields. Based on our analysis of the temporal lag between peak load and grip forces, we suggest that this was possible because in the late probing movements with delayed force feedback, participants changed the trajectory of their grip force modulation. They adjusted the trajectory such that the peak grip force slightly preceded peak load force, similarly to the slight lead of peak grip force before load force in the non-delayed elastic force fields. This observation was similar between the shoulder and wrist conditions as well as in the unconstrained joints condition of our experiment, and suggests that an accurate motor representation of delay was used to generate the appropriate grip force temporal profile. However, in contrast to this observation and consistently with previous studies (Nisky et al. 2010; Nisky et al. 2008), stiffness perception in the presence of
delay was biased, and the bias depended on the joint that was used for probing. These results provide further support to the previously suggested idea of the existence of two separate neural mechanisms underlying perception- and action-related computations (Flanagan and Beltzner 2000; Milner and Goodale 1995; Nisky et al. 2011; Pressman et al. 2008).

**Internal representation of stiffness and time delay**

Based on the results reported here, we propose that participants formed an internal representation of the environment, and that the representation relies on two key elements: time delay and stiffness. The perception of stiffness was used by participants in our task in two ways; (1) to generate accurate and efficient grip force, and (2) to provide the subjective judgment of the environment stiffness. While stiffness perception which is used to generate grip force is likely a process which participants were not aware of, the verbal stiffness judgment may be a result of a more cognitive process. To distinguish between these two processes, we refer to cognitive judgment of stiffness as stiffness *perception* and to stiffness estimation that is used to modulate grip force as stiffness internal *representation*.

Adjustment of grip force in accordance with elastic force field’s load force based on the field’s stiffness requires an internal representation of the stiffness. Using this internal representation, the grip force adjustment process may be a result of interaction between feed-forward and feedback control mechanisms. In such a view, the feed-forward mechanism is responsible for generating the grip force in accordance with a predicted load force, and the feedback mechanism is responsible for adjusting the internal representation of dynamic properties, such as the stiffness, based on the sensory input (Danion and Sarlegna 2007; Flanagan and Wing 1997). The sensory information includes position and force signals and requires integration between them to estimate stiffness (Dijkerman and de Haan 2007). Based on the temporal shift of the grip force during the repeated probing of the delayed force field, we argue that the feed-forward controller may use a representation of the delay in addition to stiffness representation to accurately adjust the grip force in both time and magnitude, allowing for the elimination of any bias in grip force magnitude adjustment in the late probing movements.

In contrast with the accurate internal representation that is used to generate the grip force, the perceptual bias indicates that perception is based on a computational mechanism that lacks information about time delay. The computational mechanism underlying the
perceptual bias due to delay is still debatable (Di Luca et al. 2011; Nisky et al. 2010; Nisky et al. 2008; Pressman et al. 2007). One of the suggested models claimed that the perceptual system combines two regression-based estimations (Nisky et al. 2010; Nisky et al. 2008). The first estimation is the slope of the regression of measured force as a function of controlled position, suggesting a relation to position control of probing movements. The second estimation is the inverse of the slope of the regression of measured position as a function of controlled force, suggesting a relation to force control of probing movements. According to this framework, during continuous contact with an elastic force field, i.e. not crossing its boundary, subjects are continuously experiencing smoothly varying forces causing them to try to regulate the hand position, and implement a position control strategy. Hence, a regression of force as a function of position successfully explained the perceptual underestimation due to delay (Nisky et al. 2008). In addition, this model suggests that when subjects use a distal joint (wrist) to interact with the elastic force field, they implement position based control since wrist motion is typically used in tasks that require position accuracy. However, when using a proximal joint (shoulder), force control is dominant, and causes a shift in perception towards overestimation (Nisky et al. 2010). For linear elastic force fields, both estimations yield the same result; however, in the case of delayed elastic force fields, the estimations are different, and can explain the difference in perceptual bias between the wrist and shoulder conditions in our experiment.

Other models were suggested in different studies of the effect of delay on perceived stiffness (Di Luca et al. 2011; Pressman et al. 2007). Importantly, none of the models suggested an explicit representation of the delay. If such delay representation was available, it could be used to re-align the position and force signals in order to obtain an accurate estimation of stiffness. The existence of the perceptual bias indicates that such representation was not available. In this study, we show that such representation of delay was formed, and was used for temporal adjustment of the grip force, but nevertheless, this representation was not used for perception.

While the temporal adjustment of grip force suggests a representation of the delay exists, it is still unknown how this representation is formed (Karniel 2011). One view suggests the existence of a neural clock that can directly count time (Miall et al. 1993; Wearden 1991). Others suggest that such clocks do not exist, and instead, the motor system represents time based on the flow of signals about the state of the motion of our body (Gavazzi et al. 2013; Karniel and Mussa-Ivaldi 2003; Lacquaniti et al. 2014; Levy et al. 2010). Such approximation
of time may be based on proprioceptive feedback such as position, velocity, or force, and one possible implementation is using discrepancies between anticipated and actual feedback of movement outcomes (Blakemore et al. 2001). One interesting suggestion by Sarlegna et al. (2010) claimed that the effect of delayed visual feedback of hand position during a tracking task can be represented by a mechanical system that link the proprioceptive and visual positions of the hand. While our current study cannot resolve the debate about which of the two representations is used, the accurate shift in grip force profile suggests that such representation is indeed formed.

Dissociation between perception and action

There is a long-going debate regarding the association or dissociation between perception and action (Bruno 2001; Ganel and Goodale 2014; 2003; Goodale and Keith Humphrey 1998; Goodale and Milner 1992). Studies examined the relationship between perceptual illusions and motor responses in grip force adjustment in the size-weight illusion (Flanagan and Beltzner 2000), in precision grip aperture preparation in the Ebbinghaus illusion (Aglioti et al. 1995; Haffenden et al. 2001), and during visually induced self-motion (Bringoux et al. 2012). It was suggested that there is a gap between perception and action (Bringoux et al. 2012; Dewar and Carey 2006; Flanagan and Beltzner 2000; Haffenden et al. 2001), but other studies claim against this hypothesis (Bruno 2001; de Grave et al. 2005; Franz et al. 2001; Franz et al. 2000; Smeets and Brenner 2006).

Common to these illusions is that they occur when there is an integration of proprioceptive and visual sensory inputs; namely, they are visuomotor illusions (Milner and Dyde 2003). This integration adds to the complexity of understanding the nature of the interaction, or the lack of it, between perception and action. Here, we chose a task of stiffness perception, and deprived the participants from any information except for the proprioceptive feedback that is used for both action and perception. By doing so, to the best of our knowledge, we provide for the first time a support for a dissociation between grip force adjustment and perception in a task that is based solely on proprioceptive feedback.

Our findings are consistent with the existence of two distinct estimations of stiffness that are used for grip force adjustment and perception. This suggests that two separate neural processes that are responsible for each of these two estimations, similarly to the view of separate processing streams in the visual system (Milner and Goodale 1995). Previous studies suggested separate, or partially separate, neural processing streams for action and
perception in the somatosensory system (Dijkerman and de Haan 2007; Sathian et al. 2011). If indeed such separation exists in our case, stiffness estimation with delay compensation, as we observed for grip force adjustment, may be processed in the dorsally directed pathways and areas within the Posterior Parietal Cortex (PPC) that are considered as specialized for grasping (Sathian et al. 2007) or in the motor cortex and premotor cortex (Coombes et al. 2010), while stiffness estimation that is responsible for the bias in perception may be processed in the insula or the PPC (Dijkerman and de Haan 2007) or involve the frontal cortex and anterior cingulate cortex (Vaillancourt et al. 2003). However, there are other views that oppose such separation claiming that the dual role of the PPC suggests common processing (Graf 2007; Travieso et al. 2007). Our study does not provide any evidence for where these two separate computations occur, but we speculate that two distinct functional pathways could be found within the brain that may be responsible for our findings of different effect of delay on perception and action. Future studies will be needed to provide more direct support to either one of these hypotheses.

A few issues remain to be clarified. First, while the effect of delay on perception without affecting grip force magnitude that we show here is clear, it still leaves the consistency of the separation between action and perception unresolved (de Grave et al. 2005). We showed the dissociation for a single constant delay, and it is still left to show a generalization of the effect for higher values of delay. This may be challenging, because the ability of users to represent significantly higher levels of delay is questionable, and may cause the compensation mechanism suggested here to fail. In such case we expect an increase of grip force magnitude to insure a firm grasp of the tool resulting in illusion effect in both action and perception (Pressman et al. 2008). Moreover, for delays that are larger than 100ms, the percept of an object may deteriorate completely (Pressman et al., 2007). Second, for objects other than elastic force fields, like viscous force fields, or nonlinear force position relationship, there might be situation where the illusion may affect solely the action and not perception (Nisky et al. 2011).

Third, it remains to be tested whether extensive interaction with the delayed force field can eliminate the biased perception of this type of force field. Here, we didn’t restrict the number of probing movements made by the participants during interaction with the force fields within a single trial. Forcing the participants to keep interacting with the force field pass the point of their voluntary decision making may provide more sensory information which can lead to a change in stiffness perception. Another possible option to extend the
exposure to delayed force fields is by prolonging the experiment by increasing the number of trials in the experiment. Based on previous studies, increasing the number of trials did not change the effect of delay on stiffness perception, and neither did repeating the experiment for three subsequent days (Nisky et al. 2010). To date the trigger for a decision making regarding the stiffness perception remains an open question (Kelly and O'Connell 2013), and further studies towards its resolution are critical before exploring how exposure to sensory inflow beyond that decision point may affect stiffness perception.

**Conclusions**

We studied the effect of force feedback delay on perception of stiffness and grip force modulation during tool-mediated probing of elastic force fields. We examined the grip force that participants apply on the stylus of a haptic device that they held in a precision grip during probing of virtual elastic force fields in a psychophysical test of stiffness discrimination. This allowed us to show a discrepancy between internal representations of the mechanical stiffness used for action and perception: we show that a delay in force feedback, such as in the case of teleoperation (Nisky et al. 2013), caused a bias in perception of stiffness, but did not change the modulation of grip force in accordance to load force when compared to probing of a linear elastic force fields without delay.

Our results suggest that a mechanism that forms an internal representation of the delay exists and that it is available for generating action but not for forming stiffness judgment. This implies minimal interaction, if any, between estimations of stiffness that are used in the adjustment of grip force and that are used in perception. Our results provide clear evidence for a functional dissociation between perception and action in the somatosensory system in a case where only proprioceptive feedback is available. In addition, this study provides evidence that some form of time delay representation (either explicit time or implicit state approximation) exists in the motor system, and that this representation is used for guiding actions but not for perception.

This study sheds light on the processes that underlie representation of mechanical properties of the environment around us during manual exploration, and the dissociation between these representations for perception and action. These processes are critical for basic understanding of the human sensorimotor system as well as for the design of efficient human-machine physical interaction devices for various applications such as teleoperation, haptic simulation, and robotic rehabilitation.
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Figures Captions

Figure 1: Experimental setup. A,B) A virtual reality system with a haptic device. The yellow square represents the horizontal position of the hand of the participant, and the green square represents a button for switching between the elastic force fields. In the constrained-joint conditions, participants pivoted their probing movement using either (A) the wrist or (B) the shoulder joints. C) Top view from above of the robot. The participant grasps a custom-made force-sensing fixture that was attached to the haptic device. D) Side view of the robot. White arrows represent direction of the force field. E) Schematics of the experimental protocol for the constrained-joints group. The participants performed two sessions of 180 comparisons between pairs of force fields. Participants performed the sessions in two consecutive days, and each session was performed with either the wrist or the shoulder joints pivoting the movement.

Figure 2: Examples of grip force and force trajectories during interaction with the linear elastic force fields. A) The upper panel depicts an example of force (solid blue) that was applied by a linear elastic force field with a stiffness level of 120 N/m, and the grip force (dashed green) of the participant during a single trial. Light blue shaded rectangles highlight the first and last probing movements. Bottom panel shows the tool position. In this example, the movements were pivoted around the wrist. B) The first and last probing movements of the trajectory in (A). The circle symbol indicates the time of probing movement start and the star symbol indicates the time of probing movement end. C) Grip force – load force trajectories of the first (orange full symbols) and last (blue empty symbols) probing movements of the example in (B). For both trajectories, we fitted linear regression lines from which we extracted the slope and intercept point. The red symbol ‘s’ represents the start of each trajectory. D) Similar to (C), but for two different elastic force field stiffness levels: 40 N/m (square markers solid line) and 130 N/m (triangle marker dashed line). While the trajectories are different in the initial probing, they become similar in the last probing regardless of the stiffness of the elastic force field.

Figure 3: Decrease in grip force magnitude during interaction with non-delayed elastic force fields. Mean intercept value (A) and slope value (B) in the first and last probing movements, averaged across stiffness levels and joint conditions. Color indicates probing movement: orange – first probing movement, and blue – last probing movement. Error bars represent the 95% confidence intervals that were calculated using t-distribution. The statistically
significant decrease in the value of the intercept between the two probing movements indicates a decrease in grip force magnitude.

Figure 4: Adjustment of grip force during interaction with linear springs. Each point represents a mean of the slopes (A,B) and intercepts (C,D) of the linear regression lines that were fitted to the grip force – load force trajectories from interactions with non-delayed elastic force fields with a given stiffness level. (A,C) Results from the shoulder condition, and (B,D) from the wrist condition of all the participants. The shaded area represents the 95% confidence intervals that were calculated using t-distribution. Colors and symbols indicate the probing movement: orange filled squares – first probing movement, and blue empty circles – last probing movement.

Figure 5: Perception of stiffness with and without force feedback delay. A) An example of psychometric curves of a typical participant: the probability to answer that the comparison force field had higher level of stiffness as a function of the difference between the stiffness levels of the comparison and the standard force fields. Dashed lines represent the trials with delayed force feedback, and solid lines represent the non-delayed standard force fields. The estimated PSE values and their 95% confidence intervals are represented by horizontal lines at probability of 0.5. B) PSE averaged across participants. Delay caused underestimation of the stiffness of the standard elastic force field, as indicated by a negative PSE in both the wrist and the shoulder joints. This effect is stronger in the wrist condition compared to the shoulder condition. C) JND averaged across participants. There were no statistically significant effects of delay or joint on subjects' stiffness discrimination sensitivity. Bars are means and error bars are 95% confidence intervals calculated using the t-distribution.

Figure 6: Comparison of movement kinematics during the shoulder session (‘s’) and wrist session (‘w’) between the delayed and non-delayed standard force fields. There were no statistically significant differences in any of the tested movement metrics between the probing movements in the delayed and the non-delayed force fields. Bars represent estimated means, and error bars are 95% confidence intervals estimated using t-distribution.

Figure 7: Examples of grip force and load force trajectories during interaction with an elastic force field with a delayed force feedback. All the notations are similar to Fig. 2B. A) Light blue shaded rectangles represent the temporal difference between peak displacement and peak force. The peak grip force shifted between the first and last probing movements, as can be seen by its position relative to these rectangles. B) In the first probing movement, the
trajectory ellipse is much wider because the grip force leads the force by additional 50ms. This temporal lead is decreased in the last probing movement, and the trajectory becomes similar to the non-delayed case (compare with Fig. 2 C-D).

Figure 8: Adjustment of grip force during interaction with elastic force fields under delayed force feedback. A) Each bar represents the mean slope value calculated using linear regression fitted to the grip force – load force trajectory. Error bars represent 95% confidence intervals calculated using t-distribution. Colors and pattern represent the probing movement and joints, respectively: orange – first probing movement, blue – last probing movement. Clear bars – shoulder movements, and pattern-filled bars – wrist movements. B) Same notation as in (A) but for the intercept of the regression line.

Figure 9: Analysis of the time lag between grip force and load force. Mean lag between the grip force and load force during the first probing (orange bars) and last probing movements (blue bars) of the three types of force fields that the participants interacted with in our experiment, comparison (non-delayed with various stiffness levels), non-delayed standard, and delayed standard. The joint is indicated by bar pattern: pattern-filled bars for the wrist and clear bars for the shoulder. Delayed force feedback causes a shift in the lag between grip force and force in the first movements, but the correct lag is restored in the last probing movements. Error bars represent 95% confidence intervals that were calculated using t-distribution.

Figure 10: Analysis of grip force magnitude, stiffness perception, and time lag between grip force and load force for unconstrained joints condition. (A) Mean intercept value and (B) slope value, averaged across stiffness levels. Between first and last probing movement, the intercept decreased while the slope remained the same suggesting that the grip force magnitude decreased during the course of interaction with non-delayed elastic force fields. Mean slope value (C) and intercept value (D) calculated from the grip force – load force trajectories in the delayed and the non-delayed standard force fields. E) PSE averaged across participants. Similar to the constrained joint condition, delay caused underestimation of the stiffness of the standard elastic force field. F) JND averaged across participants. G) Comparison of kinematic metrics between the delayed (pattern-filled bars) and non-delayed (clear bars) standard fields. All movement metrics were similar between the two force fields. H) Mean lag between the grip force and load force during the first probing (orange bars) and last probing movements (blue bars). In all panels error bars are 95% confidence intervals estimated using t-distribution.
References


de Grave DD, Biegstraaten M, Smeets JB, and Brenner E. Effects of the Ebbinghaus figure on grasping are not only due to misjudged size. *Experimental Brain Research* 163: 58-64, 2005.


Figure 1

A) (Image of a person using a device)

B) (Image of a person demonstrating something)

C) (Image of a close-up of a hand holding a device)

D) (Image of a hand and a device with arrows indicating motion)

E) 

- **Wrist/Shoulder**
  - Trial 1:
    - 85
    - Δt=0
    - 50
  - Trial 2:
    - 85
    - Δt=50
    - 120
  - Trial 180:
    - 90
    - Δt=50

- **Shoulder/Wrist**
  - Trial 1:
    - 85
    - Δt=0
    - 50
  - Trial 2:
    - 85
    - Δt=50
    - 120
  - Trial 180:
    - 90
    - Δt=50

Rotation: First Day → Night Sleep
Figure 2

A) 

B) 

C) 

D)
Figure 3

A) 

![Bar chart showing intercept [N] for first and last probing movements with p = 0.046.]

B) 

![Bar chart showing slope [au] for first and last probing movements with p = 0.59.]

probing movement
Figure 4

A) Shoulder

B) Wrist

C)

D)
Figure 5

A) Probability to answer comparison

B) PSE [N/m]

C) JND [N/m]
Figure 6

mean movement period [sec]  
mean movement amplitude [m]  
mean absolute peak velocity [m/sec]  
mean ARD [cm²]  

non-delay  
delay
Figure 7

A) 

B)
A)

B)

Figure 8

A) Slope $[au]$ vs. delay: 
- First movement - shoulder
- First movement - wrist
- Last movement - shoulder
- Last movement - wrist

B) Intercept $[N]$ vs. delay: 
- First movement - shoulder
- First movement - wrist
- Last movement - shoulder
- Last movement - wrist

$p=0.118$

$p=0.092$
Figure 9

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**Comparison of Standard and Non-Delayed Conditions**

- **Grip Force-Load Force Lag [ms]**
  - Comparison
  - Standard non-delayed
  - Standard delay

- **First Movement**
  - Shoulder
  - Wrist

- **Last Movement**
  - Shoulder
  - Wrist

*** - p<.001

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Figure 10

A) Probing movement intercept and slope for first and last movements with p-values of 0.015 and 0.21, respectively.

B) Probing movement slope for non-delay and delay conditions with a p-value of 0.143.

C) Intercepts and slopes for non-delay and delay conditions with a p-value of 0.86.

D) Intercepts for first and last movements with a p-value of 0.015.

E) PSE [N/m] for Δt=0 and Δt=50 conditions.

F) JND [N/m] for Δt=0 and Δt=50 conditions.

G) Mean movement period, amplitude, absolute peak velocity, and mean ARD for non-delay and delay conditions.

H) Grip force-load force lag comparison for first and last movements with *** p<.001.