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Effects of Stimulus Exploration Length and Time on the Integration of Information in Haptic Softness Discrimination

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Abstract— In haptic perception information is often sampled serially (e.g. a stimulus is repeatedly indented to estimate its softness), requiring that sensory information is retained and integrated over time. Hence, integration of sequential information is likely affected by memory. Particularly, when two sequentially explored stimuli are compared, integration of information on the second stimulus might be determined by the fading representation of the first stimulus. We investigated how the exploration length of the first stimulus and a temporal delay affect contributions of sequentially gathered estimates of the second stimulus in haptic softness discrimination. Participants subsequently explored two silicon rubber stimuli by indenting the first stimulus 1 or 5 times and the second stimulus always 3 times. In an additional experiment we introduced a 5s delay after the first stimulus was indented 5 times. We show that the longer the first stimulus is explored, the more estimates of the second stimulus' softness contribute to the discrimination of the two stimuli, independent of the delay. This suggests that the exploration length of the first stimulus influences the strength of its representation, persisting at least for 5s, and determines how much information about the second stimulus is exploited for the comparison.

Index Terms— Human perception, stiffness, serial integration, sequential integration.

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1 INTRODUCTION

IN haptic perception information is usually acquired by sequentially executed stereotypical exploratory movements (*exploratory procedures* [1]). For instance, to perceive softness people usually repeatedly indent the object with one finger or squeeze it between the fingers, progressively gathering relevant sensory information. The sequential nature of haptic exploration thus requires that sensory information is retained and integrated over time.

Studies involving delayed stimulus recall or a delayed comparison task, showed that humans can preserve tactile information (e.g. location of a tactile stimulus on the forearm or vibrotactile frequency) in memory over prolonged delays (up to 30 s, e.g. [2] [3] [4]). However, performance of participants declines with an increasing delay, indicating the fading of the memory representation of the (first) stimulus. Noteworthy, performance decays rapidly in the first 5s and slowly afterwards, hinting to a two-stage memory process [4]. It is known that while repetition of a stimulus (e.g. letters) improves memory performance [5], presentation of an interfering (visual) stimulus (*masking*) during the delay decreases discrimination performance. Interference is mostly effective if the masking stimulus is applied early in the delay, supporting the idea of the two-stage memory process [6]. Interference seems to be feature selective, since the delayed discrimination of a stimulus feature (e.g. spatial frequency of a Gabor) is decreased by a masking stimulus if it differes in this feature from the test stimulus, independent of changes in an other feature (e.g. the orientation of the Gabor) [7]. These results indicate that processing and retention of sensory information is likely based on the same specialized (feature selective) mechanisms. These findings are supported by collective evidence from physiology studies that neural substrates devoted to the storage of sensory information are likely the same ones involved in the processing of the same information [8]. For tactile perception physiological studies show that neurons in the primate primary (SI, [9]) and secondary somatosensory cortex (SII, [10] [11] [12] [13] [14]) that respond to haptic (objects, SI) or tactile (vibration, SII) stimuli continue firing during the delay period after stimulus presentation and before the presentation of a comparison stimulus. In humans contralateral transcranial magnetic stimulation (TMS) on SI early during the delay increases discrimination thresholds in delayed comparison of two vibrotactile stimuli, whereas TMS later does not affect performance [15]. Taken together, the retention of sensory information seems to be based on the activity of specialized neurons that are also involved in the processing of this information. Evidence suggests a two-stage memory process, including an initial short-lived vulnerable encoding of information followed by a recoding to a more robust representation [8].

The question arises how the information gathered and retained over time during haptic exploration is integrated. Several studies show that the reliability of haptic percepts of various object properties increases with additional sensory information obtained from prolonged explorations [16][17][18][19][20][21], indicating that humans benefit from additional sensory information by integrating the information over time. The integration of sensory information within a single haptic exploration (e.g. indentation of a virtual spring) was modeled as averaging [22]

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or regression [23] on the base of the entire available sensory information (e.g. force and displacement values) [22] [23]. However, DiLuca et al. (2011) [22] also showed that not all information contributes equally to the percept: Within a single exploration of virtual stiffness the more reliable information gathered during the loading phase of the indentation contributes more to the overall percept. This finding is in agreement with the statistically optimal integration model (maximum likelihood estimation, MLE, [24]), in which the n available signals s_i are weighted by their relative reliabilities r_i (defined as the inverse of variance $r_i = 1/\sigma_i^2$) and averaged:

$$\hat{S} = \sum_{i=1}^{n} w_i s_i, \text{with } w_i = \frac{\sigma_i^{-2}}{\sum_{i=1}^{n} \sigma_i^{-2}},\ w_i \geq 0 \text{ and} \sum_{i=1}^{n} w_i = 1 \quad (1)$$

The MLE model is a special case of Bayesian inference: Linear combination of available information (including apriori information) weighted by its reliability [25]. This kind of integration is considered to be statistically optimal because it maximizes the reliability of the combined estimate. In the MLE-based model of DiLuca et al. (2011), only two estimates gathered during the loading and unloading phase of the indentation were considered. In a more recent study information integration within one indentation of a virtual spring was modeled as a recursive Bayesian updating model, in which the information from previous time points is continuously integrated with new incoming information [26]. Thus, integration of information available from a single exploratory movement seems to be in agreement with models of statistically optimal integration.

The question remains how sequentially derived estimates from several exploratory movements are integrated, especially because this integration spans over longer time. Lezkan & Drewing (2014) [16] showed that sequentially derived estimates of the frequency of virtual gratings contribute unequally to the overall percept. For estimates of a constant stimulus' quality derived with the same sense the MLE model predicts equal weights, due to equal estimates' reliability (1). In a recent study [17] we extended the investigations of Lezkan & Drewing (2014) [16] to the haptic perception of softness. Further we proposed that the inequality of the weights might be related to memory effects: The task required to compare the softness of two sequentially explored stimuli, i.e. to remember the softness of the first stimulus, and to compare this memory representation to the softness of the second stimulus. In fact, we found that the weights of the estimates from the first stimulus were rather equal, whereas weights of the estimates from the second stimulus decreased with progressing exploration of the second stimulus. The decreased contribution of the estimates from the latter exploratory movements on the second stimulus might be due to the progressively fading representation of the fist stimulus. In line with this idea, we found a steeper decrease of weights in the exploration of the second stimulus for shorter explorations (two indentations) as compared to longer ones (five indentations), suggesting that a longer exploration of the first stimulus allows to exploit more information about the second stimulus to discriminate the two stimuli. However, data from [17] do not prove the latter speculation, because in [17] the exploration length of the first stimulus was not independently varied, but the first and the second stimuli were always explored with equal number of indentations. These results indicate that unlike information integration available from a single exploratory movement, information available from several exploratory movements seems to not follow models of optimal integration but might be affected by memory limitations. Specifically, in a discrimination of two stimuli, the contribution of sequential estimates in the exploration of the second stimulus might be determined by the fading memory representation of the first stimulus.

In the present study we investigated which memory effects might affect the integration of information in haptic softness perception. Softness is a psychological correlate of compliance, which is defined as the ratio between the displacement of an object's surface and the associated force applied to this object (it is measured in mm/ N). To perceive softness people usually repeatedly apply the *exploratory procedure* of *pressure* [27], which is associated with the indentation of the object with the finger or squeezing it between the fingers. Such exploratory movements generate relevant sensory information about softness. The sources of information include kinesthetic and cutaneous cues. Kinesthetic cues to softness include the information about the displacement of the finger during the indentation of the stimulus (muscle spindle) and the force applied to the object (Golgi tendon organ). The cutaneous cues likely carry the information about the local contact with the object, the deformation of its surface and the pressure on the skin. Srinivasan and LaMotte (1995) [28] and Bergmann Tiest & Kappers (2009) [29] showed that precision in softness discrimination is highest when cutaneous cues are available. However, softness can also be discriminated if only the information about the force/ displacement ratio is available (i.e. exploration with a tool [30]). Bicchi et al. (2005) [31] showed that rendering the information about the change in contact area when objects are indented improves softness discrimination as compared to the case when only the force/ displacement information is available.

In our experiments participants subsequently explored two silicon rubber stimuli using their bare index finger and decided which one felt softer. A movement segment was defined as a single indentation of a stimulus consisting of a force increase and a subsequent force decrease by which the finger moved into and then out of the stimulus. We assumed that each movement segment is the base of an indentation-specific estimate. To assess the contribution of these estimates to the overall percept we manipulated perceived softness during single indentations by applying subtle external forces to the exploring finger of the participant. Previously we showed that external forces (calculated as a fixed fraction α of the force applied by the participant) that pushed the index finger into the stimulus resulted in a softer percept and forces that pulled the finger out of the stimulus, resulted in a harder percept of the same stimulus [32]. Perceived softness changed proportional to α.

We hypothesized that in a comparison of two softness stimuli the contribution of the estimates about the second stimulus softness would be affected by two factors: 1. the strength of the first stimulus' representation and 2. the delay between the explorations of the two stimuli. We hypothesized that the representation of the first stimulus is the weaker the shorter that stimulus has been explored. A weak representation fades quickly during the exploration of the second stimulus. In contrast, after a longer exploration, the representation of the first stimulus should be stronger, fade slowly and can be still reliably compared to later estimates from the second stimulus. Further, we hypothesized that the representation of the first stimulus might decay over time.

In Experiment 1 we tested the effect of the exploration length of the first stimulus on the indentation-specific weights in the exploration of the second stimulus. We therefore systematically varied the length of the exploration of the first stimulus by letting participants explore it either with one or five subsequent indentations. The length of the exploration of the second stimulus was kept constant: It was always indented three times. For the short exploration of the first stimulus, we expected the weights to rapidly decrease. In the extreme case only the estimate from the first indentation of the second stimulus can be reliably compared with the representation of the first stimulus and thus only the first indentation receives a non-zero weight. In contrast after the long exploration, the representation of the first stimulus should persist longer and it should be possible to reliably compare estimates from later indentations of the second stimulus to this representation - resulting in less decrease of weights for later estimates. Because weights sum up to 1 and are predicted to decrease more steeply after short as compared to long exploration, we also expected that the first indentation-specific weight should be higher, but the second and third indentation-specific weights should be lower after short as compared to long exploration.

In Experiment 2 we investigated how the memory representation of the first stimulus is affected by time. To do so, we introduced a delay after the exploration of the first stimulus. We supposed that the effect of memory decay would be more pronounced given a strong representation of the first stimulus, thus we applied the delay only after the exploration with five indentations. In fact, given that for the exploration of the first stimulus with one indentation, in Experiment 1 we found that only the first indentation of the second stimulus contributes to the overall percept, potential effects of the decay on the subsequent indentation-specific weights would be very hard to detect. In Experiment 2, we repeated the two conditions of Experiment 1 (short vs. long exploration of the first stimulus) and added a new condition in which participants explored the first stimulus using five indentations, then waited for five seconds and explored the second stimulus by indenting it three times. We compared the obtained weights of estimates in the exploration of the second stimulus to the weights measured in the other two condtions (whithout a specific delay). In case the representation of the first stimulus decays over the time of the five seconds delay, we expected to find a difference to the weights in the five-indentation condition, approaching a pattern of weights that is more similar to the condition in which the first stimulus was explored with one indentation only.

This work is an extension of [33], and includes a larger participant sample for Experiment 1, testing the influence of the exploration length of the first stimulus on the decrease of weights in the exploration of the second stimulus. Further we added an additional experiment (Experiment 2) addressing the influence of time on the memory representation of the first stimulus.

2 EXPERIMENT 1: EFFECT OF STIMULUS EXPLORATION LENGTH

2.1 Methods

Participants. 16 students (naïve to the purpose of the experiment, 7 females, 20 to 29 years old, average age 23.63 years) volunteered to participate in the experiment. Participants were reimbursed for their participation (8€/ h). They were all right-handed and did not report any sensory or motor impairment at the right hand. The study was approved by the local ethics committee LEK FB06 at Giessen University and was in line with the declaration of Helsinki from 2008. Written informed consent was obtained from each participant.

Apparatus and Setup. The experimental setup (visuo-haptic workbench, Figure 1) comprised a PHANToM 1.5A haptic force feedback device (finger position measurement and force transmission), a 22"-computer screen (120 Hz, 1280x1024 pixel), a force sensor (measuring beam LCB 130 and measuring amplifier GSV-2AS, resolution 0.05 N, temporal resolution 682 Hz), a mirror, stereo glasses and headphones. The silicon rubber stimuli were placed on the force sensor in front of the participant. The mirror prevented direct view of the stimuli and the participant's hand. Instead participants viewed (40 cm viewing distance, fixated by a chin rest) via stereo glasses a virtual 3D representation of the real scene (finger and stimuli). Importantly, the visual representation of the finger (sphere of 8 mm diameter) was hidden during the exploration of the stimuli (force > 0.1 N), so that no visual information of the indentation of the stimuli was available. The virtual scene was displayed on the screen and reflected by the mirror, inclined to spatially align the virtual and the real scenes. The participant's index finger was connected to the PHANToM with a custom-made gimbal-like adapter as described in [32] allowing relatively free exploration of the silicon rubber stimuli with the bare finger pad (only rotation around the x-axis was blocked) and simultaneous transmission of external forces by the PHANToM. White noise played via headphones covered sounds of the PHANToM engines when transmitting external forces. Custom-made software controlled the experiment, collected responses and recorded relevant parameters (finger position and force) every 3 ms.

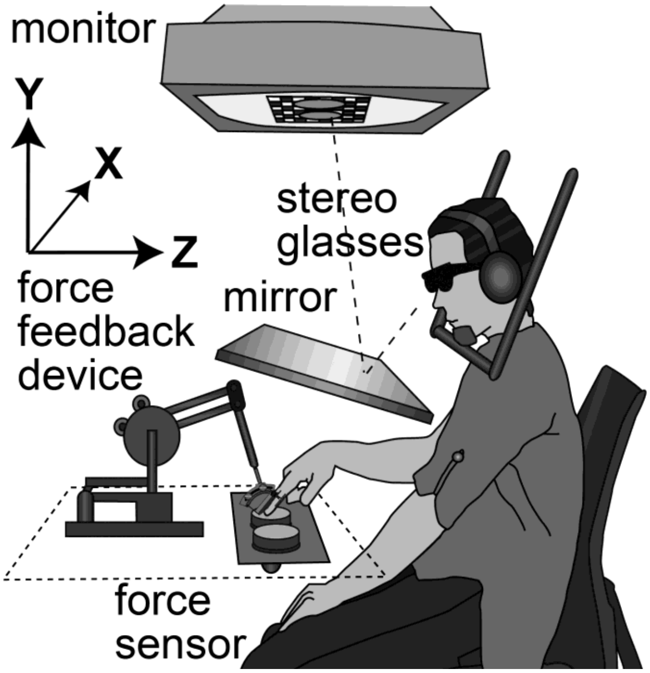

Fig. 1. Visuo-haptic workbench.

External forces were transmitted vertically to the index finger of the participant. We used downwards and upwards directed forces which either pushed the finger into or pulled it out of the rubber stimulus. The amount of external force was a fixed fraction α of ±0.16 of the force participants applied themselves. For more detail on the force manipulation see [32]. External forces were applied only during one of the indentations of the second stimulus. The algorithm to detect and count the indentations is described in detail in [17].

Softness Stimuli. We used a two-component silicon rubber solution (Alpa Sil EH 10:1) to create silicon rubber stimuli. To obtain different compliances we varied the amount of a diluent (silicone oil, viscosity 50 mPa· s) which was added to the silicon. The silicon and oil mixtures were poured in cylindrical plastic dishes (75 mm diameter, 38 mm height). After the stimuli cured we measured the compliance using our experimental setup but exchanging the adapter by a flat–ended cylindrical probe of 1 cm2 area (‘standard finger’). The probe was manually pressed into the stimulus 5 times exceeding a force of 15 N. Compliance was determined as the slope in the linear function fitted to the force-displacement traces in the range of 0-9 N. For more details on the compliance measurement see [34]. For this study only data from the increase of force (pressing into the stimulus) was analyzed to exclude hysteresis effects.

We created a series of 12 stimuli consisting of one standard stimulus and 11 comparison stimuli. The comparison stimuli spanned a range of 2.5 Weber fractions to each side (lower and higher compliance) around the standard stimulus. The value for the Weber fraction in softness perception of 20% is taken from [34]. Two neighboring comparison stimuli differed by 1/ 2 Weber fraction (0.03 mm/ N). The compliance of the standard was 0.32 mm/ N, for the comparisons it was 0.16, 0.19, 0.23, 0.26, 0.29, 0.32, 0.36, 0.39, 0.43, 0.46 and 0.49 mm/ N.

Design and Procedure. The experimental design comprised two within-participant variables: *Exploration length of the first stimulus* (1 indentation vs. 5 indentations) and *Indentation No. on the second stimulus* (external force applied in the 1st, 2nd or 3rd indentation) resulting in 6 experimental conditions. For each *Exploration length of the first stimulus* condition we had a baseline condition in which no external forces were transmitted during the exploration of the second stimulus. For every participant and experimental condition, we measured the PSEs of the standard stimulus manipulated with pulling and pushing forces as compared to non-manipulated comparison stimuli, using a two-interval forced-choice task (2IFC) combined with 1-Up-1-Down staircases. A 2IFC task is a commonly used psychophysical method to measure the subjective experience of a certain stimulus (standard). It consists of two sequential intervals in which participants are presented with two alternative stimuli (standard and comparison) between which they have to choose according to the task instruction. When combined with a staircase, the values of the comparison stimuli are adaptively varied depending on the responses of the participant. The 1-Up-1-Down staircase determines the stimulus level at which the standard is chosen 50% of times (PSE). The *Exploration length of the first stimulus* conditions were presented during two different sessions. The order of the sessions was balanced.

In every trial participants explored first the comparison stimulus and afterwards the standard stimulus and decided which one felt softer. The beginning of a trial was indicated by a signal tone and the appearance of the comparison stimulus on the screen. The position (left vs. right) was randomly chosen. Participants explored the comparison stimulus by indenting it 1 or 5 times with the index finger of their dominant hand. After participants had completed the exploration of the comparison stimulus the standard stimulus was displayed on the screen and was explored by indenting it 3 times. Subsequently participants indicated which stimulus felt softer by tapping one of the two virtual decision buttons located above the stimuli. Between trials the stimuli were changed manually by the experimenter. Meanwhile participants moved their index finger to the indicated corner of the workspace. Participants did not receive any feedback on their performance. The number of indentations allowed to explore the first stimulus (comparison, 1x or 5x) and the second stimulus (standard, 3x) was instructed before the experimental session. Trials in which the number of indentations was incorrect were repeated later in a block.

Every PSE was measured using two staircases. One staircase started with the softest comparison stimulus (downwards-directed staircase) and the other with the hardest comparison (upwards-directed staircase). The next comparison stimulus in the staircase was determined by the response of the participant. If the comparison felt softer than the standard, a harder comparison was pre-

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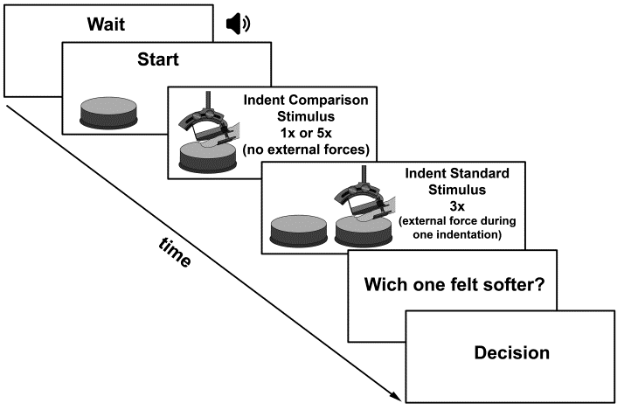

Fig. 2. Experimental procedure. Each trial started with the participants waiting for the experimenter to change the stimuli. When the schematic representation of the comparison stimulus appeared on the screen and participants heard a signal tone they started the exploration of the comparison stimulus. After the comparison stimulus was explored, the schematic representation of the standard stimulus appeared on the screen. Having explored both stimuli participants indicated their decision and moved the finger back to the waiting position. The position of the standard and the comparison stimulus (left vs. right) was randomized.

sented in the next trial of this staircase. In the opposite case the comparison of the next trial was softer. In the cases the softest comparison felt harder or the hardest comparison felt softer to the participants the same stimulus was presented in the corresponding next trial. Each staircase terminated after participants changed the direction in this staircase 15 times by changing their judgment from harder to softer and vice versa.

The experiment consisted of two sessions each of an average duration of 2.7 h, completed on two separate days within one week. Every session was split in blocks in which the current step of each staircase was presented in a randomized order, balancing the effects of fatigue or inattention between conditions. Sessions were interspersed with 1 minute pauses about every 15 min (not in phase with the change of the blocks).

Data Analysis. The PSEs were estimated as the median over all comparisons at which a reversal occurred (30 per PSE). To test whether the manipulation of perceived softness was successful we performed separately for each of the three conditions (*1 ind.*, *5 inds.*) a one-way repeated measures ANOVA on the PSEs with the within-subject factor *Fraction of external force* (-0.16,0,+0.16). To do so, we averaged over the *Indentation No. on the second stimulus* conditions.

Further we tested whether there was an overall shift in PSEs due to different conditions (*1 ind.*, *5 inds.*). For this purpose, we compared the baseline PSEs to each other and to the physical compliance of the standard (0.32 mm/ N) using paired and one-sample t-tests respectively.

We calculated indentation-specific weights for every participant and every condition from the PSEs. We had previously shown that external forces applied as a fraction of participants' force α during the whole exploration of a stimulus shifted perceived softness ($\hat{c}_m$) proportionally to α as compared to perceived softness without external force ($\hat{c}_0$) [17][32]:

$$\hat{c}_m = b\alpha\hat{c}_0 + \hat{c}_0 \qquad (2)$$

with $b = 0.26$ [17][32][1] being the extent to which the force manipulation is translated into a change in perceived softness. Accordingly, if external force is only applied during a single indentation i, the extent to which softness perception is shifted by α is given by b and the weight w_i of this indentation, with w_i being an additional multiplication factor in (2). Thus, to calculate the indentation-specific weights we first performed a linear regression of the relative PSE change ($\frac{\hat{c}_m - \hat{c}_0}{\hat{c}_0}$) on the fraction of external force α [-0.16, 0, +0.16] and divided then the slope obtained in the regression function by b.

We further analyzed whether the exploration length of the first stimulus affects the indentation-specific weights in the exploration of the second stimulus. To do so, we conducted a limited number of planned comparisons to test our directional hypotheses on weights, by means of t-tests. To compare the decrease of the weights between neighbored indentations after short versus long exploration, we compared the slopes between the first two and last two weights. Because we expected for the first two indentations a steeper decrease after short exploration, this t-test was conducted one-sided.

Further we tested our indentation-wise hypotheses on the differences between weights in the two *Exploration length of the first stimulus* conditions by indentation-wise one-sided t-tests and. Finally, to determine which estimates contributed to the estimation of the second stimulus softness, we tested each single weight in each of the two *Exploration length of the first stimulus* conditions against zero using one-sided t-tests. As a sanity check we calculated for each participant the sum of the within-stimulus weights for the second stimulus and tested the averages with a t-test against the predicted sum of weights of 1 (1).

2.1 Results

The PSEs with pulling, pushing and no forces are plotted in Figure 3 as a function of the indentation No. on the second stimulus separately for the two *Exploration length of the first stimulus* conditions. Overall pushing forces resulted in a PSE shift to higher values, indicating that the standard was perceived softer in this case, whereas pulling forces caused a PSE shift to lower values, indicating a harder percept of the standard. Separate repeated measures ANOVA on the PSEs (averaged over *Indentation*

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[1] In [32] we reported for the factor b 0.23 for rather hard stimuli (0.32 mm/ N) and 0.29 for rather soft stimuli (0.67mm/ N). Reanalyzing this data in [17] revealed that there was no significant difference between the factors for the different compliances of the stimuli, so that we use the average of the two values in this paper. In [17] factor b (termed there w_f) is reported to be 0.3. The slight deviation is due to the fact that in [17] the factor was determined on the base of PSEs which were determined with psychometric functions whereas in [32] and here the PSEs are determined from reversals in a 1-Up-1-Down staircase.

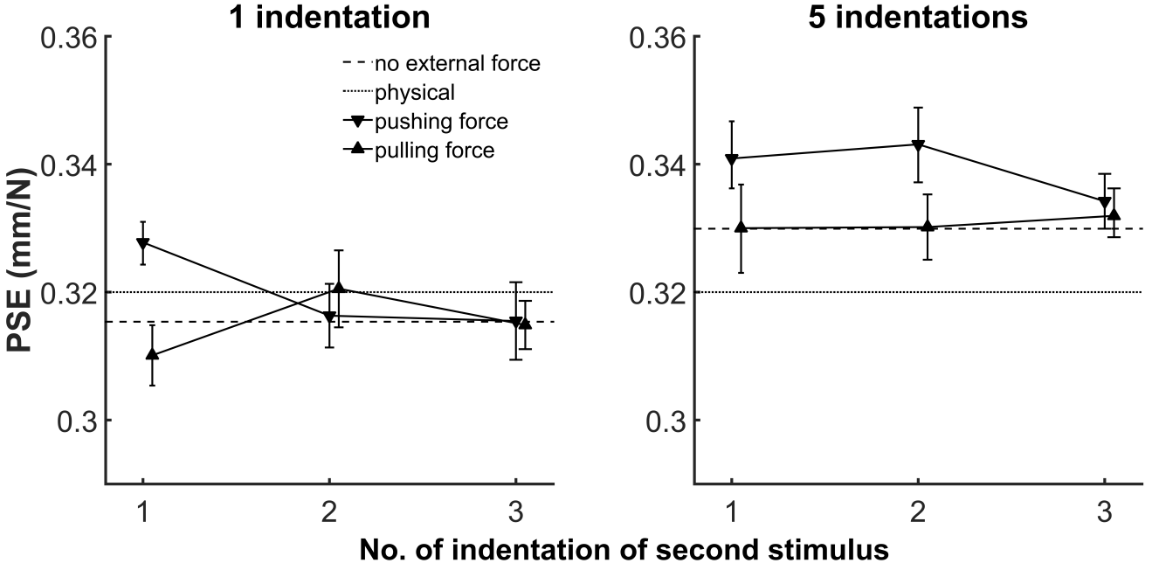

Fig. 3. Experiment 1. Average PSEs with pulling and pushing forces (downwards and upward pointing triangles, respectively) are plotted separately for the two *Exploration lenght of the first stimulus* conditions (1 and 5 indentations) as a function of the indentation No. on the second stimulus. Error bars represent 68% bootstrapped confidence intervals. The average PSEs in the condition without external forces are plotted as a dashed line. For both conditions the physical value of the standard is indicated by a dotted line.

No. on the second stimulus conditions) revealed a significant main effect of *Fraction of external force* in the *5 inds.* condition: *F*(2,30) = 3.86, *p* = .032, confirming that the manipulation of perceived softness was (as expected) successful. The main effect of *Fraction of external force* in the *1 ind.* condtion did not reach significance level *F*(2,30) = 1.29, *p* = .289. However, this does not necessarily indicate that the manipulation was generally not successfull in this condition, but it might indicate that the manipulation failed to reveal the contribution of some of the indentations in this condition, which was very small.

There was a general offset in the PSEs after the first stimulus was explored 5 times, indicating that the second stimulus was perceived differently after long as compared to short exploration of the first stimulus. Though, the baseline PSEs did not differ significantly between *Exploration length of the first stimulus* conditions, there was a trend, *t*(15) = -2.006, *p* = 0.063. When comparing the baseline PSEs to the physical compliance of the standard (0.32 mm/ N) we only found a significant positive deviation in the *5 inds.* condition (*t*(15) = 2.362*, p* = 0.032), indicating that only with the longer exploration the perception of the standard was changed (shifted to a softer percept).

Before the analysis of the weights we tested whether the assumption that they sum to 1 (1) holds. For none of the conditions, the sums of indentation-specific weights differed significantly from 1, as should be the case (all *p*s > 0.05).

In Figure 5(A) the weights of the estimates gathered from indentations on the second stimulus are plotted as a function of the indentation number on the second stimulus. During the first two indentations, the weights decreased steeper after a short exploration as compared to a longer exploration of the first stimulus, *t*(15) = 2.113, *p* = 0.026 (average slope *1 ind.*: -0.845; *5 inds.*: -0.063). The decrease of weights between the 2nd and the 3rd indentation was shallower in the *1 ind.* condition (average slope 0.159) than in the *5 inds.* condition (average slope -0.388). However, the decrease of weights during the last two indentations was not significantly different betwen conditions, *t*(15) = 1.278, *p* = 0.110. The indentation-wise comparisons of the weights between the *Exploration length of the first stimulus* conditions revealed the predicted significant difference for the 2nd indentation, *t*(15) = -2.154, *p* = 0.024. However, predicted differences for the 1st and the 3d indentations were not significant (1st indentation, *t*(15) = 0.822, *p* = 0.212; 3rd indentation, *t*(15) = -0.332, *p* = 0.372).

Finally, we conducted *t*-tests of the single weights against zero (one-sided): When the first stimulus was explored with one indentation, only the weight of the first estimate was significantly larger than zero, *t*(15) = 3.003, *p* = 0.004 (2nd indentation: *t*(15) = -0.817, *p* = 0.787; 3rd indentation *t*(15) = 0.041, *p* = 0.484). In contrast when the first stimulus was indented five times the weight of the 2nd estimate was significantly larger than zero, *t*(15) = 3.003, *p* = 0.004, at the edge of significance for the 1st indentation, *t*(15) = 1.390, *p* = 0.092 and not significant for the 3rd indentation, *t*(15) = 0.414, *p* = 0.343.

3.3 Discussion Experiment 1

We found that different exploration lengths of the first stimulus resulted in differently steep decrease in weights in the exploration of the second stimulus: more rapidly with a short exploration of the first stimulus (1 indentation) than with the longer one (5 indentations). With a short exploration only the first estimate contributed to the estimation of the second stimulus's softness, whereas with a longer exploration the first two estimates had weights larger than zero. In line, we found that after a long exploration of the first stimulus the estimate from the second indentation of the second stimulus was

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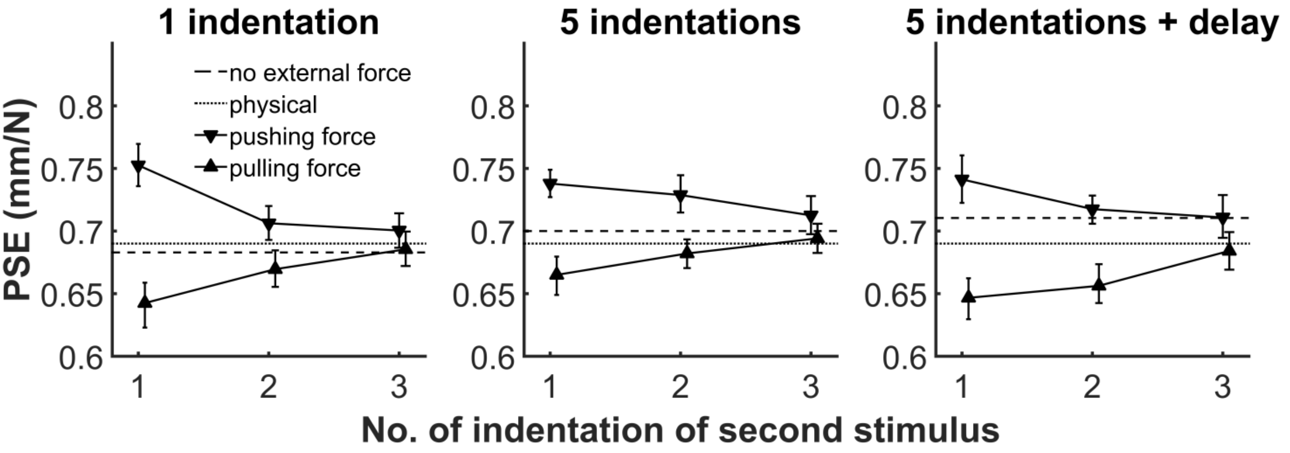

Fig. 4. Experiment 2. Average PSEs with pulling and pushing forces (downwards and upward pointing triangles, respectively) are plotted separately for the three *Exploration of the first stimulus* conditions (1 and 5 indentations without delay and 5 indentations with delay) as a function of the indentation No. on the second stimulus. Error bars represent 68% bootstrapped confidence intervals. The average PSEs in the condition without external forces are plotted as a dashed line. For all conditions the physical value of the standard is indicated by a dotted line.

weighted significantly higher than after the shorter exploration of the first stimulus. This suggests that a longer exploration of the first stimulus resulted in a longer-lasting representation of this stimulus, so that it could be reliably compared to the second estimate of the second stimulus' softness. Still the decay of the representation of the first stimulus limits the possibility to reliably compare it with the second stimulus. Our results are in agreement with the findings that repeated stimuli are better remembered [5] and discrimination thresholds decrease with the prolongation of the exploration [16] [17] [18] [19] [20] [21]. Furthermore, our results elucidate that the longer exploration of the first stimulus allows the inclusion of more information about the second stimulus.

3 EXPERIMENT 2: EFFECT OF TIME

3.1 Methods

Participants. 12 students (naïve to the purpose of the experiment, 9 females, 19 to 34 years old, average age 24.33 years) volunteered to participate in the experiment. Participants were reimbursed for their participation (8€/ h). They were all but one right-handed and did not report any sensory or motor impairment at the dominant hand.

Stimuli. The stimuli of Experiment 2 were produced and measured as described in Experiment 1; but we used more compliant stimuli. The compliance of the standard was 0.69 mm/ N and for the comparisons it was 0.39, 0.47, 0.55, 0.56, 0.64, 0.71, 0.72, 0.77, 0.85, 0.92, and 0.98 mm/ N.

Design and Procedure. The experimental procedure was the same as in Experiment 1. Experiment 2 also comprised two within-participant variables: *Exploration of the first stimulus* and *Indentation No. on the second stimulus* (external force applied in the 1st, 2nd or 3rd indentation). There were three *Exploration of the first stimulus* conditions: 1 inds./ no delay, 5 inds./ no delay, 5 inds./ delay.

The *Exploration of the first stimulus* conditions were presented during three different sessions of an average duration of 2.7h. The order of the sessions was balanced between participants according to a Latin square. The sessions were completed on three separate days. In the novel 5 inds./ delay condition after the exploration of the first stimulus a timer appeared in the upper part of the scene. Participants had to hold the index finger on the timer until it had counted down for 5 seconds. Only thereafter the second stimulus was displayed and could be explored.

Data Analysis. To analyze whether the delay between the exploration of the first and the second stimulus affected the weights of the estimates in the exploration of the second stimulus we repeated all of the analyses as described in Experiment 1 by comparing the *5 inds./ delay* condition independently to the other two conditions (*1 ind./ no delay* and *5 inds./ no delay*). In this case we used two-sided *t*-tests. Noteworthy, with this range of softer stimuli, the effect of the manipulation of perceived softness was considerably larger than in Experiment 1 (Figure 4), and larger than what we found in our previous studies [32]. Therefore, we could not longer use our previous estimate of the manipulation effect on a single indentation to compute the weights from the regression slopes. Hence, we computed the weights by normalizing the regression slopes for each condition to sum to 1. We felt confident with the assumption that weights sum to 1, because of our previous results [17] showing that empirical weights actually sum to 1.

3.2 Results

The PSEs with pulling, pushing and no forces are plotted in Figure 4 as a function of the indentation No. on the second stimulus separately for the three *Exploration length of the first stimulus* conditions. As in Experiment 1, also in Experiment 2 pushing forces resulted overall in a PSE shift to higher values and pulling forces caused a PSE shift to lower values. In each of the three conditions sepa-

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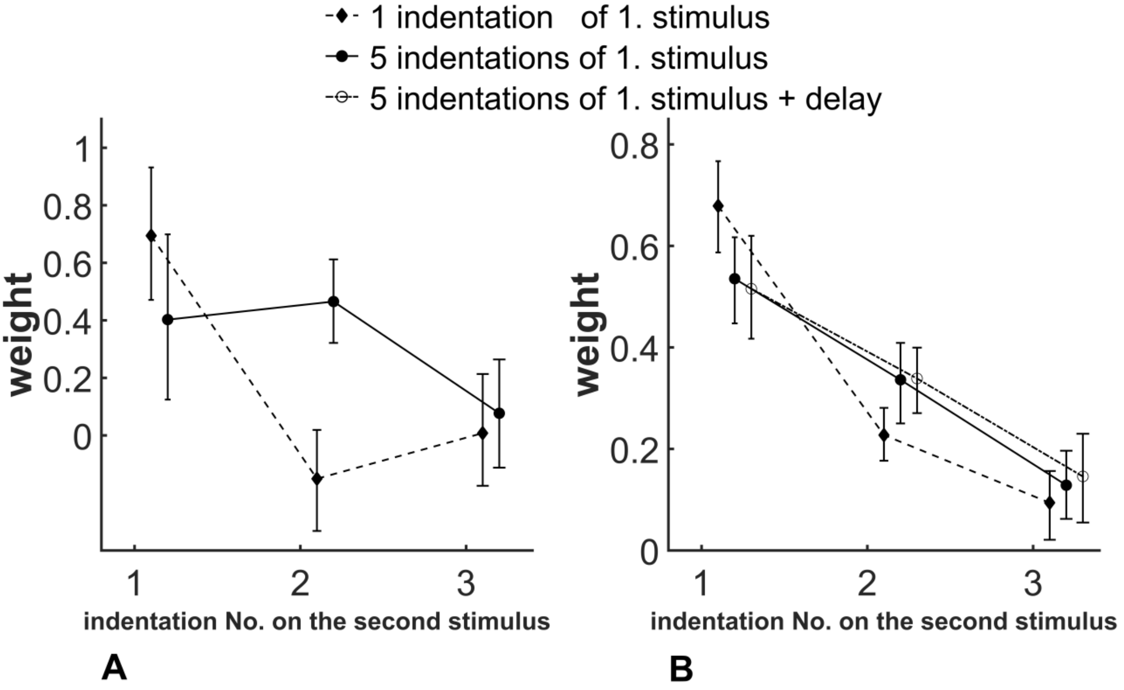

Fig. 5. Average weights of the estimates from single indentations on the second stimulus as a function of the indentation No. on the second stimulus plotted separately for Experiment 1 (A) and 2 (B) and each length of exploration of the first stimulus condition in these experiments. Error bars represent 68% bootstrapped confidence intervals.

rate repeated measures ANOVAs on the PSEs (averaged over *Indentation No. on the second stimulus* conditions) revealed significant main effects of *Fraction of external force*, *1 ind./ no dealy*: $F(2,22) = 15.7$, $p < .001$, *5 inds./ no delay*: $F(2,22) = 10.61$, $p < .001$, *5 inds./ delay*: $F(2,22) = 18.58$, $p < .001$, confirming that the manipulation of perceived softness was (as expected) also successful in every condition of Experiment 2.

In Experiment 2 the baseline PSEs did not differ significantly between the *Exploration length of the first stimulus* conditions, $F(2,22) = 1.34$, $p = 0.282$. Individual baselines also did not differ from the physical compliance of the standard (0.69 mm/ N), all $p > 0.1$.

In Figure 5(B) we plotted the weights of the indentation-specific estimates as a function of the indentation number on the second stimulus for the three *Exploration length of the first stimulus* conditions: *1 ind./ no delay* and *5 inds./ no delay* and *5 inds./ delay*. The patterns of weights in the *1 ind./ no delay* and *5 idns./ delay* were similar as in Experiment 1 but the differences were overall smaller. We replicated the main finding that the decay of weigths during the first two indentations was steeper after a short exploration of the first stimulus (*1 ind./ no delay*) as compared to a longer one (*5 inds./ no delay*), $t(11) = 3.154$, $p = 0.005$. Unlike expected the pattern of weights of estimates of the second stimulus after an exploration with 5 indentations of the first stimulus was not significantly modified by the temporal delay, and also unlike expected the pattern of weights after delay and 5 indentations was not similar to the pattern after a single indentation of the first stimulus. Consistently, the decrease of weights between the 1st and the 2nd indentation of the second stimulus did not differ significantly when comparing the *5 inds./ delay* condition to the *5 inds./ no delay*, $t(11) = 0.165$, $p = 0.872$, but only when comparing to the *1 ind.* condition $t(11) = 2.226$, $p = 0.048$ (two-sided t-test on the slopes).

In Experiment 2 we did not find significant differences in indentation-wise comparisons between the conditions (all $p > 0.2$). Instead, the weights of the first two estimates were significantly different from 0 in all three condtions (all $p > 0.05$).

3.3 Discussion Experiment 2

We predicted a steeper decay of weights due to the introduction of a time delay between the stimuli, given the same number of indentations of the first stimulus. Conversely, for the exploration of the first stimulus consisting of 5 indentations and a delay before the exploration of the second stimulus, we could not find any significant difference in the weights as compared to the same exploration length of the first stimulus without a delay. Consistently the weights in the *5 inds./ delay* condition differed from the weights in the *1 ind./ no delay* condition in the same way as the weights in the *5 inds./ no delay* condition. These results suggest that the strong representation of the first stimulus achieved after an exploration consisting of 5 indentations did not decrease during the delay of 5s. Recent reports have shown limited decay effects with the mere passage of time, with memory mostly being affected by interference [38] [39]. It is thus possible that, the representation of the first stimulus (which strength depended on the number of indentations of the first stimulus) was maintained in memory until the comparison with the second stimulus. In fact, according to the *interference theory of forgetting* [40], information decays in memory because of interference with similar memories or sensorial representations rather than due to the mere effect of time passing. In our delay condition participants were asked to only wait 5s, without being engaged in any activity, thus interference was minimized. This interpretation could be tested in following studies by engaging participants in more or less softness perception related activities during the delay period, in order to manipulate the degree of interference and study how this affects the effects of delay. This is also in agreement with the neurophysiological models of memory retention [37] which suggest that the sensory memory is implemented as short-term synaptic facilitation of selective neurons. Thus if such neurons are activated by the masking stimulus, the sensory trace cannot be maintained. However, Sinclair and Burton (1996) [4] found that also without interference performance in a tactile delayed discrimination task decreased in the first 5s. The fact that delay was not effective in our experiment, might be due to a stronger representation of the first stimulus which was achieved by repeated exploration. The vibrotactile stimuli of Sinclair and Burton (1996) lasted only 1s.

5 GENERAL DISCUSSION

In a recent study [17] we had shown that in a comparison of the softness of two silicon rubber stimuli, indentation-specific estimates of the first stimulus' softness were weighted relatively equal, whereas the weights on the second stimulus decreased during the exploration, possibly due to memory effects. In a first experiment, we tested the prediction that the decrease of the weights depends on the length of the exploration of the first stimulus, which likely determines the strength of its representation in memory. We systematically varied the length of the exploration of the first stimulus (1 vs. 5 indentations) keeping the length of the exploration of the second stimulus constant (3 indentations) and assessed indentation-specific weights by selectively manipulating perceived softness during single indentations of the second stimulus [32]. Additionally, we attempted to unravel the mechanisms of memory decay by investigating whether the decrease in weights in the exploration of the second stimulus is modulated by a temporal delay after the exploration of the first stimulus, which would indicate a time dependent decrease of the memory representation of the first stimulus. For this purpose, we conducted a second experiment in which there was a 5s delay between the exploration of the first stimulus with 5 indentations and the exploration of the second stimulus.

Both experiments provide evidence that different exploration lengths of the first stimulus affect the decrease in weights in the early (first two indentations) exploration of the second stimulus: steeper decrease with a short as compared to a longer exploration of the first stimulus (1 vs. 5 indentations). This results suggest that a short exploration of the first stimulus results in a weaker representation of this stimulus which fades away quicker, so that the estimation of the second stimulus is mostly based on the information from the first indentation. However, results from Experiment 2 suggest that also the last two indentations contribute to the overall percept but with a relatively small weight. Noteworthy, 5s delay had no effect on the pattern of weights, suggesting that the strong representation of the first stimulus achieved after an exploration consisting of 5 indentations did not decrease during the delay of 5s. These results suggest that the crucial factor explaining the decay rate of the representation of the first stimulus is how strongly this representation is built up by exploration, rather than its fading with time (at least in the range of seconds).

In all the experimental conditions we found that the weights on the second stimulus overall decreased over the sequential indentations of the second stimulus, replicating this finding from [17]. This can be explained based on what is known about retention of sensory information in memory. As mentioned before retention of sensory information is feature selective and involves the contribution of sensory cortical areas, indicating that it is based on narrowly tuned filters that also carry out its processing [8]. We showed in a previous study that haptic perception of softness is susceptible to adaptation, indicating that there are neural channels selectively tuned to haptic softness perception [35]. Retention of sensory information is commonly modeled as short-term synaptic facilitation of neurons, resulting from Calcium influx during the firing of a cell and increasing its excitability shortly after the excitation [36]. In a perceptual decision making task, the memory of the first stimulus might be implemented as synaptic facilitation of selective neurons, which are activated again when the second stimulus is presented, in order to retrieve the memory and compare the two stimuli [37]. Assuming that the memory of the first stimulus in our experiment is also implemented as synaptic facilitation of selective neurons, it would fade over sequential indentations of the second stimulus, interfering with the comparison to later estimates from the second stimulus, which would explain an overall decrease of weights in the exploration of the second stimulus.

Our findings are not in agreement with the MLE model (1), which predicts equal weights if redundant estimates are gathered from equally reliable sensory information, because equal weights would maximize overall reliability under these conditions. Such integration has been referred to as being “optimal”. However, integration with unequal weights might also represent an optimal integration that maximizes perceptual reliability - under conditions of information processing that violate implicit assumptions underlying the MLE model. In particular, when applying the MLE model to processes of perceptual integration, it is often implicitly assumed that all gathered sensory information is available during the entire process. However, in a sequential comparison task, in particular if it spans a longer interval of time, the representation of the first stimulus might fade over the gathering of information from the second stimulus, which decreases the reliability of the information from the first stimulus during the perceptual process.

We observed that the perceived softness of the second stimulus (standard) depended on the length of the exploration of the first stimulus in Experiment 1: It was higher after long as compared to short exploration. This likely indicates stronger adaptation to softness after 5 indentations than after 1 indentation of the first stimulus [20]. In line with this interpretation in [20] we found that a standard is perceived to be softer after adaptation to stimuli that are harder than the standard, and vice versa for softer adaptation stimuli. That study also showed that the PSE shift is larger for harder as compared to softer adaptation stimuli. Furthermore, we found that when participants adapted to a stimulus with the same compliance (0.32 mm/ N) as the standard the PSE was shifted to a softer percept . In Experiment 1 we used a standard with the same comliance as in [20]. and the number of comparison stimuli explored before, that were harder than the standard, was the same as the number of softer comparisons. Both the larger PSE shifts after harder as compared to softer adaptation stimuli, and the fact that adaptation to the same compliance as the standard leeds to a softer percept predict that in Experiment 1 adaptation should induce an overall shift of the standard towards a softer percept, in particular after a longer adaptation phase, i.e. after five indentations. This was indeed what we observed in Experiment 1. However, in Experiment 2, where we used a standard with a higher compliance (0.67mm/ N) we did not find significant differences between the baseline PSEs in the different *Exploration length of the first stimulus* conditions.

Taken together our results confirm that when the softness of two real stimuli is compared haptically, the information gathered about the softness of the second stimulus is weighted unequally, with the later estimates being weighted less than the first ones [17]. Moreover, our results suggest that, the unequal weighting is due to the fading representation of the first stimulus, which depends on the exploration length of the first stimulus. More precisely, it seems that with a longer exploration information gathered from more indentations of the second stimulus can be integrated in the comparison of the two stimuli, because the representation of the first stimulus lasts longer. Such strong representation seems to be not affected significantly by a temporal delay of 5s after it is build up. For modeling serial integration of redundant signals in perceptual comparison tasks we argue that models of optimal integration of information (e.g. MLE model) might need to be extended, to account for memory effects.

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