Switching Between Objects Improves Precision in Haptic Perception of Softness

Anna Metzger$^{(\boxtimes)}$ and Knut Drewing

Justus-Liebig University of Giessen, Giessen, Germany
`anna.metzger@psychol.uni-giessen.de`

Abstract. Haptic perception involves active exploration usually consisting of repeated stereotypical movements. The choice of such exploratory movements and their parameters are tuned to achieve high perceptual precision. Information obtained from repeated exploratory movements (e.g. repeated indentations of an object to perceive its softness) is integrated but improvement of discrimination performance is limited by memory if the two objects are explored one after the other in order to compare them. In natural haptic exploration humans tend to switch between the objects multiple times when comparing them. Using the example of softness perception here we test the hypothesis that given the same amount of information, discrimination improves if memory demands are lower. In our experiment participants explored two softness stimuli by indenting each of the stimuli four times. They were allowed to switch between the stimuli after every single indentation (7 switches), after every second indentation (3 switches) or only once after four indentations (1 switch). We found better discrimination performance with seven switches as compared to one switch, indicating that humans naturally apply an exploratory strategy which might reduce memory demands and thus leads to improved performance.

Keywords: Softness · Haptic · Perception · Psychophysics

1 Introduction

We usually have to actively move our sensory organs to obtain relevant information about the world around us. Such exploratory movements are often tuned to maximize the gain of information [1–4]. In active touch perception tuning of exploratory movements is very prominent. Humans use different highly stereotypical movements to judge different object properties [2]. For instance, they move the hand laterally over the object's surface to judge its roughness, in contrast, the hand is held statically on the object to judge its temperature. For each haptic property precision is best with the habitually used *Exploratory Procedure* as opposed to others [2]. Also motor parameters of *Exploratory Procedures*, such

as finger force in perception of softness and shape [5,6], are tuned to optimize performance. This fine tuning is based on available predictive signals as well as on progressively gathered sensory information [3,7]. However, it could also reflect a compensation for limitations of the perceptual system. For instance it is believed that most eye movements are not designated to gain novel information for building up an internal representation of the scene, but to obtain momentary necessary information using the world as an external memory given limited capacity of short-term working memory [8,9]. Here we study whether natural haptic exploration is tuned to compensate for memory limitations.

Integration of accumulated sensory information was in many cases shown to be consistent with Bayesian inference [10]. In this framework available sensory information and assumptions based on prior knowledge are integrated by weighted averaging, with weights being proportional to the reliability of single estimates. This integration is considered statistically optimal because overall reliability is maximized. This framework was successfully applied to describe the integration of sensory and prior information (e.g. [11]), simultaneously available information (e.g. [12]) as well as information gathered over time (e.g. [13]). For the later purpose usually a Kalman filter [14] is used: A recursive Bayesian optimal combination of new sensory information with previously obtained information, which can also account for changes of the world over time.

In haptic perception it was shown that prior information is integrated into the percept of an object's softness [15]. It was also shown that sequentially gathered information from every indentation contributes to the overall perception of an object's softness [16] and information from every stroke over the object's surface contributes to the perception of its roughness [17]. However, the contribution of these single exploratory movements to the overall percept seems to be not equal, as would be predicted if there was no loss of information and integration was statistically optimal. When two objects are explored one after the other in a two-interval forced-choice task, information from later exploratory movements on the second object contributes less to the comparison of the two objects [16,17]. These results are consistent with the idea that perceptual weights decay with progressing exploration of the second object due to a fading memory representation of the first object. Indeed it could be shown that when a stronger representation of the first object's softness is built up by longer exploration, information from later indentations contributes more than with a weaker representation [18]. Also, consistent with memory characteristics [19] mere temporal delay of 5s after the exploration of the first object does not affect the memory representation of the first object [20]. A model for serial integration of information using a Kalman filter could explain the decrease of perceptual weights in the exploration of the second object by including memory decay of the first object's representation [17]. In the modelled experimental conditions people had to discriminate between two objects that are explored strictly one after the other, i.e. in their exploration people switched only once between the two stimuli. In this case memory decay of the first object's representation should have had particularly pronounced negative effects on discrimination. However, in free explorations participants

usually switch more often between the objects in order to compare them (in softness discrimination on average 4 times, given 6–14 indentations in total and an achieved performance of 85–90% correct [7,21]). This might be a strategy to cope with memory decay and improve discrimination performance.

Using the example of softness perception here we test the hypothesis that discrimination improves when participants switch more than once between the two objects given the same number of indentations of each of them, i.e. the same sensory input. In our experiment participants were instructed to indent each test object four times. There were three switch conditions: Participants switched between the two objects after every single indentation (7 switches), after every second indentation (3 switches) or only once after four indentations (1 switch).

2   Methods

2.1   Participants

Eleven volunteers (6 female, right-handed) participated in the experiment. Written informed consent was obtained from each participant and they were reimbursed with 8€/h for their time. The study was approved by the local ethics committee at Justus-Liebig University Giessen LEK FB06 (SFB-TPA5, 22/08/13) and was in line with the declaration of Helsinki from 2008.

2.2   Apparatus

The experiment was conducted at a visuo-haptic workbench (Fig. 1A) consisting of a force-sensor (bending beam load cell LCB 130 and a measuring amplifier GSV-2AS, resolution .05 N, temporal resolution 682 Hz, ME-Messsysteme GmbH), a PHANToM 1.5A haptic force feedback device, a 22"-computer screen (120 Hz, 1280 × 1024 pixel), stereo glasses and a mirror. Participants sat at a table with the head resting in a chin rest. Two softness stimuli were placed side-by-side (distance in between 2 cm) in front of them on the force sensor. To prevent direct sight of the stimuli and of the exploring hand but in the same time indicating their position, a schematic 3D representation of the stimuli and the finger spatially aligned with the real ones was shown via monitor and mirror. The finger was represented as a 8 mm diameter sphere only when not in contact with the stimuli (force < 1N). Participants touched the stimuli with the right index finger. The finger's position was detected with the PHANToM. For this purpose it was attached to the PHANToM arm with a custom-made adapter (Fig. 1B) consisting of magnetically interconnected metallic pin with a round end and a plastic fingernail. We used adhesive deformable glue pads to affix the plastic fingernail to the fingernail of the participant. Connected to the PHANToM the finger pad was left uncovered and the finger could be moved with all six degrees of freedom within a workspace of 38 × 27 × 20 cm. Custom-made software (C++) controlled the experiment, collected responses, and recorded finger positions and reaction forces every 3 ms. Signal sounds were presented via headphones.
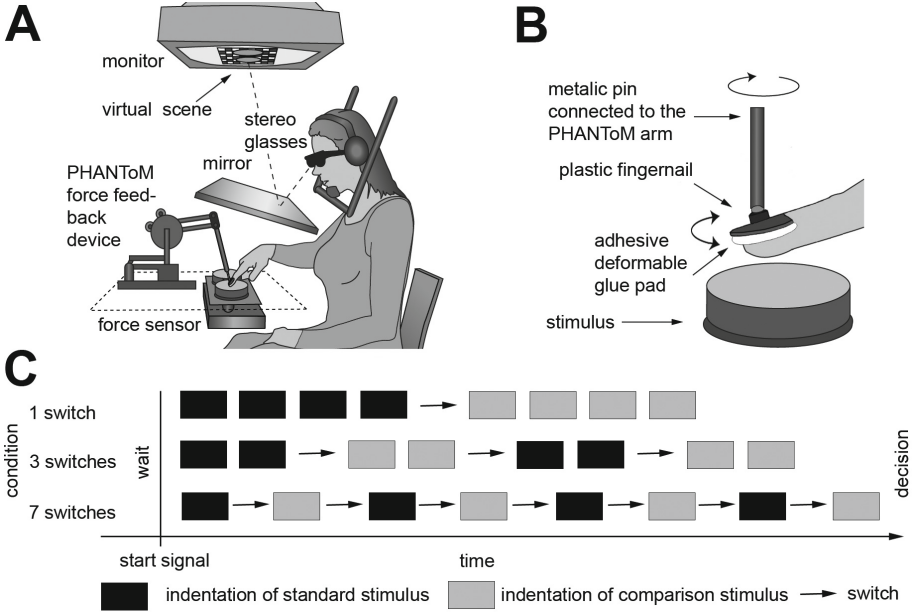
Fig. 1. A. Visuo-haptic workbench. **B.** Custom made finger PHANToM to finger connection. **C.** Experimental procedure. Timing of single trial phases was not restricted. Either the comparison or the standard stimulus could have been explored first.

2.3   Softness Stimuli

We produced softness stimuli with different elasticity by mixing a two-component silicon rubber solution (AlpaSil EH 10:1) with different amounts of silicon oil (polydimethylsiloxane, viscosity 50 mPa/s) and pouring it into cylindrical plastic dishes (75 mm diameter × 38 mm height). We produced in total 10 stimuli: 1 standard (Young's modulus of 59.16 kPa) and 9 comparison stimuli (Young's moduli of 31.23, 42.84, 49.37, 55.14, 57.04, 69.62, 72.15, 73.29 and 88.18 kPa). To characterize the elasticity of the stimuli we adopted the standard methodology proposed by [22]. From the solution mixed for every stimulus a portion was poured into a small cylinder (10 mm thick, 10 mm diameter) to obtain standardized substrates of the same material for the measurement. We used the experimental apparatus to measure elasticity. They were placed onto the force sensor and were indented by the PHANToM force feedback device. For this purpose we attached an aluminium plate of 24 mm diameter instead of the fingertip adapter. The force was increased by 0.005 N every 3 ms until a minimum force of 1 N and a minimum displacement of 1 mm were detected. Measures in which the force increased quicker than it should were considered as artefacts and removed before analysis. From the cleaned force and displacement data we calculated stress and strain. A linear Young's modulus was fitted to each stress-strain curve (only for 0–0.1 strain) in MATLAB R2017.

2.4 Design

There were three *Nr of switches* conditions: 1, 3 and 7 switches. The dependent variable was the just noticeable difference (JND), which we measured using a two-alternative-force-choice task combined with a method of constant stimuli. For each condition the standard stimulus was presented 12 times with each of the 9 comparison stimuli (overall 324 trials). The experiment was organized in 3 blocks of 108 trials, comprising 4 repetitions of each standard-comparison pairing, to balance for fatigue effects. Trials of different conditions were presented in random order. The position of the standard (right or left) and its presentation as first or second stimulus was balanced for every standard-comparison pairing. Differences between the conditions were analysed with paired two-sample *t*-tests.

2.5 Procedure

In every trial, participants sequentially explored the standard and a comparison and decided which one felt softer. A schematic of the procedure is outlined in Fig. 1C. Before a trial, participants rested the finger in the left corner of the workspace and waited until the experimenter changed the stimuli. The beginning of a trial was signaled by a tone and by the appearance of the schematic representation of the first stimulus. The number of indentations allowed to explore the stimulus (1, 2 or 4) was indicated above it. To detect and count stimulus' indentations we used the algorithm from [16]. After the necessary number of indentations the visual representation of the first stimulus disappeared and the representation of the second stimulus appeared. Participants switched to the other stimulus, and again the number of sequential indentations was indicated. Participants continued to switch between the stimuli until every stimulus was indented 4 times in total. Following this, participants indicated their decision on softness by pressing one of two virtual buttons using the PHANToM. A trial in which the stimuli were indented more then 8 times was repeated later in the block. Before the experiment participants were acquainted to the task and the setup in a training session of 12 trials. They did not receive any feedback on their performance to avoid explicit learning. Each participant completed the experiment on the same day within on average 2.5 h.

2.6 Analysis

We calculated for each participant, each condition, and each comparison stimulus the percentage of trials in which it was perceived to be softer than the standard. Combined for all comparisons these values composed individual psychometric data, to which we fitted cumulative Gaussian functions using the psignifit 4 toolbox [23]. Only the means and the standard deviations of the functions were fitted, lapse rates were set to 0. From the fitted psychometric functions, we estimated the JNDs as the 84% discrimination thresholds.
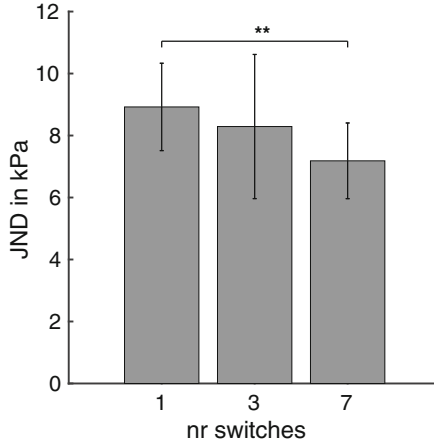
Fig. 2. Average discrimination thresholds for softness of two silicon stimuli each indented 4 times with the bare finger. Participants switched between the stimuli once after 4 indentations, after every 2. indentation (3 switches) or after every indentation (7 switches). Error bars represent within-subject standard error [24]. $**p < 0.005$

3   Results

Figure 2 depicts the average JNDs in the three different *Nr of switches* conditions (1, 3 and 7). The average Weber fractions were 15.08%, 14.01% and 12.14% for 1, 3, and 7 switches respectively. The JNDs decreased with increasing number of switches between the stimuli. Pairwise comparisons revealed that performance was significantly better, when participants switched after every indentation of the stimulus as compared to switching only once after 4 indentations, $t(10) = 4.64$, $p = 0.001$. The performance in the intermediate condition (switching after every second indentation) was numerically in between the other ones. However, we did not find significant differences in the comparisons with this condition (1 vs. 3 switches: $t(10) = 0.57$, $p = 0.578$; 3 vs. 7 switches: $t(10) = 1.07$, $p = 0.311$). We observed higher variance in this condition, possibly due to a more complicated task than in the other two conditions (Fig. 2).

4   Discussion

In the present study, we investigated whether more frequent switching between the stimuli improves discrimination performance in active touch perception of objects' softness. Participants explored two softness stimuli with the same number of indentations (4 per stimulus) but switched between the stimuli either only once after four indentations, after every second indentation or after every indentation. We showed that if participants could switch after every indentation discrimination performance was significantly better than if they could switch only once. We argue that this is due to greater memory demands, because the

first stimulus' has to be remembered longer to compare it to every indentation of the second stimulus, than when switching after every indentation. It could also be argued that integration across more indentations of the first stimulus demands greater attention, leading to worse performance, especially because here we did not manipulate factors directly affecting memory i.e. inter-stimulus delay or masking. However, we previously observed that in the exploration of the first stimulus the weights of single indentations were equal, as would be predicted for optimal integration [12] while weights of single indentations of the second stimulus decreased with time, indicating that not all information about the second stimulus could be used for the comparison. We could also show that observed decay in weights was consistent with memory decay in tactile perception [17,25], suggesting that a difference in memory demands is a more likely explanation for the observed difference in performance in different switch conditions.

The Kalman model of serial integration proposed by [17], assumes that when switching only once between the stimuli, differences between each sequentially gathered estimate of the second stimulus and the overall estimate of the first stimulus are integrated in a statistically optimal way given memory decay, modelled as increasing variance of the first stimulus' estimate over time. Thus, given the same amount of information, this model predicts that precision should be higher the shorter the first stimulus needs to be remembered, which is consistent with our results. However, to apply this model to our data, we would need to extend it by the variable containing the result of one comparison. To test the predictions of this extended model we would need additional data (e.g. precision based on one indentation per stimulus).

Overall our results suggest that in active touch perception where integration of information is limited by memory [16–18,20], the naturally applied strategy of switching between the stimuli [21] can be more beneficial for performance than prolonged accumulation of information about each stimulus.

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