The role of implicit prior information in haptic perception of softness

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Abstract. People regularly use active touch to perform daily life tasks. Imagine choosing a comfortable pillow and how you would explore its softness. It is known that people tune their exploratory behavior to get the most relevant information. In the exploration process, also prior information is used, which is available before we touch an object. For softness perception, object indentation plays a crucial role; indentation forces were higher, when people implicitly expected to explore harder as compared to softer objects. This force-tuning improved perception, and was observed when trials of the same softness level (hard or soft) were presented in longer blocks. However, it was not reported for predictable patterns in that hard and soft stimuli alternate in every or every other trial. Here, we investigated when and how implicit prior information about the softness level becomes accessible for successful force-tuning in softness discrimination. Participants were presented with hard and soft stimulus pairs in sequences of the length of 2, 4 or 6 trials. In predictable conditions, same-length sequences of hard and soft trials alternated constantly. In unpredictable conditions, we presented sequences of lengths 2, 4 and 6 randomly. We analyzed initial peak indentation forces. Participants applied higher forces to harder stimuli in the predictable condition in longer sequences (4 and 6) as compared to the unpredictable condition and shorter sequences of 2. We interpret the findings in terms of an anticipatory and incremental mechanism of force-tuning, which needs to be triggered by an initial predictable stimulus.

Keywords: softness perception, prediction, implicit mechanisms, prior information.

1 Introduction

Humans interact with different objects and assess their properties while performing everyday tasks. Imagine choosing a comfortable pillow or buying an avocado in grocery shopping. The sense of touch provides highly relevant information here. It is known that people adjust their hand movements according to the object property that they explore to extract the most relevant information–such as indenting or squeezing regarding softness [1]. The interaction with the object typically starts before the first contact with the object. Prior information about the object property such as our previous experiences, information from other sensory modalities (i.e.vision) or what we have been told about the object can guide the exploratory movement and also contribute to perception. For instance, people can use visual prior information to adjust their exploratory direction and improve perception in texture perception [2] or they use prior information about the compliance of upcoming stimuli and tune their forces accordingly to increase their precision in softness perception [3]. Here, we study mid-term mechanisms of the usage of implicit prior information in force-tuning mechanisms for softness perception. In the following, we will (1) explain the basic dissociation between implicit vs. explicit information, report what is known about prior information in softness perception in general (2) and with respect to the mechanisms of its usage (3), and detail our present research question (4).

Prior information can be acquired and utilized implicitly or explicitly. Implicit learning corresponds to information acquired without any conscious attempt to learn and when there is no clear indication of what has been learned. In contrast, explicit learning implies acquiring the knowledge that is available to consciousness and can be reported verbally [4,5]. One example from literature is implicit sequence learning: Repeated sequences of stimuli presented in predictable patterns can be learned [6,7] and markers of learning can be seen in participants' improved performance as compared to the performances in randomized presentation of the stimuli as unpredictable patterns. For example, in serial reaction time tasks, participants are asked to respond as quickly as possible to a series of stimuli, such as different letters on a screen, with stimulus-specific responses (e.g., pressing different buttons). If there is a constant, repeated pattern in the series, participants responded faster as compared to a random presentation [8]. They were however not aware of their learning. Also, more complex motor behaviors than button presses can benefit from implicit sequence learning. Baird and Stewart used a motor task that required three-dimensional whole-arm reach movements to a series of target locations [9]. If target locations followed a repeated predictable pattern, participants were able to complete this complex task faster than with a random series.

How prior information affects haptic exploration and perception has been studied, in particular, for the guidance of exploratory movements in softness perception. Softness is one of the main dimensions in haptic perception [10], and it is a multidimensional percept [11,12]. One important perceptual correlate of perceived softness is compliance, that is the deformability of an object surface under the application of physical force. It is known that people choose specific hand movements based on the haptic property that they aim to explore [1], that they finely adjust movement parameters to improve perception and that prior information can guide this fine tuning [3,13]. For compliance-related softness exploration, people often choose indentation movements and they tune their peak indentation forces. Peak forces appear to have a crucial impact on softness perception [13]. In [3], Kaim and Drewing showed that fine tuning of peak forces can take place with the very first indentation if participants can predict the softness level of the upcoming stimuli. They observed that participants applied from the beginning of each trial more force to harder stimuli versus to softer stimuli when trials with the same softness level (harder or softer) were presented in a block, and this behavior improved perceptual performance. Such force tuning was not observed when harder and softer trials were presented to the participants in a randomized order and thus the softness level was unpredictable. Initial peak forces are a reliable indicator for the use of prior information since sensory information from the present trial is not available yet. The findings, thus, suggested that prior information plays a crucial role for force tuning in softness perception. In [14], the effect of different types of prior information was systematically investigated: Participants either explored only hard or only soft stimulus pairs in a blocked fashion, or they received semantic information (verbal label “soft” or “hard”) about the compliance of the upcoming stimulus pair just before the exploration started, or a video with an indentation of a probe into a rendered stimulus (deep or shallow indentation). The former condition was considered implicit, whereas the latter two rather presented explicit prior information. In the explicit conditions harder or softer trials were presented to participants in random order. The expected force tuning (higher initial force to harder stimuli) was only found when stimuli were presented to participants in blocks of only harder or softer trials, i.e. the presumably implicit condition. In a second experiment, they investigated if explicit information interferes with implicit force tuning mechanisms [14]. One group of participants received only implicit prior information from blocking while another group additionally received explicit verbal information about the softness of the upcoming block of trials (e.g., “The next stimuli will be harder”). Force tuning was observed when participants received only implicit information, but it vanished with extra explicit information. Taken together, these studies showed that force tuning mechanisms in softness perception require prior information to be implicit, whereas explicit information interferes with the feedforward mechanism of force tuning.

To gain deeper insight into how people use implicit prior information in softness perception, Drewing and Zoeller studied force adaptation when prior information on stimulus levels could be in principle predicted from implicit sequence learning [15]. They conducted a study in which hard or soft trials were presented in 3 different predictable, but implicit patterns to the participants: 1) longer blocks in which only hard or soft stimuli were presented, 2) short pattern in which hard and soft trials were presented alternately, and 3) long pattern in which always two hard and two soft trials alternated. Indeed, participants were not aware of any of these patterns. Still, participants showed successful force tuning in the blocked condition, i.e. applied higher force to harder versus softer stimuli. In contrast, in short and long pattern conditions, the result was inverse and participants applied slightly higher forces to the softer stimuli than to the harder stimuli. The authors concluded that also in these patterns implicit mechanisms were used for force control, but that under the given conditions–i.e. the relatively short same-softness sequences—their effect was not sufficient for successful force tuning. Due to the inverse effect, the authors also discussed whether force tuning might alternatively be based on reactive trial-by-trial mechanisms rather than on anticipatory mechanisms that use prior information, because, in the alternating patterns, hard and soft trials consistently followed each other in short time. So, forces for one softness-level could have been reactive adaptations to the other level and hence inverse. We know from the literature on object lifting that anticipatory mechanisms can help people to adjust their grip force to predictable changes of object weight [16], but that people are also able to adjust their grip force to unexpected weights in a few trials by reactive trial-to-trial mechanisms [17]. However, post-hoc analyses in [15] rather tended to show that reactive trial-to-trial mechanisms were not responsible for the inverse effect.

That is, overall the above study [15] suggests that prior information from implicit sequence learning influences force control based on anticipatory mechanisms. However, it is not clear why the prior information in the given patterns was not sufficient for successful force tuning. Here, we aim to unravel how mid-term mechanisms achieve that prior information in softness perception becomes accessible for successful force-tuning, in order to better understand the processes by which humans use implicit prior information and optimize their exploratory movements. This is not only of relevance in itself, but may also contribute to improving sensing capabilities in technical systems such as robots. In particular, we studied how long same-softness sequences need to be in order to allow for successful force tuning, and we experimentally tested the assumption that anticipatory mechanisms rather than reactive ones are involved in the force tuning. We presented hard and soft stimuli in predictable and unpredictable patterns. In predictable patterns, hard and soft trials were alternating in same-softness sequences of 2, 4 or 6 trials. Thus, participants were able to learn the patterns and predict the softness level of the upcoming stimulus pair. In unpredictable patterns, we presented sequences of 2, 4 and 6 same-softness trials in random order. Hence, presentation of hard and soft trials did not follow a constant pattern and participants were not able to implicitly learn and predict the softness level of the upcoming stimulus pair. Participants did not receive any information about patterns in the experiment. We expected that when stimuli were presented in a predictable pattern, participants successfully tune their force (higher force to a harder stimulus) compared to the unpredictable pattern thanks to implicit predictive mechanisms. We also expected that participants tune their force only in the longer predictable sequences based on the previous findings.

2 Method

2.1 Participants

A total of 24 participants (19 females, aged between 19 and 35 with mean age of 24.5, SD= 4.04) took part in the study. All of the participants were right-handed and they did not report any cutaneous and motor impairments in the past. Their two-point discrimination threshold was equal to or smaller than 4 on the index finger of their dominant hand. We calculated the required sample size using G*Power [18] for a repeated measure ANOVA, a factor with 2 levels, a power of 80%, alpha level of 5% and a medium-to-large effect size f=0.325 (from data in [15]) resulting in a sample size of 21. All participants were naïve to the purpose of the study and gave written informed consent before the experiment. They received 8€ per hour for participating. Methods and procedures of the experiment were approved by the Local Ethics Committee of Giessen (LEK FB06), and were carried out in accordance with the Declaration of Helsinki (2013) except for preregistration.

2.2 Setup and Stimuli

Participants performed the experiment on a custom-made visuo-haptic workbench (Fig.1a) which includes a 24'' 3D computer screen with 120 Hz and 1600 x 900 pixel, a PHANToM 1.5A haptic force feedback device with 1000 Hz temporal and 0.03 spatial resolution, and a force sensor with 682 Hz and 0.05 N resolution to collect normal force data. Participants sat in front of the experimental set up and connected the index finger of their dominant hand to the PHANToM arm via a spherical magnet adapter which sticks to the finger nail and enables them to move their finger in the 38 x 27 x 20 cm^3 workspace. Participants were able to explore stimuli with the bare finger since the adapter was only fixed to the finger nail and did not cover the finger pad. A chin rest stabilized their head and participants wore stereo glasses (NVidia 3D Vision 2) to see a 3D visual scene through a mirror. 3D stimuli in the visual scene were aligned with the haptic stimuli to allow for an exploration that is as natural as possible while eliminating direct visual feedback from the haptic stimuli. Haptic stimulus pairs were placed on a plate above the force sensor next to each other, with a distance of approximately 11 cm from center to center. The finger's position was presented as a green dot (8mm) which however disappeared as soon as the force applied to the stimulus was higher than 0.01 N to prevent any visual feedback about deformation. All participants wore ear plugs to eliminate any potentially confounding noise.

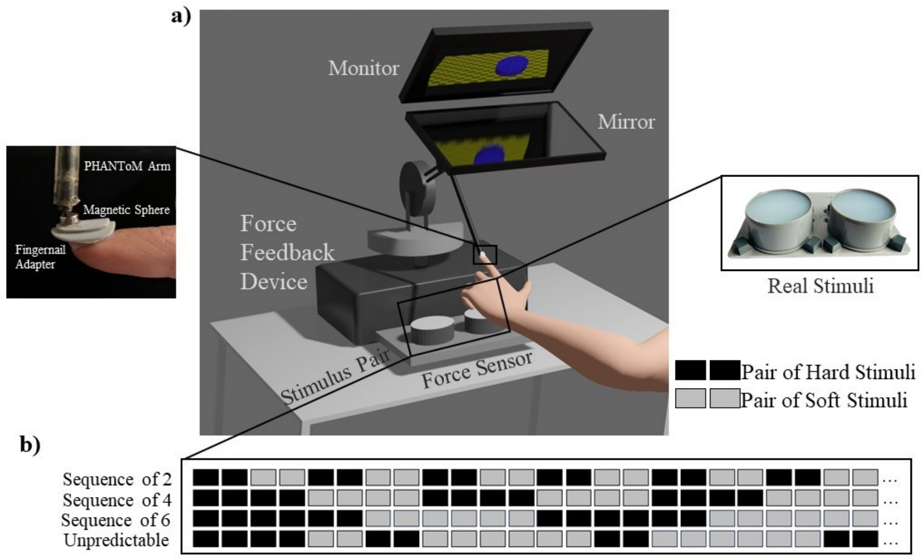

Fig. 1. **a)** Illustration of custom made visuo-haptic setup. **b)** Depiction of finger connection of Phantom to finger nail. **c)** Picture of real stimuli. **d)** Visualization of stimulus presentation in Predictable Condition with Sequence Length 2,4,6 and Unpredictable Condition (random presentation of Sequence Length 2,4 and 6).

We used six cylindric silicone rubber stimuli (height: 38 mm, diameter: 75mm, see [3] for details of production). Three of the six stimuli were classified as hard, and the other three were classified as soft. We used one standard stimulus (hard: 159.62 kPa, soft: 50.12 kPa) and two comparison stimuli (hard: 174.95 kPa and 132.00 kPa, soft: 60.33 kPa and 42.34 kPa) from each category. The stimuli from both groups were selected based on their elasticity measured as Young's modulus and based on their perceptual distinctness. We followed the standard method to measure the elasticity of the stimuli introduced by [19]. For that purpose, we obtained standard samples from each stimulus by pouring, during stimulus creation, the mixed solutions also into small cylinders with a defined height of 10 mm and a diameter of 10 mm. The standard samples were positioned on a force sensor. Using the PHANToM we pressed an aluminium plate with diameter of 24 mm on the sample–increasing the force by 0.005 N every 3 ms until a minimum force of 1 N and a minimum displacement of 1 mm were detected. We transformed the force and displacement data into stress-strain data and fitted a linear regression line to determine Young's modulus (in MATLAB R2022a). We selected stimuli so that the differences between the two comparisons per category and their standard is as similar as possible regarding their Young's moduli and that each comparison was correctly discriminated from its standard in about 80% of trials (73% - 87% in a pilot study with 4 participants).

2.3 Design and Procedure

The experiment comprised three within-participant variables: Predictability (Predictable or Unpredictable), Compliance category (Hard and Soft) and Length of Sequences (2, 4 and 6), (Fig.1b): Stimulus pairs of each softness-level were presented in sequences of 2, 4 or 6 trials including pairs of the same softness level (either hard or soft). Hard and soft sequences always alternated. In the predictable condition sequences of the same length were blocked, so that participants would be able to learn patterns implicitly and predict the softness level of upcoming stimuli. Each predictable block included 48 trials, i.e. 24, 12 or 6 sequences (of lengths 2, 4, or 6, respectively). In the unpredictable condition, sequences of different lengths appeared in random order, and the unpredictable block included 144 trials (again, 48 trials per sequence length). In this block, participants were not able to predict upcoming stimuli since the sequence length of a hard or soft sequence differed due to randomization and did not follow a regular pattern. We balanced the order of the 4 block types with a Latin-square design. Further, half of the participants started the experiment with a soft sequence while the other half started with a hard sequence pair.

In each trial the standard stimulus and one of the two comparison stimuli of the same category (hard or soft) were presented. Standard and comparison were randomly assigned to the left or right position. In the beginning of each trial, a visual representation of the left stimulus indicated the participant to start exploration. After they had indented the left stimulus two times, a visual representation of the right stimulus appeared. After two indentations of the right stimulus, the participant was asked to choose which of the stimuli they had perceived to be softer using a virtual button.

Participants performed 8 test trials before the main experiment to familiarize themselves with the task. In the test trials, hard or soft pairs were presented to the participants in a random order. After they completed the experiment, participants were given a questionnaire to measure their explicit knowledge about presentation patterns in the experiment (blocks of 2-4-6 same category trials). The questionnaire included 8 different presentation patterns, including the 3 actual patterns in the experiment (alternating sequences of 2 soft - 2 hard, 4 soft - 4 hard, 6 soft - 6 hard) and 5 distractor patterns (alternating sequences of 1 soft – 1 hard, 3 soft – 3 hard, full soft, full hard, 3 hard – 1 soft). They were first asked if they had realized any presentation pattern and if yes, they were required to choose which of the patterns had been included.

2.4 Data Analysis

First of all, we analyzed the discrimination performance in the experiment by calculating the percentage of correct responses. In order to warrant that participants had focused on the task, we excluded participants with bad discrimination performance. We eliminated data from 3 participants (64%, 66%, 73%) setting a criterion of 75% correct, on average.

Mainly, we analysed initial peak forces during the exploration of each stimulus pair, indicating the use of prior information [3]. In the first step, we smoothed the measured normal force values with a moving-averaging window with a kernel of 45 msec [15]. Afterwards, we captured the force maxima by detecting turning points where the first derivative of force shifted from positive to negative over time. We filtered out force maxima below 5 Newton (N) and defined that the time interval between two valid peak forces has to exceed 180 msec. With these restrictions we aimed to minimize artifacts in the data stemming from local maxima, small finger tremor movements or movement rests occurring after valid indentations. In case there was more than one local maximum force within the specified time frame, the highest maximum was considered as peak force. The initial peak force was the very first peak force in a trial, the maximum force captured at least 180 msec after the initial peak force was assigned as second peak force. We applied standardized data filtering procedures consistent with those used in previous research [15] to ensure comparability. In addition to this, inspection of individuals force profiles suggested by all appearances that 180 ms is an appropriate border to dissociate separately planned indentation movements from each other—in line with previous reports suggesting that a single indentation lasts around 200-230 ms [20, 21]. As for the force criterion of 5 N, we also checked for a lower value of 2N, which however did not change our main conclusions.

We performed a repeated-measures ANOVA to compare initial peak forces with Predictability (Predictable and Unpredictable), Length of Sequence (2, 4 and 6) and Compliance category (Hard or Soft) being within-participant variables. p-values and degrees of freedom were corrected according to Greenhouse-Geiser [22] in case the sphericity assumption was violated. Afterwards, we compared initial peak forces between the predictable and unpredictable conditions for each compliance and length of sequence condition with planned paired t-tests. We expected participants to apply higher forces to hard stimuli in the predictable condition versus the unpredictable condition when they use prior information.

Furthermore, we averaged the initial peak forces corresponding to the same trial position in a sequence of certain length (2, 4, or 6) to see how initial peak forces develop across trials. On these data we conducted per length of sequence a within-participants linear contrast over trial positions separately for Hard and Soft softness levels and for Predictable and Unpredictable conditions to check for systematic developments of applied peak force. We expect that forces increase for hard stimuli in the predictable condition, which would show force-tuning, but we do not expect any other developments.

3 Results

The repeated-measure ANOVA on initial peak forces revealed a significant main effect of the Length of Sequences, $F_{2,40} = 3.770$, $p=.032$, $\eta^2_p = 0.159$ and a significant interaction effect between Predictability and the Length of Sequences, $F_{2,40} = 3.542$, $p=.038$, $\eta^2_p = 0.150$. These results support our hypothesis that participants adjusted their initial peak forces dependent on the length of the sequence when the compliance of the upcoming stimulus pair was predictable (see in Fig. 2.). Other effects were not significant (main effects of Predictability, $F_{1,20} = 3.542$, $p=.331$, and Softness Level, $F_{1,20} = 3.542$, $p=.091$; interactions Predictability X Level, $F_{1,20} = 2.168$, $p=.156$, Softness Level X Length of Sequences, $F_{1,20} = .204$, $p=.816$, Predictability X Length of Sequences X Softness Level also failed to reach significancy, $F_{1,40} = 1.014$, $p=.372$.

The planned paired *t*-tests of initial peak forces confirmed the expected results in detail: A) participants applied higher forces to hard stimuli in the predictable condition than in the unpredictable condition for patterns with sequence length 4, $t(20)=1.996$, $p=.030$, and for patterns with sequence length 6, $t(20)=1.948$, $p=.033$. B) Also as expected, we did not find significant predictability effects on force for hard stimuli in patterns of sequence length 2, nor for soft stimuli for any sequence length (all $p>.91$).

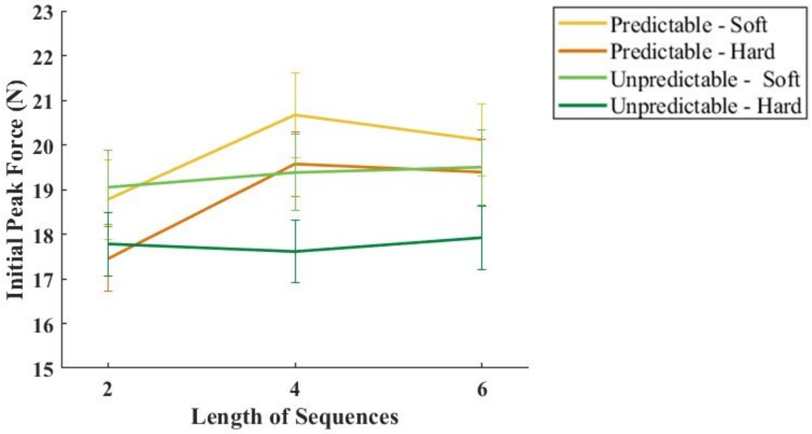

Fig. 2. Initial peak forces as a function of Length of Sequence and Compliance Category. The error bars show the standard error of the mean (SEM). Note that SEMs are based on and represent dispersion between participants and thus provide an additional aspect of the data that is not informative for the significance of within participant analyses.

The averaged initial peak forces as a function of trial position in the sequences of different lengths are depicted in Fig. 3. Within-participant linear contrasts per predictability and softness level revealed the following insights about how initial peak force develop across trials:

A) For Sequence Length 2, there is a linear contrast of increasing forces from the first to the second trial for hard stimuli in the predictable condition as expected, $F_{1,20} = 4.741$, $p=.021$ (one-tailed), $\eta^2_p = 0.192$, but also for soft stimuli in the unpredictable condition, $F_{1,20} = 12.269$, $p=.002$, $\eta^2_p = 0.380$ (Fig.3a) (all other ps > .209).

B) For Sequence Length 4, we also found the expected significant linear contrast showing increasing forces for hard stimuli in the predictable condition $F_{1,20} = 11.692$, $p=.002$ (one-tailed), $\eta^2_p = 0.369$, and unexpectedly for soft stimuli in the unpredictable condition $F_{1,20} = 7.771$, $p=.011$, $\eta^2_p = 0.280$ (Fig.3b) (all other ps > .061).

C) For Sequence Length 6, we again observed the expected contrast for hard stimuli in the predictable condition, p=.035 (one-tailed) (Fig.3c) (all other ps > .071).

Lastly, we analyzed the participants' response to the survey. 56% of the participants did not realize the patterns, further 20% responded there were patterns, but marked the same number of wrong and correct patterns in the questionnaire. Also, none of the remaining participants accurately exclusively marked all the correct patterns. So, overall while a minority of participants might have had limited recognition, most did not.

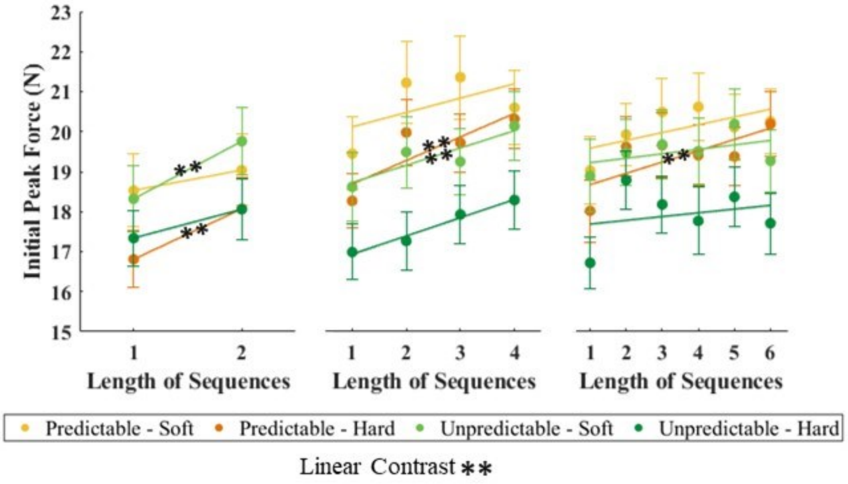

Fig.3. Initial peak forces as a function of Trial Position for each Length of Sequence: **a)** Sequence Length of 2. **b)** Sequence Length of 4. **c)** Sequence Length of 6. Lines and the significance level are included to graphically represent linear contrasts (lines are actually regression lines, but only serve representational purposes here). The error bars indicate the standard error of the mean.

4 Discussion

In the present study, we investigated how and where prior information on softness level (hard or soft) becomes accessible for successful force tuning in softness perception. Previous studies had indicated that participants apply higher force to harder stimuli versus softer stimuli (=force tuning) when stimulus pairs were presented in longer sequences with trials of the same softness level [3,14]. An inverse effect was observed when soft and hard pairs alternate in every, or every other trial [15]. To provide insight into the mechanisms of force tuning and to understand how and where the prior information becomes accessible, we varied the length of sequences from the same softness level to be 2, 4 or 6 trials and presented them in predictable and unpredictable conditions. We found out that participants successfully adjusted their force by applying higher force to harder stimuli when the longer sequences followed a predictable pattern compared to the unpredictable pattern. This confirms that anticipatory mechanisms are involved in force-tuning in softness perception. According to the questionnaire, most participants were not aware or did not recognize the presentation patterns, suggesting that we studied implicit mechanisms here.

Note that, in [15], authors compared the initial peak forces applied to the hard and soft stimuli across softness levels. In the present study, we compared hard and soft stimuli only with themselves between predictable and unpredictable conditions to investigate anticipatory mechanisms by studying hard and soft stimulus independent from each other. Overall, our results are in line with the previous findings: If participants anticipated that they will explore harder stimuli in the predictable condition, they exerted a higher peak force in the very initial contact with the stimuli compared to unpredictable conditions. We found this effect between predictable and unpredictable conditions only if the same-softness sequences were a length of 4 or 6 trials. We already knew that longer blocks result in successful force tuning. The present results now specify that force tuning is already successful when same-softness sequences are just 4 trials long, whereas a length of 2 is insufficient as already observed by [15].

The analyses of the development of initial peak forces across trial positions showed that participants apply increasing force to the hard stimuli in the predictable condition during each same-softness sequence of lengths of 2, 4 and 6. We did not observe this linear contrast for hard stimuli in unpredictable conditions, nor for soft stimuli in the predictable conditions. These findings are well in line with our conclusions from previous studies. The increasing forces over trials for hard stimuli fit with the expectation that participants apply higher forces when they expect to explore hard stimuli. The lack of this linear trend in the unpredictable conditions and in the predictable soft conditions is in line with a crucial role for anticipatory mechanisms: Only if harder stimuli can be really predicted, participants tune their forces by increasing them. Moreover, we know from previous study [15] and from our results that sequence length of 2 is not long enough for successful force-tuning, which we also did not observe in the overall analysis. However, the linear contrast observed for sequence length 2 promotes a view that participants still use implicit learning cues to trigger the process to optimize their sensory intake. Taken together, the analysis of peak forces over position, and the overall findings on the effect of predictability suggest an anticipatory mechanism of force tuning, which however needs to be triggered by an initial stimulus of the predictable stimulus level. Only, then forces will be slowly tuned over about 2-3 trials. This may be because the participants were learning whether the sequences were predicably longer or not, rather than learning exactly how long the sequences were. As a result, based on predictability of some sequence, they might undertake the effort to fine-tune their forces.

Note that we also observed unexpected trends: Participants applied increasing forces over trial position to the soft stimuli in the unpredictable condition with sequence lengths of 2 and 4. One idea could be that this again results from optimizing of sensory intake but this time because of uncertainty: participants might develop a strategy to apply a high force to the following stimulus, because a hard stimulus might appear in the next trial. However, this is highly speculative and we did not observe such a strategy for unpredictable sequences of length 6. Note besides that 80% of our participants were females. However, it seems very unlikely that our results are considerably biased by this unbalanced gender distribution, because psychological studies including a study on haptic perception [23] hardly report gender differences, least of all ones of considerable magnitude.

Considering all these findings, our present knowledge suggests that usage of implicit prior information and anticipatory mechanisms play a crucial role in successful force-tuning for softness perception as long as presentation conditions are stable enough which is sequence length of 4 in our study. This finding enhances the understanding of exploratory mechanisms guided by prior information in haptic perception. In previous studies, it already became evident that the type [14] or the quality of prior information [2] affects the exploration in haptic perception. The present study makes a valuable supplement to previous studies in terms of understanding mid-term mechanisms by that prior information becomes accessible for exploratory control. In particularly, we suggest that there is an anticipatory and incremental mechanism of force tuning based on prior information, which however needs to be triggered by an initial stimulus corresponding to the predicted stimulus conditions. These insights could have practical implications to improve haptic guidance systems such as robotic arms and artificial robotic skin. Robots can use the prior tactile information while learning new objects [24]. A comprehensive understanding of mid-term mechanisms regarding usage prior information in human haptic perception is essential in advancing the development of these systems, also in terms of implementing optimized learning and exploration process. Future studies are needed to explore whether similar mechanisms apply to other types of prior information. Last but not least, it may also be of future interest to investigate the roles of memory and learning over longer periods of prior information use.

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