Haptic aftereffect of softness

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Abstract. Past sensory experience can influence present perception. We studied the effect of adaptation in haptic softness perception. Participants compared two silicon rubber stimuli, a reference and a comparison stimulus, by indenting them simultaneously with the index fingers of their two hands and decided which one felt softer. In adaptation conditions the index finger that explored the reference stimulus had previously been adapted to another rubber stimulus. The adaptation stimulus was indented 5 times with a force of >15N, thus the two index fingers had a different sensory past. In baseline conditions there was no previous adaptation. We measured the Points of Subjective Equality (PSEs) of one reference stimulus to a set of comparison stimuli. We used four different adaptation stimuli, one was harder, two were softer and one had approximately the same compliance as compared to the reference stimulus. PSEs shifted as a function of the compliance of the adaptation stimulus: the reference was perceived to be softer when the finger had been adapted to a harder stimulus and it was perceived to be harder after adaptation to a softer stimulus. We conclude that recent sensory experience causes a shift of haptically perceived softness away from the softness of the adaptation stimulus. The finding that perceived softness is susceptible to adaptation suggests that there might be neural channels tuned to different softness values and softness is an independent primary perceptual quality.

Keywords: softness · stiffness · haptic · tactile · perception · adaptation · aftereffect

1 Introduction

Prolonged exposure to a stimulus can change neural responses, i.e. physically identical stimuli can be perceived to be dramatically different given different preceding sensory experiences. This form of plasticity (though difficult to be distinguished from other forms, e.g. learning) is usually referred to as perceptual adaptation [1]. One psychophysically measurable effect of adaptation is an aftereffect, which refers to a shift in perception of a test stimulus (reference) along a perceptual dimension after prolonged exposure to another stimulus (adaptation stimulus) with a certain value along this dimension, usually away from the adaptation stimulus ([2], [1], [3]). A well-known example is the visual aftereffect of motion, which was described as the "waterfall illusion" in 1834 by Robert Addams [4]: He perceived static rocks as moving upwards after prolonged viewing of a waterfall. The established explanation of

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aftereffects is that a perceptual dimension is represented by the activity of neural channels with narrowly tuned but overlapping sensitivities to the values along this dimension [5], [3]. A stimulus with a certain value along a perceptual dimension activates mostly the channel tuned to this value and also a little the channels sensitive for the surrounding values. From the relative activities of the channels the value of the stimulus can be "read out" and it is assumed that this mediates our perception [3]. Prolonged exposure to a narrowband adaptation stimulus would cause a reduction in the sensitivity of the corresponding channel and its neighbors. When a reference stimulus with a value close to the value of the adaptation stimulus is presented afterwards, the channel which should respond maximally would respond less and the activity of the channels sensitive to the neighboring values would be lower at the side close to the value of the adaptation stimulus than on the other side. As a consequence the overall activity would be shifted away from the value of the adaptation stimulus, which would cause a corresponding shift in the perception of the reference - a "repulsion aftereffect" [1]. As neurophysiological studies supported the described model of sensory encoding by providing examples of adaptable cells responding to narrow ranges of a perceptual dimension [6], adaptation became the "psychologist's microelectrode" [3], i.e. revealing how perceptual attributes are encoded in the brain by measuring response changes after adaptation [1]. In the present study we addressed the influence of adaptation in haptic perception of softness.

An early report of an aftereffect in haptic perception was made by John Locke in the seventeenth century. He observed a difference in perceived temperature between his two hands when they were put in a bucket with water: The water felt warm to the hand which had experienced cold water before and cold to the hand, which had been adapted to warm water [7]. Later, haptic aftereffects have been described and studied also in the perception of size, shape and weight of an object, roughness, curvature, vibration and motion. For an extensive overview of aftereffects in the sense of touch see [8]. Most of the observed haptic aftereffects are "repulsion aftereffects", i.e. perception of a reference stimulus shifts away from the adaptation stimulus. This finding is in concordance with the established multichannel model of aftereffects.

Here we study the perception of softness. Softness refers to the subjective measure of an object's compliance. Compliance is defined as the ratio between displacement of the object's surface and the force applied to the object; compliance can be expressed in mm/N. Active exploration of softness usually involves the stereotypical *Exploratory Procedure of Pressure,* meaning that an object is repeatedly squeezed between the fingers or it is repeatedly indented with a finger or a tool usually in direction normal to the object's surface [9], [10]. It has been speculated that SAI fibers are involved in softness perception [11]. However, SAI discharge rates cannot be solely responsible for encoding softness, because these discharge rates also vary with the velocity of skin indentation during exploration, which is not observed for perceived softness [11]. Most authors assume that softness is perceived through a combination of information about the displacement of the object's surface and information about the force being applied to the object [12], [13]. Such information can be obtained from the cutaneous and kinesthetic afferent systems [12], [13], [14], [15] and in certain cases even from vision [16], [17] and audition [18].

We hypothesized that perceived softness would also be subject to adaptation effects. We investigated whether the perception of a reference stimulus would change by preceding stimulation with an adaptation stimulus as compared to the case when the reference is explored without previous adaptation. We asked participants to compare a reference and a comparison stimulus by indenting them simultaneously with the two index fingers of their left and right hand. In adaptation trials the index finger that explored the reference stimulus had been previously adapted to another stimulus. The adaptation stimulus was indented 5 times with a force of >15N. The other index finger that explored the comparison stimulus was not adapted. In baseline trials neither finger underwent previous adaptation. We measured the Points of Subjective Equality (PSEs) between the reference stimulus (0.32 mm/N) and comparison stimuli using a 1-Up-1-Down staircase and an Alternative Forced Choice (AFC) task. We compared the PSEs measured in the adaptation conditions to PSEs measured in the baseline condition. We used different adaptation stimuli: one was harder than the reference (0.16 mm/N), two were softer (0.49 and 0.92 mm/N) and one adaptation stimulus had the same compliance as the reference. One soft adaptation stimulus was chosen to have the same physical difference to the reference stimulus as the hard adaptation stimulus and the other soft adaptation stimulus had a greater difference. Two soft adaptation stimuli were used to account for potential effects of the nonlinearity of the perceptual softness space, which was found to be a power function with a negative exponent (-0.8) of the physical space [19]. Consequently larger physical differences in compliance between the reference and the softer adaptation stimulus might be required to achieve perceived differences in softness which yield well observable adaptation effects.

Given that the dimension of softness is encoded in narrowly tuned channels [5], [3] – as it seems to be the case for other perceptual dimensions – we can expect that the reference stimulus is perceived to be softer with preceding adaptation to a harder stimulus and harder when the finger is adapted to a softer stimulus as compared to the perception without adaptation. In the case of the adaptation to the stimulus with the same compliance, no perceptual shift can be expected.

2 Experiment

2.1 Methods

Participants. 10 right-handed participants were tested (5 males, mean age: 24.2 years, range: 19-30 years). They were naïve to the purpose of the experiment, volunteered to participate and were refunded. None of them reported any sensory or motor impairment of the index fingers at both hands. The study was approved by the local ethics committee LEK FB06 at Giessen University and was in line with the declaration of Helsinki from 1964. Written informed consent was obtained from each participant.

Apparatus. The experiments were conducted at a visuo-haptic workbench, which comprised a PHANToM 1.5A haptic force feedback device, a 22"-computer screen (120 Hz, 1280x1024 pixel), stereo glasses, a mirror and a force sensor consisting of a measuring beam (LCB 130) and a measuring amplifier (GSV-2AS, resolution 0.05 N, temporal resolution 682 Hz). Three real silicon rubber stimuli - one adaptation stimulus, the reference and one comparison were placed side-by-side in front of the participant. The adaptation stimulus and the reference were placed on the force sensor, which recorded the force exerted by the participant (Fig. 1). The mirror prevented direct sight on the stimuli. To guide the participants through the experiment, a virtual schematic 3D-representation of the stimuli and the finger (a sphere of 8 mm diameter; hidden during stimulus exploration) were displayed on the monitor, which was positioned over the mirror. Additionally signal tones were displayed via headphones. The virtual representation of the setup, viewed via stereo glasses, was aligned to its real counterpart in a way that the participant had the impression to directly view the real setup. The head was stabilized by a chin rest limiting the viewing distance to 40 cm. The left index finger was connected to the PHANToM which detected its position via a custom-made adapter. The adapter consisted of a pin with a metallic ball affixed to its end and a plastic fingernail with a magnet on its outer surface. The plastic fingernail was affixed to the dorsal side of the finger via an adhesive deformable pad and via the magnet to the metallic pin, which was attached to the PHANToM arm. This way the adapter left the finger pad uncovered and allowed for free finger movements including all six degrees of freedom. A custom-made software controlled the experiment, collected responses and recorded relevant parameters every 3 ms.

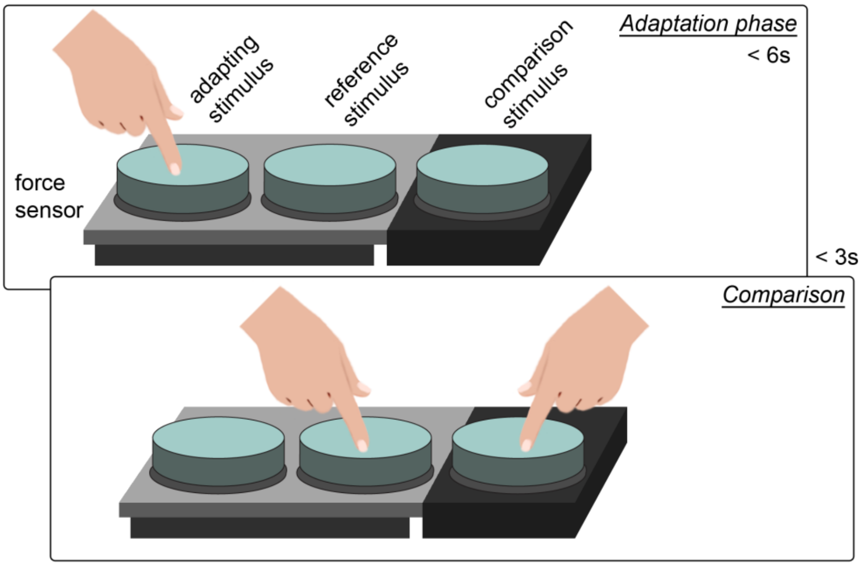

Fig.1. The arrangement and exploration of the stimuli during the adaptation and the comparison phase.

Softness Stimuli. We produced stimuli with varying compliance using a two-component silicon rubber solution (AlpaSil EH 10:1), which was mixed with different amounts of a diluent (polydimethylsiloxane, viscosity 50 mPa·s). The stimuli were cast in cylindrical plastic dishes (75 mm diameter x 38 mm high) and had no discriminable differences in size and texture. The compliance was measured using the experimental apparatus. For this purpose instead of the finger-adapter a flat–ended cylindrical probe of 1 cm^2 area ('standard finger') was fixed to the PHANToM arm. This standard finger was pressed 5 times into the stimulus using forces approximately between 15N and 25N. To calculate the compliance we fitted regression lines to the measured displacement–force traces for forces of 0-9 N and estimated the slopes. We used only the trajectories caused by the increase of force for analysis, to exclude hysteresis effects during the decrease of force. Possible non-uniformity in data sampling during the measurement due to manual indentation of the stimuli were reduced by calculating mean displacements for every 1N step over bins of +/-0.4 N. For further details and discussion on the measurement method see [10].

We produced two sets of rubber stimuli – a set of adaptation stimuli consisting of three stimuli and a set of test stimuli, consisting of one reference and ten comparison stimuli. In the test set, half of the comparisons had increasingly lower compliance and the other half increasingly higher compliance as compared to the reference. As reference we used a stimulus with 0.32 mm/N compliance. The compliances of the harder comparisons were 0.16, 0.19, 0.23, 0.26 and 0.29 mm/N and of the softer comparisons 0.36, 0.39, 0.43, 0.46 and 0.49 mm/N. The compliance difference between two neighbored comparison stimuli was about 1/2 Weber fraction and the range covered by the comparisons was about 2.5 Weber fractions in each direction. We assumed the Weber fraction to be 20% (value from [10]). To reduce effects of wear we produced each stimulus of the test set in two similar versions. The use of the two versions was balanced. The adaptation set comprised three stimuli. The hard adaptation stimulus was about 2.5 Weber fractions harder (0.16 mm/N) than the reference stimulus. There were two soft adaptation stimuli, one which had approximately the same difference to the reference as the hard adaptation stimulus but in opposite direction (0.49 mm/N, about 2.5 Weber fractions softer) and another, which was even softer (0.92 mm/N, about 9 Weber fractions softer). Additionally we used a stimulus with approximately the same compliance as the reference as an adaptation stimulus. It was balanced between participants which version of this stimulus served as reference stimulus and which version served as adaptation stimulus.

Design. The experimental design comprised the within-participant variable *Compliance of Adaptation Stimulus* $a \in [\,0.16, 0.32, 0.49, 0.92]\; mm/N$. We measured individual Points of Subjective Equality (PSEs) of the reference stimulus which was explored with the index finger that was adapted to one of the adaptation stimulus (adaptation conditions) or not adapted (baseline condition). The PSE was assessed as compared to comparison stimuli which were always explored with the other index finger that was not adapted. We used a two-alternative-force-choice task combined with a 1-Up-1-Down staircase paradigm, to measure the PSEs. We analyzed the differences caused by adaptation as compared to the baseline condition.

Procedure. In total four staircases were performed for each condition: two downwards-directed staircases, which started with the comparison stimulus of highest compliance in the test set and two upward-directed staircases, which started with the comparison stimulus of lowest compliance in the test set. The comparison stimulus for the next trial in the staircase was determined by the response of the participant. In case the participant responded that the comparison felt softer than the reference, the next comparison in the staircase was chosen to be harder (0.03 mm/N step). Whereas, a softer comparison was presented in the next trial of the staircase if the comparison felt harder. In case the participant perceived the softest comparison of the test set as softer or the hardest comparison as harder, the same comparison was presented again in the next trial for this staircase. The estimation of the PSE by one staircase was considered terminated after 10 reversals. A reversal refers to the change of direction in the staircase, which occurs when participants change their judgment from softer to harder and vice versa. The 10 reversals were reached on average after 17.66 trials.

The experiment was split into two sessions. In each session the PSE for each condition was estimated by completion of one downwards and one upwards directed staircases. Each session consisted of blocks in which the current step of each staircase was presented once, in a randomized order. Each block consisted originally of 10 trials (two staircases per condition). Towards the end of one session the number of trials in a block decreased, because the number of terminated staircases increased. There were pauses of 1 min duration after each 45 trials (about every 15 min). Before the first session the participants completed a practice session consisting of 8 trials to familiarize with the setup and the task.

Before each adaptation trial one adaptation stimulus and the reference were placed on the force sensor. The adaptation stimulus was always placed on the left side and the reference was always placed on the right side of the force sensor. The comparison stimulus was placed to the right of the reference (Fig. 1). A tone presented via headphones signaled the beginning of the trial. A visual representation of the adaptation stimulus was displayed and participants were instructed to indent the stimulus 5 times with the left index finger by increasing the force up to 15N and decreasing it then again down to 3N. The force was visualized by a schematic level indicator gauge in which the level increased in 3N steps and turned red when the force exceeded 15N. Additionally a signal tone indicated when the force had increased to 15N and decreased to 3N. If the participant did not reach the threshold of 3N or 15N once, the number of required indentations increased. The adaptation phase had to be completed within 6s. Thereafter visual representations of the reference and the comparison stimuli were displayed. A different signal tone indicated that the participant should start to compare these two stimuli within the next 3s (a countdown was displayed). Participants indented the reference stimulus with the left index finger and the comparison stimulus with the right index finger simultaneously and only once. Participants were instructed to touch each stimulus in its center and to restrict the contact with the stimuli to the touch of the upper surfaces. After the exploration the participants decided which stimulus had felt softer by pressing a virtual decision button. The participants did not receive any feedback about the correctness of their response. In order to allow for readaptation, the participants had to wait for 20 s before the next trial started. Trials of the baseline condition directly started with comparing the reference and the comparison stimulus. In all other aspects these trials were identical to trials in the adaptation condition including the final period of readaptation. Between trials the experimenter manually changed the stimuli. A trial was repeated later in the block, in case the duration of adaptation exceeded 6s or if after adaptation more than 3s passed before the participant started to explore the reference and the comparison stimulus.

Analysis. For each participant and each condition we calculated the PSEs as the mean over all comparisons at which a reversal occurred (40 for each condition). We individually subtracted the baseline PSE from the PSEs with adaptation. These individual PSE shifts entered a one-way repeated measurements ANOVA with the within-participant factor *Compliance of Adaptation Stimulus*. We tested whether the individual adaptation stimuli shifted the PSE significantly away from the baseline with one-sided paired *t*-tests for all adaptation stimuli besides the adaptation stimulus with approximately the same compliance as the reference, for which we used a two-sided *t*-test (in total 4 comparisons). Additionally we performed individual regressions of the log10 of relative PSE shifts (ratio between the PSE with adaptation and the baseline PSE) on the log10 compliance of the adaptation stimulus. The log-log scaling was chosen to account for the power function between physical and perceived softness [19].

2.2 Results

Fig. 2 depicts the individual and average PSE shifts of the reference stimulus in the adaptation conditions relative to the baseline condition without adaptation (ratio between the PSE with adaptation and the baseline PSE) in log-log space. The PSE increased with preceding adaptation to a stimulus with lower compliance and decreased after adaptation to a stimulus with higher compliance. That is, the reference was perceived to be softer after the finger had been adapted to a harder stimulus and it was perceived to be harder when a softer stimulus was touched before. The main effect of the factor *Compliance of Adaptation Stimulus* was significant, $F(3,9) = 19.31$, $p < 0.001$. The linear models fitted individually to the log10 relative PSE shifts and log10 compliance of the adaptation stimulus described the individual data quite well (average variance explained $r^2 = 0.81$). Also the overall linear model fit the data well ($r^2 = 0.60$) and, thus, explained well the between participant variance. The slopes of the regression functions were significantly negative as confirmed by a one-sample *t*-test against zero, $t(9) = -4.9$, $p < 0.001$. Comparisons against the baseline, revealed, that adaptation to a harder stimulus induced a significant shift to a softer percept, $t(9) = 5.27$, $p < 0.001$ as also adaptation to a stimulus with approximately the same compliance as the reference stimulus, $t(9) = 4.24$, $p = 0.002$ (two-sided test). The PSEs shifted to a harder percept after the adaptation to the softer stimuli. The shift was significant for the stimulus with the larger difference to the reference stimulus (0.92 mm/N) $t(9) = -2.47$, $p = 0.018$ and not significant for the other softer adaptation stimulus (0.49 mm/N) $t = -1.46$ $p = 0.089$.

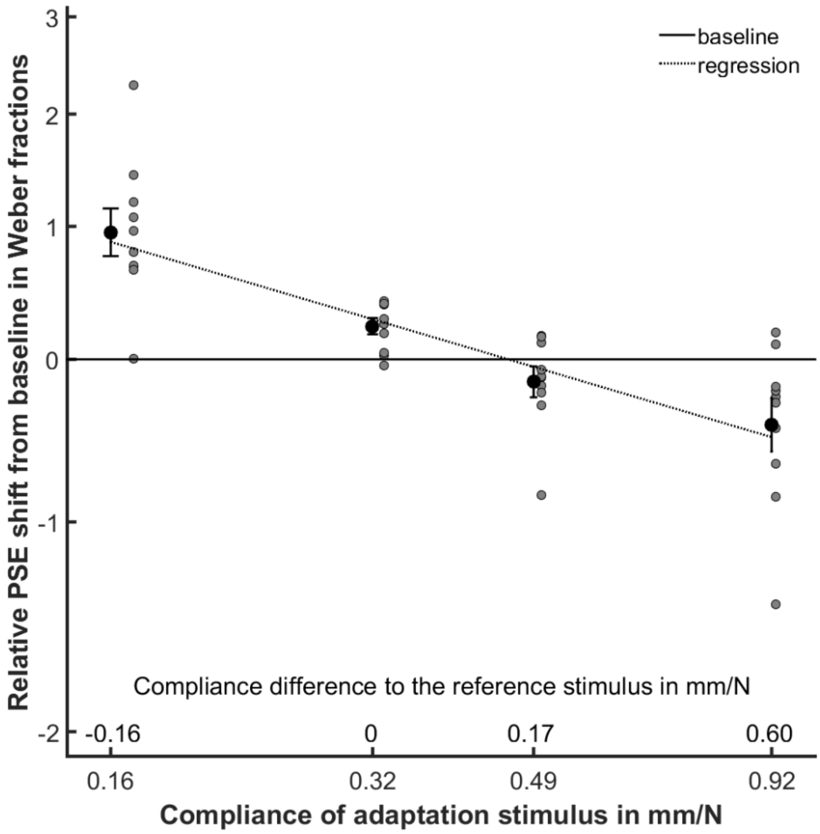

Fig.2. Average (black dots) and individual (grey dots) shifts of the PSE with adaptation as compared to the baseline PSE without adaptation ($PSE_{with\ adaptation}/PSE_{baseline}$). PSE shifts are plotted as a function of the compliance of the adaptation stimulus in log-log space. Y-axis is spaced in Weber fractions (1 Weber fraction = 20%).

2.3 Discussion

In the present study we investigated the impact of adaptation on haptic softness perception. Participants compared two silicon rubber stimuli - a reference and a comparison stimulus - by exploring them simultaneously with their two index fingers. In adaptation trials an adaptation stimulus was indented 5 times with considerable force by one finger before exploring the reference stimulus with the same finger. We found that preceding sensory experience influenced perceived softness. The reference stimulus was perceived to have different softness, depending on the sensory history of the exploring index finger. After the finger was adapted to a comparably harder stimulus the reference was perceived as being softer and after the finger was adapted to comparably softer stimuli it was perceived as being harder. As could be expected from the properties of the perceptual space [19], a larger perceptual shift (about 1 Weber fraction) was induced by the adaptation to a harder stimulus than by the adaptation to a softer stimulus with the same difference in compliance to the reference. The adaptation stimulus with a difference of about 9 Weber fractions shifted the perception of the reference stimulus by about 1/2 Weber fraction. However, the perceptual shifts fall on a straight line in the log-log space, indicating that adaptation causes shifts along the perceptual dimension of softness. We found "repulsion aftereffects", i.e. perceptual shifts in the opposite direction as compared to the physical difference between the adaptation stimulus and the reference. This was observed for most of the previously studied aftereffects [1] and it is in concordance with the multiple channel model of adaptation.

We found also a significant shift in the perception of the reference's softness after adaptation to a stimulus with approximately the same physical compliance. This finding implies that extended exploration of an object's softness makes it appear softer. The multiple channel model of adaptation does not necessarily predict a shift from self-adaptation. However, there are many examples in visual perception with a similar form of adaptation: prolonged viewing at colors let them fade away, faces appear more average, blurred or sharpened images appear more focused [1]. These aftereffects are referred to as renormalization aftereffects. It is suggested that this kind of aftereffects can be observed when the perceptual dimension is represented in the activity of rather broadly tuned channels and the information is encoded as the difference to a unique neutral status rather than by absolute values [1]. According to this model adaptation would modulate the sensitivity of all channels inducing a shift of the neutral point towards the adaptation stimulus. Consequently after prolonged exploration of a stimulus, the same stimulus would appear closer to the neutral point [1]. A similar mechanism is also imaginable for softness perception, as the compliance of the finger might be the neutral point and thus the division between "hard" and "soft" [20]. Adaptation to our rather hard reference stimulus [20] would hence shift the neutral point to a harder value. When the reference is presented again it would appear to be closer to the neutral point and hence perceived to be softer.

It has also to be mentioned that adaptation likely begins at the receptor level and affects the processing of the stimulus at different sensory and perceptual levels. It was e.g. shown that local adaptation to simple shapes can induce face aftereffects [21]. Hence, the observed perceptual shift in the perception of the adaptation stimulus itself might be the result of a renormalization or similar process at one of the processing levels involved in softness perception.

Taken together our results suggest that, like several haptic properties [8], also softness perception is changed by preceding sensory experience. A physically unchanged stimulus is felt to be softer after adaptation to a comparably harder stimulus and harder after adaptation to a softer stimulus. The bidirectionality of this perceptual shift is in concordance with the multiple channel model of encoding [5], [3]. Changed perception of the adaptation stimulus might be a result of a renormalization process. However, further research is required to reveal perceptual representation of softness.

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