Haptically perceived softness of deformable stimuli can be manipulated by applying external forces during the exploration*

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Abstract—**The perception of softness is the result of the integration of information provided by multiple cutaneous and kinesthetic signals. The relative contributions of these signals to the combined percept of softness was not yet addressed directly. We transmitted subtle external vertical forces to the exploring human finger during the exploration of deformable silicone rubber stimuli to dissociate the force estimates provided by the kinesthetic signals and the efference copy from cutaneous force estimates. This manipulation introduced a conflict between the cutaneous and the kinesthetic/efference copy information on softness. We measured Points of Subjective Equality (PSE) of manipulated references to stimuli which were explored without external forces. PSEs shifted as a linear function of external force in predicted directions - to higher compliances with pushing and to lower compliances with pulling force. We found relative contribution of kinesthetic/efference copy information to perceived softness being 23% for rather hard and 29% for rather soft stimuli. Our results suggest that an integration of the kinesthetic/efference copy information and cutaneous information with constant weights underlies softness perception. The kinesthetic/efference copy information seems to be slightly more important for the perception of rather soft stimuli.**

I. INTRODUCTION

Softness is the subjective measure of an object’s ability to deform under pressure. The physical correlate of perceived softness is *compliance*, which is defined as the ratio between displacement of the object's surface and the force applied to the object. The information about softness is usually gathered by an active, successive manipulation of the object. Typically humans perform a stereotypical movement (*Exploratory Procedure* of *Pressure* [1]) in which they press the finger pad into the object or squeeze it between two fingers. The resulting haptic perception is commonly viewed to be mediated by two afferent subsystems: *cutaneous* and *kinesthetic* [2]. The cutaneous subsystem involves the mechanoreceptors innervating the skin of the finger pad and refers to the sense of the nature of contact with the object [3]. The kinesthetic information provided by muscles, tendons and perhaps joints refers to the sense of position and motion of limbs along with the associated forces [3]. Though softness is mainly perceived through haptic information, it has been shown that also available visual information can play a role in perceiving softness [4], [5], [6], [7], [8]. It has been further suggested that the central neural system uses an *efference copy* of its motor commands to generate an internal representation of the current state of the motor system (‘forward model’) which is used to estimate the sensory and motor consequences of the performed movements without sensory delay [9]. This is necessary to correct motor output, by adjusting movements, as well as to correct sensory information by distinguishing between self-generated and external sensory activation (reviewed in [10]). Focusing on perception, the efference copy signal could be considered as additional sensory information which is integrated with the afferent information (similar reasoning see in [11] on the size-weight illusion). In haptic softness perception such an internal representation might provide additional information about force applied by the finger.

Aiming to analyze the contribution of the different haptic signals to the perception of softness, previous work mostly focused on limiting the availability of haptic information and comparing discrimination performance. In their pioneering work, Srinivasan and LaMotte [3] conducted a series of ranking and discrimination experiments with silicone rubber stimuli, in which they partly excluded signals associated with softness perception. The authors showed that cutaneous information is sufficient for softness perception. In a condition, where the stimuli were passively touched, that is only cutaneous signals were available, the performance was good. However, when the compliant specimens were covered by rigid surfaces, passive touch was not sufficient to judge softness and kinesthetic information had to be added. Given these results, it can be assumed that, the cutaneous information includes information about the dynamics of the object’s surface during the touch, which can be substituted with kinesthetic information if the surface is not deformable. This indicates that the surface dynamics can be estimated with both subsystems – cutaneous and kinesthetic. It is reasonable to assume, that redundancy applies also for the estimation of applied force. Using a similar experimental paradigm Bergmann Tiest and Kappers [12] extended the results of Srinivasan and LaMotte, by theoretically quantifying the contributions from the cutaneous and the kinesthetic information to the perception of softness. For this purpose they assumed that the information provided by the two sensory subsystems is integrated in a statistically optimal fashion [13]. This implies that the combined estimate of softness results from weighting the estimates from the

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cutaneous and kinesthetic subsystems according to their variance and averaging them. Consequently, this assumption allows to calculate the relative contribution of the two sensory signals from their variance which can be measured as precision in a discrimination task. In one of the experiments of Bergmann Tiest and Kappers the participants compared silicone rubber stimuli (approximately ranging between 0.1 and 0.6 mm/N) by squeezing them between two fingers. The precision in a condition using bare fingers was compared to the precision in a condition where the compliant specimens were covered by rigid surfaces, thus cutaneous information about surface dynamics was absent. From the comparison of discrimination thresholds they concluded that the majority (90%) of the information in perceiving softness originates from the cutaneous perception of surface deformation. Kinesthetic information would then contribute just 10% to the combined estimate of softness.

However, with the experimental approaches used in previous work the relative contribution of the different haptic signals to softness perception remains (1) limited, because only those signals which can be isolated can be analyzed and (2) speculative because the calculated weights are only valid if the assumption of optimal integration holds. In the present study we introduce a paradigm, (1) to analyze also the signal from the efference copy, which might play a role in softness perception but cannot be isolated and (2) to directly measure the relative contribution of different haptic signals in softness perception - cutaneous vs. kinesthetic and efference copy signal, without the assumption of statistically optimal integration. The main methodological advantage of our paradigm, which allows to overcome the limitation and the dependency from the assumptions on the integration in previous work, is that we disentangle the cutaneous and the kinesthetic/efference copy signals by selective perturbation, while both types of signals were available. This allows to directly estimate the signals' contributions to the percept of softness independent of whether the integration is optimal or not. The perturbation was implemented as application of subtle external forces. We used pushing or pulling forces, which were calculated as a fraction from the force the participants applied themselves, each in two levels: 11% and 16%. The force was transmitted during the exploration of deformable silicone rubber stimuli to the participants’ finger. We assumed that two estimates of softness are formed using the cutaneous and kinesthetic/efference copy information about displacement of the object’s surface and the interaction force. Further we assumed that external forces would not change the cutaneous estimate of softness, because the ratio of the cutaneously sensed force and surface displacement is independent of the total force (applied + external force). In contrast, the kinesthetic/efference copy estimate of softness would change with external force, because the kinesthetic information about the surface displacement changes as a function of total force, while the kinesthetic/efference copy force estimates would not take the external force in account and reflect just the force applied by the participant. We assume this, because the finger of the participant is passively moved by external force, thus kinesthetically, only the force applied by the participant is sensed through the Golgi tendon organ, which provides information about the tension of the muscle. Also the information about force conveyed by the efference copy of the motor command refers just to the force applied by the participant. In consequence if e.g. a pushing force would be used, the kinesthetic subsystem and the efference copy would underestimate the total force, resulting in an overestimation of compliance, i.e. a softer percept. Compliance should be estimated to be 11% or 16% larger, because in the kinesthetic/efference copy estimate of the displacement-force ratio the force estimate should be 11% or 16% smaller as compared to the cutaneous estimate. Analogously, if a pulling force is used, the kinesthetic subsystem and the efference copy should overestimate the force, resulting in an underestimation of compliance (11% or 16% greater dividend in the displacement-force ratio as compared to the cutaneous estimate). This conflict between the two estimates of softness would result in a shift of the perceived softness. Assuming that the cutaneous estimate would be accurate, it would be the same as in the condition without external force. When expressing the relative perceptual change as a function of external force this estimate would refer to the zero line (slope = 0). In contrast the kinesthetic/efference copy estimate of softness would change as a function of external force. The relative perceptual change would be equal to the relative force modulation and thus refer to the unity line (slope = 1). If the combined estimate results from the integration with constant weights for both signals which sum up to 1, it should refer to a line located between the zero and the unity lines, with a slope reflecting the weight of the kinesthetic/efference copy signal.

II. EXPERIMENT

We conducted a discrimination experiment, where we measured the Points of Subjective Equality (PSE) for the perception of softness of silicone rubber stimuli, by combining a 2-IFC paradigm with staircase methods. In each trial participants compared a reference stimulus with a comparison stimulus from one series of comparisons. We used reference stimuli with two different basic compliances: one rather hard (0.32 mm/N) and the other rather soft (0.67 mm/N). When participants explored the reference stimuli, a PHANToM force feedback device transmitted external forces to the exploring finger; comparison stimuli were always explored without presenting any external forces. Because we aimed to manipulate the slope of the displacement-force function, the total force had to be proportional to the finger force applied by the participant. Thus the external force was calculated as a fraction of the finger force applied by the participant. We presented each of the two reference stimuli with pulling and pushing vertical forces in two levels (-16%, -11%, +11%, +16%) and in a control condition without external force.

A. Methods

Participants — 10 students - naïve to the purpose of the experiment - participated for pay (9 right-handed, 1 left-handed, mean age 23.8 years, range 19-29 years, 4 females, 6 males). None of them reported sensory or motor impairments of the index finger at the dominant hand. Informed consent was obtained from each participant. The study was approved by the local ethics committee LEK FB06 at Giessen University.

Apparatus — Participants sat in front of a visuo-haptic workbench (Figure 1), which comprised a PHANToM 1.5A haptic force feedback device, a 22"-computer screen (120 Hz, 1280x1024 pixel) and a force sensor. The force sensor consists of a measuring beam (LCB 130) and a measuring amplifier (GSV-2AS, resolution 0.05 N, temporal resolution 682 Hz). Force-feedback devices are often used to simulate haptic objects. In our experiment we used the PHANToM to measure the position of the index finger and to transmit external forces to the finger during the exploration of silicone rubber stimuli. The stimuli were located on the force sensor and the participants touched them with their index finger using a downwards directed movement being connected to the PHANToM arm.

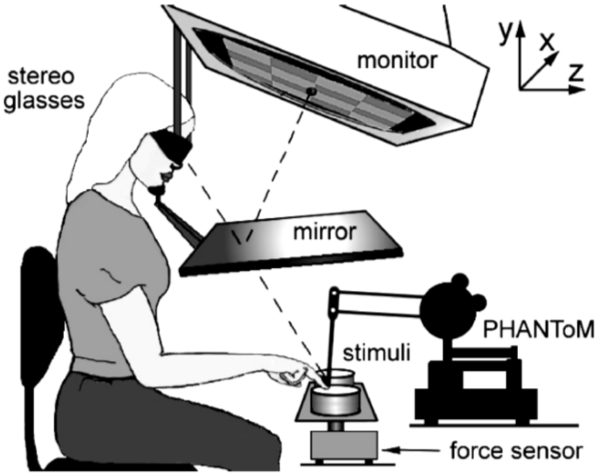

Figure 1. Experimental setup

To connect the participant's index finger to the PHANToM we used a custom-made gimbal-like adapter (Figure 2). The adapter do not cover the finger pad to allow direct touch and has no vertical degrees of freedom to ensure the transmission of forces. It allows for controlled inclination of the finger, which is required for a natural and comfortable exploration of the stimuli. To ensure that the center of mass as also the calibrated zero-position of the PHANToM do not change due to the change of the inclination, we used a circular design for the adapter, in which the inclination is achieved by rotating the main gimbal of the adapter around the center of mass. The participants could adjust the adapter to their preferred inclination between 0° to 40° before the experiment, which was then fixed during the experiment. To exclude any movement of the finger without the adapter, the adapter was additionally affixed to the dorsal side of the finger by adhesive deformable pads. The weight of the adapter was counterbalanced with a constant upward force produced by the PHANToM (0.2 N). Attached to the PHANToM the participants were able to move freely in a 38x27x20 cm workspace.

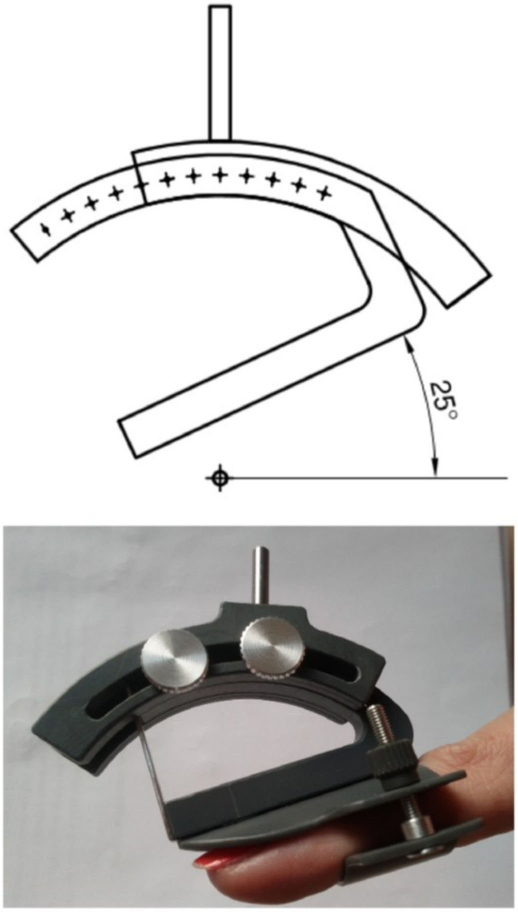

Figure 2. The adapter (scheme and real) used to connect the index finger of the participant to the PHANToM arm.

Via the adapter external forces were transmitted to the index finger. Forces were transmitted in vertical direction, either pushing the finger into the rubber stimulus orthogonal to the stimulus' surface or pulling it out of the stimulus. The amounts of external force were fixed fractions (11% and 16%) of the force applied by the participant. The total of vertical forces was measured with the force sensor. In order to calculate the force applied by the participant, we subtracted the external force, which we transmitted at the previous time point from the value measured by the force sensor. The force values were updated every 3 ms.

To guide the participants through the experiment and control the available visual information a virtual, schematic 3D-representation of the finger and the stimuli was displayed. The participants looked at it from 40 cm viewing distance, fixated by a chin rest, via stereoglasses and via a mirror (Figure 1). The mirror prevents participants from seeing their hand and enables spatial alignment of the 3D-visual with the haptic display. A custom-made software controlled the experiment, collected responses and recorded finger positions and reaction forces every 3 ms. White noise presented via headphones masked sounds.

Stimuli — Silicon rubber discs were cast in plastic dishes (75 mm diameter x 38 mm high). The compliance was varied by mixing a two-component silicon rubber solution (Alpa Sil EH 10:1) with varying amounts of a diluent (polydimethylsiloxane, viscosity 50 mPa·s). The surfaces of the stimuli were flat and had no discriminable differences in texture and size. We created two series of stimuli, a hard and a soft one, each consisting of one reference stimulus and 10 comparison stimuli. One half of comparisons had increasingly lower compliance, the other half increasingly higher compliance as compared to the reference. The compliance difference between two neighbored comparison stimuli was 1/2 Weber fraction and the range covered by the comparisons was 2.5 Weber fractions in each direction. Different Weber fractions of about 20% and 15% were used for the hard and the soft series respectively. The values are taken from [14]. The compliance of the hard reference was 0.32 mm/N and the step size 0.03 mm/N. The comparisons were 0.16, 0.19, 0.23, 0.26, 0.29, 0.36, 0.39, 0.43, 0.46 and 0.49 mm/N. The soft series had a reference with a compliance of 0.67 mm/N and a step size of 0.05. The comparisons in this series were 0.47, 0.52, 0.56, 0.62, 0.72, 0.77, 0.82, 0.87 and 0.92 mm/N. To measure compliance we used our experimental environment but exchanged the adapter by a flat–ended cylindrical probe of 1 cm^2 area ('standard finger'). The 'standard finger' was then repeatedly pressed into the stimulus. The compliance was calculated as the slope of the regression line, fitted to the measured displacement– force traces. We only used data from indentations to avoid hysteresis effects. Forces of 0-9 N were analyzed. Possible biases from non-uniformly distributed data collection were avoided by calculating mean displacements from bins of +/-0.4 N using steps of 1 N. For further details and discussion on the measurement method see [14].

Design, Procedure and Data Analysis — The experimental design comprised two within-participant variables: *Softness Series* (hard vs. soft) and *External Force* (-16%, -11%, +/-0%, +11%, +16%), resulting in 10 conditions. For each condition we measured individual PSEs of the manipulated reference stimulus as compared to non-manipulated comparison stimuli. For that purpose we used a two-interval-force-choice task combined with a 1-Up-1-Down staircase paradigm.

The participants used the index finger of their dominant hand for the exploration of the stimuli. During the experiment the current finger position was displayed as a small sphere (8 mm diameter) and used to control the course of the experiment. In the beginning of each single trial one stimulus was displayed on the screen as a three-dimensional cylindrical disc on the left or the right side of a virtual 3D-scene. A signal tone indicated that the participant could start the exploration. The participants were instructed to press only once in the middle of each stimulus, which was visually displayed as a cross. During the indentation into the stimulus (force > 0.1 N) the visual finger representation was hidden to prevent the availability of visual information about the object's compliance. As soon as the first stimulus was touched the second stimulus appeared on the corresponding other side of the scene. After the participants had explored the second stimulus they decided which one had felt softer. For this purpose they moved their finger to one of the decision buttons displayed above each stimulus. The participants did not receive any feedback about the correctness of their response. Between the trials the participants moved their finger to an indicated position in the corner of the 3D-scene to wait until the experimenter manually changed the stimuli as indicated by a display on a separate screen. The order (first, second) and the position (left, right) in which the stimuli were presented were randomized.

There were four staircases for each condition. In two staircases in the first trial the reference stimulus was paired with the comparison stimulus of highest compliance in the series (downwards-directed staircase). The other two staircases started with the comparison stimulus of lowest compliance in the series (upwards-directed staircase). The comparison stimulus for the next trial in the staircase depended on the participant's response. In case the comparison felt softer to the participant than the reference, the next comparison in the staircase would have been less soft (0.03 mm/N step for the hard and 0.05 mm/N step for the soft reference). In case the comparison felt harder, a less hard comparison would have been presented in the next trial of this staircase. In case the calculated comparison was out of the range of the staircase, which was possible for the most outer comparisons, 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 PSEs for each condition were then calculated as the mean over all comparisons at which a reversal occurred (40 for each condition).

The experiment consisted of blocks in which the current step of all staircases was presented once. The trials in each block were randomized. The total duration of the experiment was about 5 h. The experiment was split into two sessions (2.5 h each, on 2 days within one week). In each session the estimation of the PSE of each condition was completed by one upwards and one downwards directed staircases. To keep the participants concentrated, avoid tiredness of the finger and to mask the change of the blocks small pauses were interspersed after each 45 trials (about every 15 min). In the first session before the experiment the participants completed a practice session consisting of 10 trials to familiarize with the setup and the task. After the last session participants completed a survey, in which they reported whether they noticed differences between the trials, to assess whether they could perceive the external forces.

B. Results

The results from the survey confirm that the participants were not aware of external forces. For all force conditions we observed a shift in the PSEs in the predicted direction. In Figure 2 all measured PSEs are expressed relatively to the PSEs in the no force condition (zero line) and plotted as a function of the magnitude of external force. The data indicate that with pushing external force participants perceived the reference stimuli to be softer as compared to the condition with not manipulated force, whereas when we externally transmitted a pulling force, the same reference stimuli appeared harder. With the highest fraction of external force (16%) the PSEs shifted by approximately 4% for both the soft and the hard references. The effects of external forces were analyzed using one-tailed *t*-tests. In both series the PSEs of the reference were significantly higher with pushing forces (+11% and +16%) as compared to the no force condition (hard, +11%: $t(9)=-2.05$, $p=0.035$; hard, +16%: $t(9)=-2.21$, $p=0.027$; soft, +11%: $t(9)=-1.90$, $p=0.045$; soft, +16%: $t(9)= -6.07$, $p<0.001$). In the conditions with pulling forces (-11% and -16%) the PSEs were overall lower than in the no force condition but a significant deviation was only found in the soft condition with 16% pulling force (soft, -16%: $t(9)=3.63$, $p=0.003$). However to further analyze the relationship between the magnitude of external force and the resulting PSE shifts we performed a liner regression of the relative PSE shift on the magnitude of external force. The resulting regression lines are plotted as dashed lines in Figure 3. The linear trend was significant for both compliance series (hard: $F(1,8)=17.69$, $p<0.001$; soft: $F(1,8)=41.96$, $p<0.001$).

The slopes of the regression lines were 0.23 for the hard and 0.29 for the soft series and the intercepts were 0.86 in the hard condition and 0.64 in the soft condition. In order to test the difference between the slopes for the hard and the soft conditions, we performed separate linear regressions on the data of individual participants. A paired *t*-test showed a significant difference in the average slope between the hard and the soft condition ($t(9)=3.28$, $p=0.010$). To analyze whether the functions are asymmetric, we performed a *t*-test analysis, which showed that the intercepts of regression functions are not significantly different from zero, for both the hard ($t(9)=1.03$, $p=0.328$) and the soft ($t(9)=0.65$, $p=0.534$) series.

C. Discussion

We investigated the effect of the transmission of external force to the exploring finger on the perceived softness of silicone rubber stimuli. External forces were not noticed by the participants. Our underlying assumption was that the percept of softness is the result of the integration of two estimates for softness provided by the cutaneous information and the information conveyed by the kinesthetic afferent subsystem and the efference copy. Thus by introducing a conflict between the two estimates we would be able to shift the perception of softness. To introduce a conflict we transmitted external forces. We speculated that external forces change the kinesthetic and the efference copy displacement-force ratio because the external forces are not included in the force estimate formed by kinesthetic information and the efference copy but effectively contribute to the kinesthetically perceived displacement of the surface. For the cutaneous subsystem the displacement-force ratio would be unaffected by external forces because they will be included in the cutaneous force

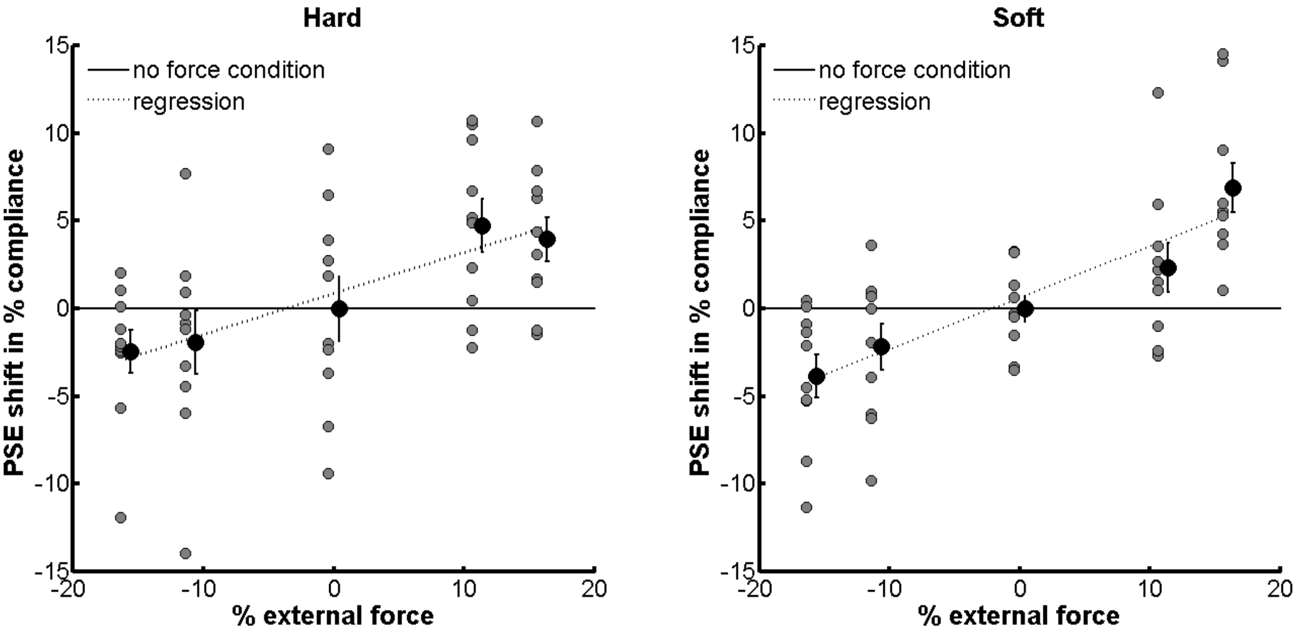

Figure 3. Individual (grey dots) and average (black dots) PSE shifts as a percentage of the PSEs in the no external force condition with standard errors. Values are given as a function of the magnitude of external forces and of the softness series

estimate and will be effective in the sensed surface displacement. Thus we speculated that the cutaneous receptors would provide an accurate estimate of the softness associated with the object's softness, but the softness estimated by the kinesthetic signal and the efference copy would be higher or lower by the percentage of the external pushing or pulling force (11% or 16%). For all force conditions we indeed found shifts in the PSEs in the predicted direction. With a pushing force the same stimuli were judged to be softer and with a pulling force they were judged to be harder. The significant linear trend in the relationship between the magnitude of external force and the resulting PSE shift supports the assumption that external force introduces a conflict in haptic signals for softness, which are integrated with constant weights. Another possible explanation, for the linear trend could be that the perceived magnitude of softness depends on the interaction force. This would mean that participants generally tend to perceive objects softer when higher forces are associated ignoring the unchanged displacement-force ratios. Though there are several evidences to refuse this assumption. For example Friedman et al. showed that ratings of softness were independent of variations in compressional force [15].

The lack of a significant effect in most of the conditions with a pulling force might be due to a circumstance that the pulling forces were not consistently effective in the participants' perception of softness. One might speculate that the pushing and pulling forces transmitted by the PHANToM are differently interpreted by the perceptual system. The finger of the participants was fixed to the PHANToM via an adapter during the experiment. Maybe, a pulling force could be also interpreted as the resistance of the PHANToM arm or the adapter rather than being attributed to the stimulus. The difference between pulling and pushing force would then be that a resistance of the apparatus might be expected, but a supporting force might not. Given this speculation, the fraction of the external force that is attributed to the stimulus would have been reduced for the pulling force.

We further wanted to know, whether the external forces produce consistent effects over different compliances. For this purpose we measured the effects on two references with different compliances. The relationship between the magnitude of the external force and the PSE shift was slightly but significantly different for the two compliances used in the experiment. For the soft series the slope of the regression line was steeper than for the hard series, indicating that a greater PSE shift was caused by the same fraction of external force. This difference might be due to a different perceptual scale for hard and soft stimuli. Kaim and Drewing found different Weber fractions for different compliances [14]. They analyzed the discriminability of softness of silicone rubber discs using a hard reference, with a compliance of 0.159 mm/N and a soft one with the compliance of 1.250 mm/N. They found for the hard reference a Weber fraction of 13.5% whereas the Weber fraction for the soft reference was 21.2%. We tested whether the regression functions would still differ in slope when the PSE shifts were rescaled to the Weber fractions found by Kaim and Drewing. After rescaling, the difference between the regression functions was not significant but there was still a trend ($t(9)=2.07$, $p=0.070$). Thus it is possible that the function relating the magnitude of external force and the resulting PSE shift is actually slightly but significantly different. This would be in concordance with the finding of Bergmann Tiest and Kappers [12] that for different compliances the available signals contribute differently to the overall perception. They conducted matching experiment using stimuli with varying relation between stiffness (N/mm) and Young's modulus (N/mm^2, taking the surface area in account to which force is applied). They found that the participants' attention shifts more towards stiffness for soft stimuli and more towards Young's modulus for hard stimuli. This indicates a greater importance of the displacement-force ratio as provided by the kinesthetic subsystem for the soft stimuli and a greater importance for the deformation-force ratio as provided by the cutaneous subsystem for the hard stimuli. Thus the steeper regression function in the soft condition might reflect the higher weight of the kinesthetic estimate und thus a greater effect of external force as compared to the hard condition.

In the present study we directly measured the relative contributions of the estimates for force provided by the cutaneous information and the information from kinesthetic signals and the efference copy in softness perception. The measured weights for the kinesthetic and efference copy information are higher (23% for the hard and 29% for the soft condition) than this (10%) predicted by Bergmann Tiest and Kappers [12] from precision measurements under the assumption of statistically optimal integration. Our results are also valid without the assumption of optimal integration. They might then differ from the results of Bergmann Tiest and Kappers because haptic signals are integrated suboptimally.

Furthermore the results of our study show that a subtle transmission of external force in the vertical direction to the exploring finger (as a fraction relative to the force the participants apply themselves) can be used to purely hapticaly manipulate the perception of softness of silicone rubber stimuli during the exploration. This might be a useful tool for different questions addressing softness perception. A similar approach of softness manipulation was developed in the context of augmented reality [16], [17]. The authors developed algorithms to augment the stiffness of real objects. Similarly to our approach, the stiffness of real elastic objects was manipulated using external forces. The difference is that the cutaneous information about surface deformation was excluded (uninformative), because the objects were explored with a palpation tool. The approach was tested in a discrimination experiment, where participants were asked to compare the hardness of a real reference stimulus with modulated stiffness and a virtual comparison stimulus. The participants could not directly touch the stimuli but were instructed to use a palpation tool to which external forces were transmitted. In concordance with our findings, the authors show that stiffness of real stimuli could be manipulated by external forces, though the effect might be only due to partially lacking cutaneous information. Our study additionally shows that external forces can be used to alter objects' softness with all haptic signals being available.

Taken together, our results suggest that the perception of softness is the result of weighted integration of the cutaneous information and information provided by the kinesthetic subsystem and the efference copy. The kinesthetic signal and the information from the efference copy about force contribute to 23% for rather hard and for 29% for rather soft stimuli. The concrete nature of the integration of the haptic signals in softness perception as well as a possible systematic relationship between the weights of kinesthetic and efference copy information and the compliance of objects require further investigation.

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REFERENCES

[1] S.J. Lederman and R. L Klatzky, “Hand movements: A window into haptic object recognition,” *Cognitive Psychology,* vol. 19, no. 3, pp. 342-368, 1987.

[2] S.J. Lederman and R. L Klatzky, “Haptic perception: A tutorial,“ *Attention, Perception, & Psychophysics,*vol. 71, no. 7, pp. 1439-1459, 2009.

[3] M.A. Srinivasan and R.H. LaMotte, “Tactual Discrimination of Softness,“ *J. Neurophysiology*, vol. 73, no. 1, pp. 88-101, 1995.

[4] M.A. Srinivasan, G.L. Beauregard, and D.L.Brock, “The impact of visual information on the haptic perception of stiffness in virtual environments,“ *Proceedings of the ASME Dynamic Systems and Control Division*, vol. 58, pp. 555–559, 1996.

[5] A. Lécuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet, “Pseudo Haptic Feedback: Can Isometric Input Devices Simulate Force Feedback?” *Proc. Virtual Reality Ann. Int'l Symp.,* pp. 83-90, 2000

[6] M. Kuschel, F. Freyberger , B.Färber, and M. Buss, “Visual-haptic perception of compliant objects in artificially generated environments,“ *Visual Computer*, vol. 24, no. 10, pp. 923–931, 2008.

[7] C. Cellini, L. Kaim, and K. Drewing, “Visual and haptic integration in the estimation of softness of deformable objects,“ *i-Perception,* vol. 4, no. 8, pp. 516-531, 2013.

[8] K. Drewing, A. Ramisch, and F. Bayer, “Haptic, visual and visuo-haptic softness judgments for objects with deformable surfaces, “ *Hollerbach J (ed) Proc. 3rd Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, IEEE, Salt Lake City, UT, USA*, pp. 640–645, 2009.

[9] R.C. Miall and D.M. Wolpert, “Forward models for physiological motor control,“ *Neural Networks*, vol. 9, no. 8, pp. 1265-1279, 1996.

[10] K.E. Cullen “Sensory signals during active versus passive movement,“ *Current Opinion in Neurobiology*, 2004, vol. 14, no. 6, pp. 698-706, 2004.

[11] L.A. Jones, “Motor Illusions: What Do They Reveal About Proprioception?,“ *Psychological Bulletin*, vol. 103, no. 1, pp. 72-86, 1988.

[12] W.M. Bergmann Tiest and A.M.L. Kappers, “Cues for haptic perception of compliance, “ *IEEE Transactions on Haptics*, vol. 2, no. 4, pp. 189–199, 2009.

[13] M.O.Ernst and M.S. Banks, “Humans integrate visual and haptic information in a statistically optimal fashion,“ *Nature*, vol. 415, no. 6870, pp. 429-433, 2002.

[14] L. Kaim and K. Drewing, “Exploratory strategies in haptic softness discrimination are tuned to achieve high levels of task performance,“ *IEEE Transactions on Haptics 4,* pp. 242-252, 2011.

[15] R.M. Friedman, K.D. Hester, B.G. Green, and R.H. LaMotte, “Magnitude Estimation of Softness,” Experimental Brain Research, vol. 191, no. 2, pp. 133-142, 2008.

[16] S. Jeon, S. Choi, “Haptic Augmented Reality: Taxonomy and an Example of Stiffness Modulation,” *Presence: Teleoperators and Virtual Environments*, vol. 18, no. 5, pp. 387-408, 2009.

[17] S. Jeon, S. Choi, “Real stiffness augmentation for haptic augmented reality,” *Presence: Teleoperators and Virtual Environments*, vol. 20, no. 4, pp. 337-370, 2011.