It is not Likely that Tactile and Kinesthetic Information are Integrated According to Maximum-Likelihood

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***Abstract*— We investigated if the two haptic modalities (kinesthetic and tactile) may be integrated according to maximum likelihood. We designed two stiffness discrimination tasks in which participants received varying levels of kinesthetic (load force) and tactile (skin stretch) information. Two different methods were designed to manipulate the uncertainty in the haptic modalities with the goal of affecting the weighting between them. We did not succeed in creating tactile uncertainty, but did successfully create kinesthetic uncertainty. Our results suggest that tactile and kinesthetic information are not integrated according to maximum likelihood.**

I. Introduction

The nervous system integrates tactile information, sensed by mechanoreceptors, and kinesthetic information, sensed by our muscles and tendons, to form stiffness perception. Tactile stimulation in the form of artificial skin stretch has been shown to increase the perceived stiffness of objects [1], yet how tactile and kinesthetic information are combined is currently unknown. In a study on the integration of visual and haptic information, Ernst and Banks [2] found the weighting between them to be in accordance with maximum likelihood integration by introducing uncertainty into the visual information.

We set out to find if the integration of tactile and kinesthetic information may too be in accordance with maximum likelihood. If so, kinesthetic uncertainty would cause a decrease in the weight attributed to the kinesthetic information and an increase in the weight given to the tactile information. As the tactile information includes artificial skin stretch, which increases the perceived stiffness, maximum likelihood would predict an even larger perceptual augmentation. Contrarily, tactile uncertainty would cause a decrease in the weight attributed to the tactile information, leading to the prediction of a decrease in the augmentation effect caused by the artificial skin stretch.

II. Methods

The participants sat in front of a virtual reality system which contained a haptic device and a screen that blocked the view of their hand. Participants probed virtual objects and received both kinesthetic and tactile feedback. The kinesthetic feedback was generated by a haptic device (PHANTOM® Premium 1.5 haptic device (Geomagic)), and the tactile feedback was created using a skin stretch device that was mounted on the haptic device. Participants grasped the skin stretch device with the thumb and index finger of their dominant right hand. Tactors came into contact with the skin of the fingers and moved in the vertical direction to stretch the skin. The movement of the tactors and the kinesthetic force were applied when participants were in contact with a virtual object. The stimuli were proportional to the penetration into the object, and the proportion gains were defined by the tactor displacement gain and object stiffness level, respectively.

We conducted two forced-choice experiments in which participants probed pairs of virtual objects and decided which was stiffer. The stiffness level of the *comparison* object changed between trials, whereas the *standard* object had the same stiffness levels for all the trials, and in some trials had an added element of uncertainty. Both experiments contained 40 different standard-comparison pairs (four standard conditions, and 10 comparison stiffness levels), each of which was repeated eight times. Participants completed the resulting 320 test trials over two days, and began each session with 20 training trials. All participants signed an informed consent form approved by the Human Subject Research Committee of Ben-Gurion University of the Negev, Be’er Sheva, Israel.

In **Experiment 1** (N=25) we attempted to introduce uncertainty into the tactile information by adding within-probe noise to the skin stretch signal. The four *standard* conditions were: (1) a baseline condition in which no artificial skin stretch was applied; (2) skin stretch with no noise; (3) skin stretch with low noise; and (4) skin stretch with high noise. The standard object stiffness level was 85 [N/m], and in the skin stretch conditions, skin stretch with a constant mean tactor displacement gain of 66 [mm/m] was applied. In both noise conditions, we added tactile noise to the linear skin stretch signal. The noise was a sum of five sinusoid functions [3], which differed in their frequencies (between 10Hz and 12Hz) and phases (selected arbitrarily). There were two noise levels, defined by a gain that multiplied the noise signal, creating a low and high noise level.

In **Experiment 2** (N=20) the goal was to introduce uncertainty into either the kinesthetic or tactile information by introducing variability between the eight consecutive probes participants made into each of the virtual objects. The four experimental conditions were: (1) baseline; (2) kinesthetic force (stiffness level of 85 [N/m]) with skin stretch (tactor displacement gain of 85 [mm/m]); (3) kinesthetic variability; and (4) tactile variability. In the kinesthetic variability condition, the standard object had a constant tactor displacement gain of 85 [mm/m] and the eight stiffness levels were selected from a normal distribution $k_i \sim N(85, 26)$ [N/m]. In the tactile variability condition, the stiffness level

*Research supported by the ABC Robotics Initiative at BGU, the BSF (grant no. 2016850), and the ISF (grant 823/15). MF is supported by the Negev Fellowship. HK is supported by the Lachish and Ariane de Rothschild fellowships

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was 85 [N/m] and the tactor displacement gains were chosen from a normal distribution $g_i \sim N(85, 26)$ [mm/m].

For each of the experimental conditions, we fit psychometric curves to the probability of responding that the comparison was stiffer than the standard, as a function of the difference between the stiffness levels of the two objects. We then computed the Point of Subjective Equality (PSE – a measure of bias in the perceived stiffness) and Just Noticeable Difference (JND –an indication of the amount of uncertainty) and examined the effect of each of the experimental conditions on these two values using Repeated Measures ANOVA. The independent variables were the experimental condition (fixed categorical, df=3), and the participants (random, df=N-1). Following this, we performed post hoc t-tests to compare between every two conditions with the Holm-Bonferroni correction for multiple comparisons.

III. Results

The psychometric curves of typical participants from Experiments 1 and 2 are presented in Fig. 1(a) and Fig. 2(a), respectively. In both plots, in all the conditions with skin stretch, regardless of the noise (Experiment 1) or variability (Experiment 2), the curves were shifted rightward, indicating an increase in the perceived stiffness. The effect of the different conditions on the PSE and JND are presented in Fig. 1(b-c) for Experiment 1, and Fig. 2(b-c) for Experiment 2.

In **Experiment 1** the artificial skin stretch, both with and without the noise, increased the perceived stiffness [Fig. 1(b); PSE, rm-ANOVA, main effect of 'tactile feedback': $F_{(3,72)} = 29.54$, $p < 0.0001$], however post hoc t-tests revealed no significant difference between them. Furthermore, the addition of the noise to the skin stretch did not increase participants' uncertainty more than the skin stretch without the noise (Fig. 1(c)).

In **Experiment 2** all three artificial skin stretch conditions increased the perceived stiffness [Fig. 2(b); PSE, rm-ANOVA, main effect of 'tactile feedback': $F_{(3,57)} = 13.86$, $p < 0.0001$]. Post hoc t-tests showed no significant difference between the effect of artificial skin stretch with and without tactile variability on the perceived stiffness and measure of uncertainty (Fig. 2 (b) and (c)). On the other hand, kinesthetic variability did increase the uncertainty and may have led to a decrease in the augmentation caused by the artificial skin stretch (Fig. 2 (b) and (c)).

IV. Discussion

We investigated if tactile and kinesthetic information may be integrated in accordance with maximum likelihood by introducing uncertainty [2] into each of the haptic modalities to affect the weighting between them. In Experiment 1, we found no difference between the effect of skin stretch with and without noise both on the perceived stiffness and measure of uncertainty. Gurari et al. [4] showed that adding haptic white gaussian noise degraded participants' ability to perceive stiffness. However, in [4] the noise was low-pass filtered with a cutoff frequency of 2 Hz and added to the kinesthetic information, whereas our higher frequency noise was added to the tactile information.

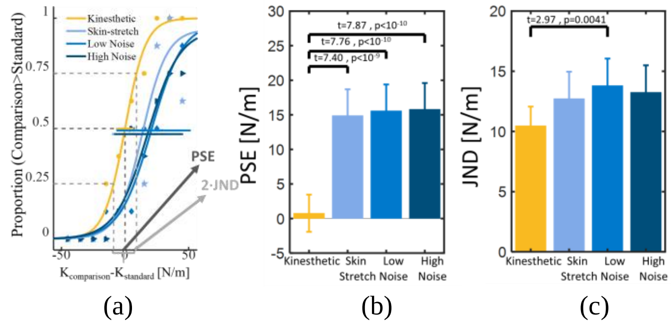

Figure 1. Experiment 1 results. (a) An example of the psychometric curves of a typical participant for the different experimental conditions. (b) and (c) The average PSE and JND values of all the participants (N=25) as a function of the different experimental conditions, respectively.

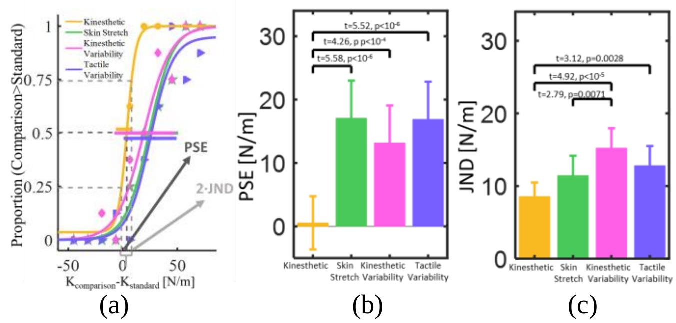

Figure 2. Experiment 2 results. (a) An example of the psychometric curves of a typical participant for the different variability conditions. (b) and (c) The average PSE and JND values of all the participants (N=20) as a function of the different variability conditions, respectively.

Although Experiment 1 shed light on the effect of noisy skin stretch, it did not indicate if tactile and kinesthetic information might be integrated according to maximum likelihood. In Experiment 2, we found that skin stretch with and without tactile variability had a similar effect on both the perceived stiffness and uncertainty. This result, coupled with that of Experiment 1, demonstrates the robustness of the effect caused by artificial skin stretch. Kinesthetic variability did lead to kinesthetic uncertainty. In this event, maximum likelihood predicts a larger increase in the perceived stiffness than that caused by the skin stretch alone. However, our results showed that this was not the case, and that the kinesthetic uncertainty may have had the opposite effect (albeit not statistically significant). This leads us to believe that tactile and kinesthetic information are not integrated according to maximum likelihood and leads to the question, how are the two integrated? In our future work we will conduct additional experiments to answer this question.

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