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To cite this version:
Alessandro Moscatelli, Matteo Bianchi, Alessandro Serio, Alexander Terekhov, Vincent Hayward, et al.. The Change in Fingertip Contact Area as a Novel Proprioceptive Cue. Current Biology - CB, 2016, 10.1016/j.cub.2016.02.052 . hal-01301663

HAL Id: hal-01301663
https://hal.sorbonne-universite.fr/hal-01301663
Submitted on 12 Apr 2016

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The Change in Fingertip Contact Area as a Novel Proprioceptive Cue

Highlights
- Pushing a finger against a soft surface provokes an increase of the contact area
- This increase in contact area potentially provides a cue to finger displacement
- We ran psychophysical experiments to test this hypothesis
- Results revealed a novel proprioceptive cue, i.e., the change in contact area

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In Brief
Pushing a finger against an external surface provokes an increase of the contact area. Moscatelli, Bianchi, et al. show with psychophysical experiments that this increase in contact area provides a cue to finger displacement, similarly to looming in vision. Their results show that the change in contact area provides a novel proprioceptive cue.
The Change in Fingertip Contact Area as a Novel Proprioceptive Cue

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SUMMARY

Humans, many animals, and certain robotic hands have deformable fingertip pads [1, 2]. Deformable pads have the advantage of conforming to the objects that are being touched, ensuring a stable grasp for a large range of forces and shapes. Pad deformations change with finger displacements during touch. Pushing a finger against an external surface typically provokes an increase of the gross contact area [3], potentially providing a relative motion cue, a situation comparable to looming in vision [4]. The rate of increase of the area of contact also depends on the compliance of the object [5]. Because objects normally do not suddenly change compliance, participants may interpret an artificially induced variation in compliance, which coincides with a change in the gross contact area, as a change in finger displacement, and consequently they may misestimate their finger’s position relative to the touched object. To test this, we asked participants to compare the perceived displacements of their finger while contacting an object varying pseudo-randomly in compliance from trial to trial. Results indicate a bias in the perception of finger displacement induced by the change in compliance, hence in contact area, indicating that participants interpreted the altered cutaneous input as a cue to proprioception. This situation highlights the capacity of the brain to take advantage of knowledge of the mechanical properties of the body and of the external environment.

RESULTS

The size of the image that an object projects on the retina, referred to as the retinal size of the object, changes with the distance of the object to the observer. In order to use the retinal size as a depth cue, observers assume heuristically that two otherwise identical objects in the visual scene, such as two identical columns in a colonnade, have the same physical size [4]. A violation of this assumption produces a misestimate in the perceived depth. For instance, the baroque architect Borromini scaled the physical size of the columns in the colonnade of Galleria Spada to produce an illusory sensation of depth [6]. Similarly, a progressive increase in the retinal size of an object produces the sensation of the object approaching the observer, a phenomenon known as visual looming [7–9]. In this study, we investigated whether an analog of looming exists in the sense of touch and whether the tactile system can be deceived, similarly to vision, by altering unbeknownst to the observer some of the object properties that are usually assumed to remain stable.

The formation of contact between the skin of the fingertip and an external object produces a progressive recruitment of strained tissue that evokes characteristic neural responses [10–12]. Thus, in principle, an observer could infer the relative displacement of the finger from this change in the area of contact, because a larger area corresponds to a greater finger displacement from initial contact (Figure 1). The rate of change of the area of contact also depends on the compliance of the object that the observer can estimate by combining multisensory cues and prior knowledge [5, 13]. Compliance is usually a stable property of each specific object. If the compliance of a given object would suddenly change between two sequential tactual interactions, an observer might attribute the resulting change in the contact area to a difference in the finger indentation. This occurrence should result in a misestimate of the relative finger displacement. Therefore, by modifying the compliance of an object in a controlled manner, we can quantitatively assess the contribution of the change in gross contact area as a cue to relative finger displacement.

Each trial consisted of a reference and a comparison stimulus randomly presented in two sequential time intervals. In each interval, the elastic surface of the apparatus (Figure 2) was lifted to come in contact with the participant’s index finger and to passively move it up and down. Participants reported in which of the two intervals the extent of the angular displacement of the finger (i.e., the angle $\gamma$ in Figure 2B) was greater. In each of the two
Figure 1. The Change in Contact Area
(A) The area of contact between the skin and the silicon increases as the finger moves toward the bottom edge of the object.
(B) The increase in the area recorded from the camera of the softness display for a surface compliance comparable with the silicon. The expanding contact area can be seen as successive frames of a movie of a looming stimulus.
(C and D) A more-compliant object is associated with a higher rate of change of the area of contact.

Figure 2. Experimental Setup and Protocol
(A) The setup included the lift, the softness display FYD-2, and the angle encoder. The FYD-2 modified the compliance of an elastic contact surface by adjusting its stretching state. A rotational spring produced a linear increase of the force exerted by the finger on the surface through the lifting phase of the stimulus. (Adapted with permission from Moscatelli, Bianchi, et al., Eurohaptics Conference 2014, Paris.)
(B) In each interval, the elastic surface (in red in the figure) was lifted to contact the participant’s index finger and to passively move it up and down. The angle of the metacarpo-phalangeal joint, γ, was measured from the angle encoder and used to control the movement of the lift.

the point of subjective equality (PSE) from each psychometric function corresponding to the stimulus value yielding a response probability of 0.5. If participants used the change of the contact area as a cue for the finger displacement, as in hypothesis 3, the PSEs would be significantly different between the two experimental conditions, with \( PSE_{\text{large}} < PSE_{\text{small}} \). We analyzed the data of all participants (n = 11) using a paired t test and confirmed the result with a generalized linear mixed model (GLMM) \([16]\).

Overall, the value of the \( PSE_{\text{large}} \) was significantly lower than the \( PSE_{\text{small}} \) (paired t test; \( t_{10} = 4.47; p = 0.001 \), in accordance with hypothesis 3 (Figure 3C). The mean of the difference was 2.2°, corresponding to 18% of the reference stimulus (12°). The GLMM confirmed the result of the t test. Accordingly, the 95% confidence interval (CI) of the difference in PSEs did not include zero (95% CI: 10.1° - 11.3°). The PSE was significantly lower than the reference stimulus in the large condition (\( PSE_{\text{large}} = 10.7°; 95\% \text{CI}: 10.1° - 11.3° \)) and significantly higher in the small condition (\( PSE_{\text{small}} = 12.7°; 95\% \text{CI}: 12.2° - 13.2° \)). The GLMM fit is illustrated in Figure S1 and shows that the effect sign was consistent across participants. In summary, a more-compliant surface produced a greater expansion of the area of
contact, which was in turn associated with a greater perceived angular displacement of the finger.

In experiment 1, the difference in compliance between the two conditions generated small differences in finger kinematics. The initial movement of the lift (Figure 2) produced an increase in the conditions generated small differences in finger kinematics. The initial movement of the lift (Figure 2) produced an increase in the contact, which was in turn associated with a greater perceived angular displacement of the finger.

In summary, we provided evidence that observers were sensitive to the change in the area of contact with an external surface and used it as a cue to the relative motion of the finger, i.e., as a cue for proprioception. The change in contact area is qualitatively different from other displacement cues because it provides information that is expressible in units of surface and not in units of length. This observation raises the question about the integration of this newly described cue with other proprioceptive cues. Landy et al. proposed a model for the integration of qualitatively different cues in vision, known as “modified weak fusion” [20]. We applied a similar model to our results (Supplemental Experimental Procedures and Figure S3). The model was based on a two-step algorithm. The contact area cue was first calibrated (or promoted) using auxiliary information (i.e., with auxiliary
proprioceptive cues conveying information expressed in units of length). In the second step, the calibrated cue was combined with the other cues to provide the fused estimate. The model predicted that the perceptual bias was proportional to the difference in contact area (computed at the same angular displacement of 12') between the reference and the comparison stimulus. Hence, the model predicted a negative bias for the large condition and positive bias for the small condition and a larger absolute value of the bias in case of the large condition. The two predictions were consistent with the results of the experiment 1. The weight of the area-based cue in the fused estimate changed between the two experimental conditions, in accordance with a robust estimation hypothesis [20].

Visual and tactile looming are both ambiguous cues. In vision, the retinal size of an object depends multiplicatively on its actual size and on its proximity to the viewer. In touch, the tactile size of a deformable object depends multiplicatively on its compliance and on finger displacement. In touch, as in vision, the observer can resolve these ambiguities by assuming object constancy, i.e., by assuming that objects have a constant size [4], or a constant compliance. A Bayesian model assuming an observer’s prior belief that the compliance of a given object does not change fits our behavioral data with the consequence that a violation of the constancy assumption generates a perceptual illusion. To use Palmer’s words [4], “constancy and illusion are therefore opposite sides of the same perceptual coin.”

DISCUSSION

Many mammals, birds, and other species have soft pads on the volar side of their extremities. The soft pads rapidly conform to external surfaces ensuring secure grips and stable interactions with objects [1]. Soft fingers have been also used in robotic hands to increase grasp stability [2, 21]. Besides having advantages for grasping, the patterns of pad deformation (such as the change in contact area and the deformation due to slip and roll motion) also provide rich information to the tactile system [12]. The evolution of skin strain patterns during tactile slip provides relative motion information similar to optic flow in vision [22]. Observers can reproduce displacement paths by integrating tactile slip motion over time [23] and experience the shape of curved objects from a rolling interaction of finger pads with an object [24]. The evolution of the gross contact area provides information about the softness of touched objects [5, 15, 17–19], a finding which is confirmed by our third experiment.

Although the role of pad deformation in cutaneous touch is well established, its contribution to proprioception is less clear. In the present study, we demonstrated that a change in the contact area provides a cue to finger displacement relative to an object. According to classical studies in physiology, muscle spindles, Golgi tendon organs, and receptors in the joints provide crucial information on the static position and movement of our limbs [25]. Information from cutaneous mechanoreceptors also contributes to our sense of position [26–28]. Stretching the skin around the proximal interphalangeal joint, i.e., around the second knuckle, induced a vivid sensation of movement in anesthetized fingers [29]. Furthermore, during the movement of the elbow joint, skin stretch in a direction in line with muscle stretch applied simultaneously with external vibrations increased the perceived movement sensation [30]. The literature has largely overlooked the role of finger pad deformation due to object interaction as a cue to relative motion. In the current study, changes in the gross contact area produced during the indentation of an elastic surface induced a sensation of relative finger motion. Recently, it was found that, when pushing with a finger against a stiff, stationary object, microscopic fluctuations in the counter-surface could elicit a sensation of finger displacement [27]. These results provide converging evidence that an important source of proprioceptive information comes from skin deformation during interaction with external objects.

In the experiments presented here, the change in gross contact area provided a motion cue that could be compared to looming in vision. This effect, termed “tactile looming,” supports the hypothesis that similar motion detection processes are implemented in vision and touch [31]. In the two sensory systems, a 2D sensory sheet (i.e., the retina or the skin) provides important information about the relative motion of our own body with respect to external objects. Moreover, previous studies showed an analog of visual looming in audition [32, 33], which might suggest a canonical computation of looming stimuli across different senses.

SUPPLEMENTAL INFORMATION

Supplemental Information includes three figures and Supplemental Experimental Procedures and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2016.02.052.

AUTHOR CONTRIBUTIONS

A.M., M.B., A.S., V.H., M.O.E., and A.B. conceived and designed the experiments. M.B., A.M., and A.S. performed the experiments. A.M. and M.B. analyzed the data. A.T. developed the explanatory model. All authors interpreted results of experiments. A.M., M.B., and A.S. prepared figures. A.M. and M.B. drafted the manuscript. All authors edited, revised, and approved the final version of the manuscript.

ACKNOWLEDGMENTS

This work was partially supported by the European Commission funded projects WEARHAP (project 601165), SOMA (project 645598), and SOFTPRO (project 688857) and by ERC Advanced Grants 291166 SoftHands and 247300 Patch. Preliminary results from experiment 1 (sample size = six participants) were presented at the Eurohaptics Conference 2014 (Paris) and were awarded the Best Paper Award (poster presentation). We thank Simone Fani, Omar Al Atassi, Simone Ciotti, and Mattia Poggiani for helping with the apparatus and Irene Senna, Cesare V. Parise, Jessica Hartcher-O’Brien, and Francesco Lacquaniti for useful comments and suggestions.

Received: September 16, 2015
Revised: February 3, 2016
Accepted: February 19, 2016
Published: April 7, 2016

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