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Research report

Path integration in tactile perception of shapes

Alessandro Moscatelli [a,b,*], Abdeldjallil Naceri [a,b], Marc O. Ernst [a,b]

[a] Cognitive Neuroscience Department, Bielefeld University, 33615 Bielefeld, Germany
[b] Cognitive Interaction Technology—Center of Excellence, Bielefeld University, 33615 Bielefeld, Germany

HIGHLIGHTS

- We studied path integration in the tactile system.
- Participants estimated the path of a moving tactile stimulus.
- Similar response pattern as in navigation studies involving locomotion.
- Direction bias that we explained the as a motion aftereffect.

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ABSTRACT

Whenever we move the hand across a surface, tactile signals provide information about the relative velocity between the skin and the surface. If the system were able to integrate the tactile velocity information over time, cutaneous touch may provide an estimate of the relative displacement between the hand and the surface. Here, we asked whether humans are able to form a reliable representation of the motion path from tactile cues only, integrating motion information over time. In order to address this issue, we conducted three experiments using tactile motion and asked participants (1) to estimate the length of a simulated triangle, (2) to reproduce the shape of a simulated triangular path, and (3) to estimate the angle between two-line segments. Participants were able to accurately indicate the length of the path, whereas the perceived direction was affected by a direction bias (inward bias). The response pattern was thus qualitatively similar to the ones reported in classical path integration studies involving locomotion. However, we explain the directional biases as the result of a tactile motion aftereffect.

1. Introduction

Whenever we move the hand across a surface, proprioceptive signals provide information about the velocity and the position of the hand with respect to the body. At the same time, tactile signals provide information about the relative velocity between the skin and the surface. If the system were able to integrate tactile velocity over time, cutaneous touch may also provide an estimate of the relative displacement between the hand and the surface. Here, we asked whether humans are able to form a reliable representation of a motion path from tactile cues only, integrating cutaneous motion information over time.

Humans are sensitive to tactile motion cues, which do not require temporal integration, such as the orientation, the direction, and the speed of motion [1–3]. To form a global motion percept, the tactile system spatially integrates the local motion signals provided by primary afferents across the skin [4]. Accordingly, Pei and colleagues showed that the perceived direction of motion of a plaid surface (i.e., a surface formed by superimposing two gratings of different orientations) is the result of spatial integration of the different local motion components [5]. Conversely to decode the motion path of an object sliding over a fixed area of the skin, direction and speed information, which are directly available to the nervous system [6–9], would need to be integrated *over time*. However, it is still unknown whether the tactile system can actually integrate tactile motion information over time in order to from a spatial representation of the tactile path.

Here, we developed three experimental paradigms to address the issue of path integration in touch. These tasks may be considered as the tactile equivalent of a well-established locomotion

* Corresponding author at: Bielefeld University, Universitätstrasse 25, D-33615 Bielefeld, Germany. Tel.: +49 521 106 6861; fax: +49 521 106 5701.
E-mail addresses: alessandro.moscatelli@uni-bielefeld.de, moskante@gmail.com (A. Moscatelli).

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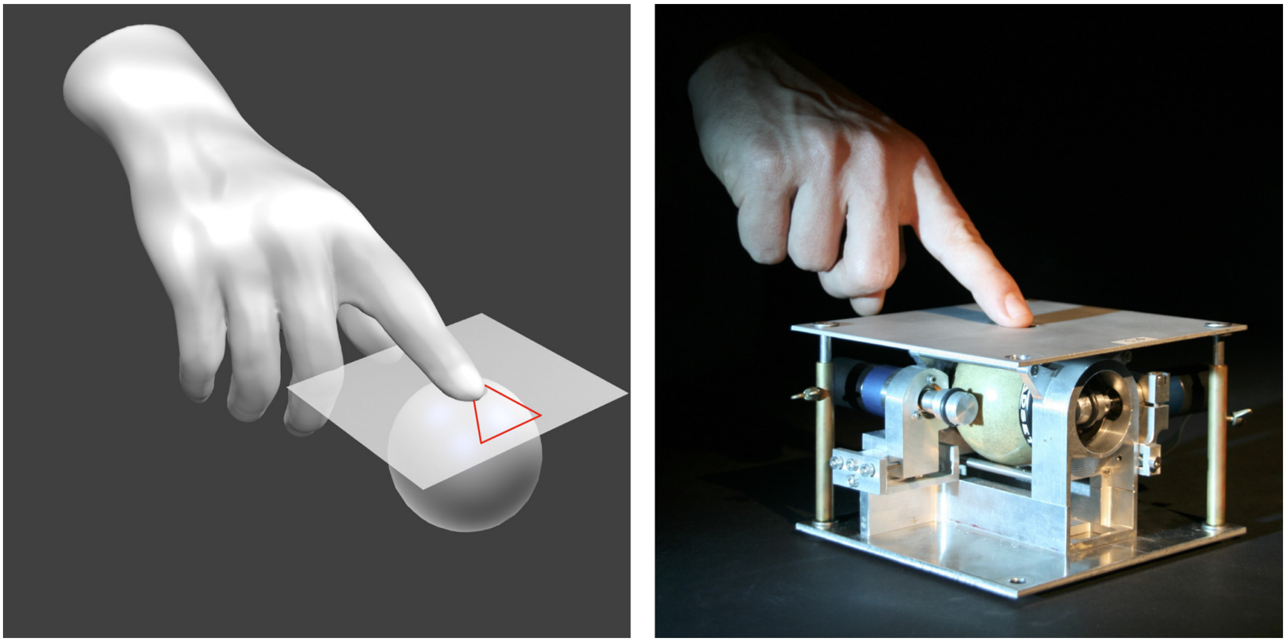

Fig. 1. The device and the tangential motion of the ball in the transverse plane. In Experiments 1–3, tactile stimuli were generated by means of the Slip Force Device, which consists of a billiard ball driven by two servomotors and it provides slip forces in both lateral axes of the fingertip. The participants touched the ball through a small aperture of 2 cm diameter in the cover plate. For the purpose of our experiments, we considered the tangential motion of the ball in the transverse plane. The red path shows an example of path in the transverse plane.

task—the triangle completion task [10,11]. In the locomotion task, a blindfolded participant is guided along an L-shaped path and then asked to walk back to the starting position along the shortest path, that is, via the hypotenuse of the triangle. Since the participant cannot use absolute landmark cues from, e.g., vision or audition, she/he has to integrate the velocity information over time in order to find back to the starting position (supplementary video SV1). This skill, based on both vestibular and proprioceptive cues, is usually referred to as *path integration* [11,12]. We developed the putative analogue in touch of this locomotion task (supplementary video SV2). Using the tactile device described in [13] we rendered the displacement of a surface along different paths. We asked participants to keep their hand world-stationary during the presentation of the stimulus. Therefore, proprioceptive and kinaesthetic inputs were not informative about the path of motion. Participants touched the moving surface with the tip of the index finger, and reported the perceived path length of the hypotenuse of a triangle using a discrimination task (Experiment 1). This experiment provides insights into the capabilities of humans to integrate tactile motion signals to form a spatial representation and a distance estimate. The results show that participants are surprisingly accurate to estimate the length of the hypotenuse. In order to further assess participants' ability to form a spatial representation of shape, in the second experiment participants had to reproduced a triangular-shaped path by drawing (**Experiment** 2). Next to information about distance perception from tactile motion, this experiment provided insights into the perceived direction of motion and shape perception. The results indicate that the angles of the triangle were systematically underestimated. In order to provide further insights into this underestimation of angle, in Experiment 3 we assessed the role of a potential motion aftereffect in tactile path integration. Indeed Experiment 3 revealed that the biases on the perception of the angle between two line segments were consistent with the interpretation of a tactile motion aftereffect distorting the orientation estimate of the second of two consecutively presented line segments. Taken together, the experiments reported below show that humans are surprisingly well able to integrate tactile motion information in order to form a spatial representation of shape.

2. Materials and methods

2.1. Participants

In total 21 naïve participants plus author AM (average age ± SD: 25 ± 4 years; 10 males; two of them were left-handed) participated in the three experiments. None reported any sensorimotor deficits. The sample size was 8 in Experiment 1a and 6 in Experiment 1b, Experiment 2a, Experiment 2b and Experiment 3. Six of the participants performed more than one experiment. All experiments were approved by the Ethics Committee of the University Clinics Tübingen, Germany. Informed written consent was obtained from all participants involved in the study.

2.2. Apparatus

In all experiments the tactile stimuli were generated by means of a Slip Force Device (Fig. 1; [13]). The device consisted of a billiard ball (diameter 6.02 cm) driven by two servomotors (Faulhaber DC-micromotors 2232UO24 combined with MCDC2805 Motion Controller) and it provided slip forces in both lateral axes of the fingertip. The two servomotors were orthogonally arranged, each with a driving wheel attached to its output shaft. These wheels rotated the ball in the two lateral axes of motion, thus causing slip friction to the fingertip of the participant (maximum torque: 523 mNm; maximum slip speed: 39.3 cm/s). As a consequence of the orthogonal arrangement of the driving wheels, each of the two lateral axes could be actuated independently using one motor each. Using both motors in combination, any linear combination of the axes was possible.

Each motor driver module included a closed-loop position/velocity control accessed via a serial RS-232 connection from the operating PC (resolution of the encoder: 512 pulses per revolution). We used a custom-made Matlab code to send commands