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Research report

The contribution of cutaneous and kinesthetic sensory modalities in haptic perception of orientation

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ABSTRACT

The aim of this study was to understand the integration of cutaneous and kinesthetic sensory modalities in haptic perception of shape orientation. A specific robotic apparatus was employed to simulate the exploration of virtual surfaces by active touch with two fingers, with kinesthetic only, cutaneous only and combined sensory feedback. The cutaneous feedback was capable of displaying the local surface orientation at the contact point, through a small plate indenting the fingerpad at contact. A psychophysics test was conducted with SDT methodology on 6 subjects to assess the discrimination threshold of angle perception between two parallel surfaces, with three sensory modalities and two shape sizes. Results show that the cutaneous sensor modality is not affected by size of shape, but kinesthetic performance is decreasing with smaller size. Cutaneous and kinesthetic sensory cues are integrated according to a Bayesian model, so that the combined sensory stimulation always performs better than single modalities alone.

1. Introduction

Free exploration of an object with bare fingers involves proprioceptor and cutaneous mechanoreceptor stimulation [17]. In particular the exploration of shape leads to the simultaneous stimulation to all four types of cutaneous mechanoreceptors in human glabrous skin, slowly adapting type I (Merkel, SAI) and II (Ruffini, SAII), fastly adapting I (Meissner, FAI) and II afferents (Pacininan FAII) [14].

Both kinesthetic and cutaneous afferent feedback affect human capability of distinguishing shapes and objects. During shape recognition procedures, active proprioception regards kinesthetic sense and it is related to a contour-following behavior, while passive cutaneous mechanoreception relies on the pressure or distortion applied on the human finger by the contact with an object [17].

The elimination of the cutaneous contribution in haptic exploration of shapes leads to a detriment of performance in resolving the orientation of raised bars, in locating 3-D artificial lumps in artificial “tissues” [16] and in discriminating objects with different compliance [22].

Also during the blind haptic exploration of common objects, the identification performance increases with the number of involved fingers only if the task is performed with bare fingers, but if hard sheaths are attached to the fingers inhibiting the cutaneous sensory modality [13] or if virtual shapes are explored with a haptic interface providing only kinesthetic feedback [8].

This suggests that the absence of cutaneous mechanoreception can blunt shape perception in haptic exploration of objects, and the kinesthetic sensory modality cannot compensate for the lack of the cutaneous information.

Haptic object recognition is determined by both material (texture, weight and compliance) and geometric (curvature, orientation, size) properties [2], and referring to the latter, local curvature, orientation and size stimulate mechanoreceptive afferents at contact [11].

In particular, according to the original psychophysics findings by Verrillo, Ruffini SAII receptors are responsible of the spatial summation of stimuli and sensitive to size of stimulation, while SAI receptors may play an important role in curvature discrimination being able to provide precise information about the skin contact with local contours, small and sharp borders [15,22], and responding with increased magnitude when in contact with spheres with increasing curvature [27].

Information about physical size may be more important for haptic than for visual object recognition and haptically perceived size typically depends on several factors, including the spread of the fingers on initial contact with an object and the compliance of the object's surface [4].

Haptic object representations are size-sensitive, in terms of generalization across changes in haptic object recognition. Haptic

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size-change costs are of the same order of magnitude as haptic orientation-change costs [5], and size is weighted strongly during the learning of haptic classification of 2-D planar shape differing for size, shape, texture, and hardness [20].

As far as curvature, different experimental studies have confirmed that curvature discrimination is linked to the perception of the orientation of the object's surface at the contact points, since local surface orientation seems to be a dominant source of information for haptic curvature not only in static conditions, but also in dynamic touch [26]. Curvature discrimination can be carried out providing only surface orientation/slope cues at the fingertip without any kinesthetic information and with a planar motion of the finger [6] and is significantly enhanced when both kinesthetic and cutaneous, as local surface orientation, cues are available to the user [9].

As far as orientation, according to Voisin et al. [25] both cutaneous (provided in passive touch condition) and kinesthetic modalities contribute to the perception of macrogeometric angles, suggesting that the 2D angle discrimination task is an integrative task relying on the two different cutaneous and kinesthetic submodalities. But the same authors in a following study [18], where cutaneous cues were provided in a active touch condition, found a contrasting evidence, since the performance in a task of haptic discrimination of 2-dimensional angles with the index finger did not improve with the addition of kinesthetic feedback.

In this study we hypothesize that the stimulation of mechanoreceptors in the fingerpad is fundamental for the perception of shape in active touch, and this information is integrated in synergy with perceptual information encoded through the kinesthetic sense.

As already found in curvature discrimination [9], we expect that the display of local surface orientation is sufficient also for the haptic discrimination of orientation and that the integration of kinesthetic and cutaneous modalities is performed within a Bayesian framework of multisensory integration [7], where each modality contributes in proportion to the reliability of its afferent sensory input. To analyze in deeper the role of kinesthetic and cutaneous modalities in haptic perception of orientation, in this study we have experimentally characterized the discrimination threshold for orientation during the haptic exploration of two virtual planar surfaces, under the feedback of cutaneous (C) only, kinesthetic (K) only or combined (KC) cues, through an experimental robotic apparatus specifically devised for this purpose. To take into account a possible cross-interaction between the two geometric factors of size and orientation, the experiment was conducted with different distances among the virtual planes.

According to a Bayesian framework of multisensory integration [12], we hypothesize that the integration of the two sensory modalities, cutaneous (C) and kinesthetic (K) is implemented at a perceptual level, in such a way that the observed combined (KC) performance S_{kc} of the single modalities can be explained as the linear combinations of the output of two shape unimodal estimators:

$$S_{kc} = w_c S_c + w_k S_k \tag{1}$$

The weights w_c and w_k are proportional to the reliability of each unimodal shape estimator S_c and S_k, and this reliability is inversely proportional to the variance of sensory afferents [7].

Based on the above finding, it can be deduced that each time both cutaneous and kinesthetic modalities are combined, a lower discrimination threshold should be obtained than single modalities.

2. Methods

2.1. Participants

Six male participants were recruited for the experiment. All were right-handed and did not have any dysfunction to the fingers or the hand. They were complete novices to haptic interfaces and they were informed about the procedure. They were not trained to use the experimental apparatus before the test and they were not informed about the aims of the experiment.

2.2. Experimental apparatus

The experimental apparatus was composed of two haptic interfaces, i.e. robotic systems devised to reproduce haptic stimulations, capable respectively of displaying cutaneous and kinesthetic cues.

The first apparatus, shown in Fig. 1, is a portable haptic interface for the stimulation of the fingertip composed of two thimbles that can be worn on two fingers through a circular ring where the finger is inserted, hereinafter called cutaneous haptic interface [21].

Each thimble is capable of displaying the local surface orientation at the contact point, by arbitrarily orienting in two directions around the fingertip a small circular plate (contact plate) through the action of two motors (orientation unit), so that the plate can be oriented always along the tangent plane to the virtual surface.

Moreover the distance of the plate from the finger is also regulated by another motor (actuation unit), so that the plate can be brought into contact with the fingertip with fast transition from the non-contact to the contact condition, giving the illusion of touching a surface.

Kinesthetic cues were displayed by means of a second apparatus, consisting of two robotic arms with 6 degrees of freedom each, hereinafter called kinesthetic haptic interfaces [3], that can display the force of contact with a virtual object at each point.

The cutaneous haptic interfaces are mounted through an orientation unit on the top of the two kinesthetic haptic interfaces, so that their weight is entirely sustained by the latter, as shown in Fig. 2. The rotational degrees of freedom of the orientation unit are sensed with three incremental encoders, so that the position and orientation of fingers during the haptic exploration is always measured. Moreover in this way, forces can be transmitted directly to the fingers, through the circular rings used to wear the active thimbles.

2.3. Stimuli

The participants, after wearing the thimble of the cutaneous haptic interface, could actively explore in the workspace two virtual planes, in such a way that they could squeeze them between the thumb and index fingers and freely move and orient their fingers with respect to the virtual surface (Fig. 3). The kinesthetic haptic interface simulated the contact with a force normal to the surface and proportional to the penetration into the surface, with a normal stiffness set to 1 N/mm. The plate of the cutaneous haptic interface touched the subject's fingertip exerting a force, also in this case, proportional to the penetration distance. As soon as the subject's finger came off the virtual plane, the plate did not touch the fingertip any more, and no feedback is provided. The plate was always oriented as the plane locally tangent to the virtual surface.

The experiment was conducted on the basis of a 2 × 3 within subjects factorial design, including two distance conditions among the index and thumb fingers d_1 = 80 mm, d_2 = 90 mm (measured at the center of the stroke h as shown in Fig. 3) to take into account the effect of size of the explored object and 3 stimulus presentation conditions, kinesthetic only (K), cutaneous only (C) and combined kinesthetic plus cutaneous (KC).

In the K condition the kinesthetic feedback was provided by the kinesthetic haptic interface, while the cutaneous haptic interface was turned off. The plate was not in contact with the fingertip and its orientation was fixed.

In the C condition the cutaneous feedback was provided by the cutaneous haptic interface, but the kinesthetic haptic interface did not provide any force to the subject. Its function was only to track the position of the two fingers and to sustain the weight of the cutaneous haptic interfaces.

In the KC condition, kinesthetic plus cutaneous feedbacks were given by both the haptic interfaces working in synergy.

The stimuli consisted of two virtual planes: planes could be vertical and parallel to each other or inclined with respect to the vertical direction at 3, 6 or 9° (angle α). At the center of the workspace the distance between the planes was set either to d_1 or d_2. The four values of the angle and the two distances between the planes were combined so that eight different stimuli were presented to the subjects.

2.4. Procedure

Subjects were asked to judge the parallelism between two virtual planar surfaces, presented to them through the experimental apparatus, described in Section 2.2. The subjects stood at the left of the experimental apparatus and they used comfortably the interfaces with the right hand. A cover prevented them from seeing the movements of their hand and it avoided a visual feedback of the haptic interfaces.