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

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\textbf{A B S T R A C T}

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.

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\section{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 (Pacinian 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
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:

$$S_{KC} = w_C S_C + w_K S_K$$

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.

2.2. 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 $2 \times 3$ within subjects factorial design, including two distance conditions among the index and thumb fingers $d_1 = 80 \, \text{mm}, \, d_2 = 90 \, \text{mm}$ (measured at the center of the stroke 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 $\alpha$). 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.
Each subject was instructed to grip the planes simultaneously with the thumb and index fingers and then to move vertically from top to bottom and vice versa for an overall length $h$. The arrows on the planes in Fig. 3 represent the allowed exploratory movement. At the end of the movement each participant was asked to judge whether the two planes were parallel or not, by pushing one of two keys on a keyboard with its non-stimulated hand. The exploration time was automatically recorded by the system. No limit was imposed on the exploration time, but the subjects were not allowed to repeat the exploratory movement.

The stimuli were randomly presented to the participants. Each subject explored 250 stimuli per condition, resulting in 750 stimuli per subject; the entire experiment lasted approximately 1 h.

The stimuli were blocked by condition, changing the condition presentation order for each participant. There were six possible permutations for the arrangement of the three experimental conditions K, C and KC, so that each of the six subjects performed the experiment following a different condition order.

Before the beginning of the experiment, the participants made practice with the experimental apparatus during some training sessions in all the conditions, which were not been recorded.

The experimental procedure was designed in order to analyze the data with a signal detection theory (SDT) model. The yes–no procedure was implemented to evaluate the discrimination threshold for the relative orientation of two planes.

2.5. Data analysis

Data were collected from all the participants and experimental sessions, and the discrimination thresholds of each participant were computed for the three different stimulus presentations and for the two distances.
The data were analyzed separately for each subject and condition of stimulus presentation and distance. The percentage of “not parallel” responses was calculated for each angle of inclination of the planes. According to SDT, the percentage of “not parallel” responses when the angle is 0 (parallel planes) represents the false alarm rate $p_f$. For the other values of the angle (3, 6 and 9) the “not parallel” answer percentage stands for the hit rate $p_h$.

Both the false alarm and hit rate were converted to z-score of the normal distribution, so that $z_i = z$-score($p_f$) and $z_h = z$-score($p_h$). The sensitivity index $d'$ for the three values of the angle (3, 6 and 9) was then calculated as the difference between the two z-scores:

$$d' = z_h - z_i$$

According to the criterion commonly adopted in similar studies [23], the discrimination threshold was defined as the angle of inclination for which $d'$ is equal to 1. The threshold was computed for each subject for the three conditions C, K and KC and for the two distances $d_1$ and $d_2$, assuming a linear proportionality between the values of $d'$ and the stimulus, according to the following procedure:

- for each of the three stimuli (3, 6 and 9) the corresponding value of $d'$ was computed, so that three experimental points are obtained;
- a least-square error method was used to construct the interpolating line which fitted the three experimental points;
- from the interpolating line, the stimulus value that corresponded to $d'$ equal to 1 was calculated, and was assumed as the discrimination threshold.

The discrimination threshold for each condition and distance was calculated as the mean of the values obtained for the six subjects. The coefficient of determination $R^2$ was calculated for each individual linear fit as:

$$R^2 = 1 - \frac{SS_{residual}}{SS_{total}}$$

where $SS_{residual}$ is the residual sum of squares and $SS_{total}$ is the total sum of squares.

The response bias in the three conditions was assessed calculating the mean value for the six participants of the relative criterion location $C$, according to Gescheider [10]. $C$ represents the value of the criterion $C$ expressed as a proportion of the sensitivity measure $d'$, and so it is an adimensional number. It is calculated as:

$$C = \frac{d'}{d} = \frac{0.5(z_C + z_h)}{d}$$

where $z_C$ is the z-score conversion of $(1 - p_f)$ and $z_h$ is the z-score conversion of $(1 - p_h)$. For each subject the corresponding $C$ was evaluated as the mean of the values obtained for the three stimuli.

Statistical analysis was conducted with SPSS 13.0 and R 2.9.0. Within subjects ANOVA with two fixed factors was conducted according to Myers and Welli [19], with test of planned contrasts among means for the comparison of KC vs C and KC vs K conditions, and post hoc contrasts for the K vs C condition computed with a Bonferroni adjustment.

### 3. Results

The mean value of the coefficient of determination for all the linear fits was $R^2 = 0.9493$, confirming the assumption of linear proportionality between the sensitivity and the stimulus magnitude.

The mean response bias resulted as $C = 0.1087$ in the C condition, $C = 0.2088$ in the K condition and $C = 0.1366$ in the KC condition, with no significant difference across the stimulus presentation conditions.

A 2 (Distance condition) × 3 (Stimulus presentation, i.e. cutaneous only, kinesthetic only, and both) within-subjects ANOVA was conducted for the threshold discrimination and exploration time.

Discrimination thresholds as computed from SDT are reported in Table 1 for all subjects in the different conditions, while summary data are reported in Table 2 and are graphically represented in Fig. 4.

A lower discrimination threshold was observed in trials conducted with the largest distance between the fingers ($M = 1.36$, SD = 1.07), compared to the smaller distance ($M = 1.24$, SD = 1.24), $[F(1,5) = 13.73, p = 0.014]$.

Significant differences were observed for the stimulus presentation $[F(2,10) = 10.90, p = 0.003]$ condition, but for the interaction factor $[F(2,10) = 3.26, p = 0.081]$.

As expected, tests of main effects for the stimulus presentation, showed a significant difference between the combined presentation of stimuli (kinesthetic and cutaneous, $M = 1.15$, SD = 0.90) compared to cutaneous only ($M = 2.40$, SD = 1.27), $[t(5) = 4.53, p = 0.006]$, and kinesthetic only ($M = 1.73$, SD = 1.18), $[t(5) = 3.05, p = 0.028]$ presentation of stimuli (see Table 2), and a post hoc test showed no difference between the cutaneous only and kinesthetic only $[t(5) = 2.09, p = 0.27]$, Bonferroni post hoc adjustment).

To better understand the effect of distance and presentation condition on the perceptual threshold, simple effects were computed, reported graphically in Fig. 5.

### Table 1

Discrimination thresholds observed in all subjects.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$d_1$</th>
<th>$d_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>K</td>
</tr>
<tr>
<td>A</td>
<td>1.40</td>
<td>1.34</td>
</tr>
<tr>
<td>B</td>
<td>3.80</td>
<td>2.69</td>
</tr>
<tr>
<td>C</td>
<td>2.89</td>
<td>2.68</td>
</tr>
<tr>
<td>D</td>
<td>4.36</td>
<td>4.76</td>
</tr>
<tr>
<td>E</td>
<td>1.61</td>
<td>1.63</td>
</tr>
<tr>
<td>F</td>
<td>1.63</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>$M \pm SD$</td>
<td>$M \pm SD$</td>
</tr>
<tr>
<td></td>
<td>2.61 ± 1.27</td>
<td>2.3 ± 1.32</td>
</tr>
</tbody>
</table>

### Table 2

Summary data (mean and standard deviation) for discrimination threshold in the 3 (stimulus presentation C, K, KC) × 2 (distance $d_1$, $d_2$) conditions.

<table>
<thead>
<tr>
<th>Distance</th>
<th>C</th>
<th>K</th>
<th>KC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_1$</td>
<td>$M \pm SD$</td>
<td>$M \pm SD$</td>
<td>$M \pm SD$</td>
</tr>
<tr>
<td>80 mm</td>
<td>2.61 ± 1.27</td>
<td>2.3 ± 1.32</td>
<td>1.58 ± 1.1</td>
</tr>
<tr>
<td>90 mm</td>
<td>2.19 ± 1.37</td>
<td>1.17 ± 0.75</td>
<td>0.72 ± 0.35</td>
</tr>
</tbody>
</table>

First the effect of discrimination threshold was evaluated for the three levels of the stimulus presentation factor across only one level of the distance factor; then the same analysis was conducted for the two levels of distance factor across one level of stimulus presentation.

Both for distance \( d_1 \) \([F(2,10) = 17.47, \ p = 0.001]\) and \( d_2 \) \([F(2,10) = 7.51, \ p = 0.010]\) a significant difference was observed among the three stimulus presentation conditions (single factor ANOVA).

By analyzing in particular C, K and KC conditions, we found that there is no significant effect of distance on the perception in C \([t(5) = 2.40, \ p = 0.061]\) and KC \([t(5) = 2.50, \ p = 0.053]\) presentation of stimulus, while this holds for K presentation \([t(5) = 4.19, \ p = 0.008]\). So distance affects perceptual discrimination for stimuli presented only in K condition.

At small distance \( (d_1) \), as expected there was significant difference between KC condition both vs K alone condition \([t(5) = 4.13, \ p = 0.009]\) and C alone condition \([t(5) = 8.59, \ p = 0.0003]\), but between K vs C conditions \([t(5) = 1.39, \ p = 0.67, \text{Bonferroni post hoc adjustment}]\).

At large distance \( (d_2) \) only the difference between C vs KC conditions was significant \([t(5) = 3.23, \ p = 0.023]\), while no significant difference was observed between K vs KC \([t(5) = 2.07, \ p = 0.09]\), and between K vs C \([t(5) = 2.28, \ p = 0.21, \text{Bonferroni post hoc adjustment}]\).

For the exploration time, summary data are reported in Table 3 and graphically in Fig. 6.

Only the stimulus presentation factor was a significant condition \([F(2,10) = 7.67, \ p = 0.009]\), while the distance \([F(2,10) = 0.003, \ p = 0.96]\) and interaction term \([F(2,10) = 0.059, \ p = 0.94]\) were completely uninfluential.

In particular the longest exploration time was observed for the C condition \((M = 6.47, \ SD = 1.55 \text{ s})\), followed by the KC \((M = 4.41, \ SD = 1.55 \text{ s})\) and K \((M = 3.83, \ SD = 0.68 \text{ s})\) condition. The exploration time in condition C was found to be significantly higher than time needed in condition K \([t(5) = 4.12, \ p = 0.03, \text{Bonferroni post hoc adjustment}]\).

Table 3

<table>
<thead>
<tr>
<th>Distance</th>
<th>C (M ± SD (s))</th>
<th>K (M ± SD (s))</th>
<th>KC (M ± SD (s))</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>6.47 ± 1.55</td>
<td>3.84 ± 0.68</td>
<td>4.41 ± 1.55</td>
<td>12</td>
</tr>
<tr>
<td>( d_1 = 80 \text{ mm} )</td>
<td>6.46 ± 1.59</td>
<td>3.83 ± 0.73</td>
<td>4.44 ± 1.62</td>
<td>6</td>
</tr>
<tr>
<td>( d_2 = 90 \text{ mm} )</td>
<td>6.48 ± 1.67</td>
<td>3.85 ± 0.69</td>
<td>4.38 ± 1.63</td>
<td>6</td>
</tr>
</tbody>
</table>

4. Discussion

The experimental results confirm that the hypothesis that the perceptual condition KC provides the best performance in orientation discrimination, followed by K and C conditions, and that cutaneous stimulation alone allows to correctly estimate the parallelism of two surfaces. The performance is depending on the distance between the fingers (size effect). When the fingers get closer the performance of orientation discrimination in the K condition decreases and this was the only sensory modality affected by the distance among the fingers. It emerged from our investigation that the participants, when asked to express shape judgment, probably for keeping the fingers permanently in contact with the explored surface.

The performance in the K only condition is largely based on the kinesthetic discrimination of finger joint-angle using active motion,
and this is the main perceptual underlying mechanism in this discrimination task.

In fact the threshold value found in the K only condition is compatible with the kinesthetic discrimination threshold associated with the MCP (metacarpophalangeal) and PIP (proximal interphalangeal) joints of index finger, in the following indicated respectively with symbols $\gamma$ and $\theta$.

Referring to the notation shown in Fig. 3, we know from the experimental set-up that the subjects covered with their fingers a vertical distance of $h = 14$ cm, during the exploration of the virtual walls performed with phalanxes forming an angle of about $30^\circ$ at the PIP joint ($\theta$).

Assuming average lengths of the 1st, 2nd and 3rd phalanxes of the index finger respectively equal to $L_1 = 48$ mm, $L_2 = 27$ mm, $L_3 = 22$ mm [24], we can assume an approximated distance of the index fingertip from the MCP joint as $L = L_1 + (L_2 + L_3) \cos(\theta) = 9.0$ cm.

When the two virtual planes form an angle equal to the discrimination threshold $\alpha$ for the kinesthetic modality, the index finger covers an horizontal distance, perpendicular to the vertical direction, equal to $h \tan(\alpha)$, and so, the MCP ($\gamma$) proprioceptive discrimination threshold for small angles can be computed as the ratio $h \sin(\alpha)/L$ (Fig. 3).

From the data of the central column (K condition) in Table 2, the discrimination thresholds $\alpha$ for the two distances $d_1$ and $d_2$ are $2.3^\circ$ and $1.17^\circ$, and so the MCP ($\gamma$) proprioceptive discrimination thresholds follow respectively equal to $3.6^\circ$ and $1.8^\circ$.

The above values are compatible with the observed average kinesthetic discrimination threshold of $2^\circ$ for the finger MCP joint in Tan et al. [23], considering that a different value of $\gamma$ angle was used in this previous experiment.

It should be noted that discrimination thresholds were computed according to SDT. An interpretation of thresholds could be also given in terms of psychometric functions relative to the same task.

In Fig. 7 we show the psychometric functions relative to the six experimental conditions ($3 \times 2$ factors), obtained from an analysis of proportion of correct answers and computed with logistic curves according to Voisin et al. [25]. Clearly the threshold derived from psychometric curves (here set to the 75% of correct answers) is biased by the decision criterion adopted by the subject, and it is not an objective measurement of the discrimination threshold. From this plots it is more evident how size, factor $d$, plays an important role, since at distance $d_1$ both cutaneous and kinesthetic modality perform equally, while at distance $d_2$ the kinesthetic modality performs better.

In all conditions, the combined KC modality presents a better performance that single unimodal sensor modalities.

According to the Bayesian framework of multisensory integration, a prediction of the combined performance $S_{kc}$ is given by (1), where each weight can be estimated based on the experimentally observed discrimination thresholds for the kinesthetic ($T_k = \sqrt{2\sigma_k}$) and cutaneous ($T_c = \sqrt{2\sigma_c}$) sensor modality:

$$w_c = \frac{\sigma_k^2}{\sigma_k^2 + \sigma_c^2} \quad \text{and} \quad w_k = \frac{\sigma_c^2}{\sigma_k^2 + \sigma_c^2}$$

The unimodal variances can then be used to derive prediction for the optimal cross-modal performance ($T_{kc} = \sqrt{2\sigma_{kc}}$) [1] considering that

$$\sigma_{kc} = \sqrt{\frac{\sigma_k^2 \sigma_c^2}{\sigma_k^2 + \sigma_c^2}}$$

We obtain in particular a Bayesian bimodal estimate of the discrimination threshold $T_{kc}$ for the two distance conditions that is reported graphically in Fig. 8, compared to observed experimental values.

At distance $d_1$, the prediction from the model is accurate, since we obtain an estimate that is a good approximation of the observed experimental value for the observed $T_{kc}$ (Pearson Correlation factor $R = 0.98$, $p = 0.0003$).

But, we also see that at the higher distance $d_2$, the Bayesian model predicts a less accurate estimate of the value of the observed $T_{kc}$. We observe a better correlation with the K only condition (Pearson Correlation factor $R = 0.97$, $p = 0.0009$), rather than the predicted combined KC condition (Pearson Correlation factor $R = 0.82$, $p = 0.04$).

The explanation of this effect in this second case, is that according to the Bayesian prediction, the information coming from the cutaneous afferents is not reliable enough to significantly influence the integrated percept, that is more biased by $T_k$ alone. But this prediction does not fit completely with the experimental observations, where still we achieve a better performance in the KC bimodal condition, also when one sensory cue is much less reliable than the other.
5. Conclusions

Results from this study show that, in the haptic discrimination of orientation by active touch exploration, the cutaneous sensor modality is not affected by the size of the explored shape, but the kinesthetic performance decreases with smaller size. Cutaneous sensory modality, in the absence of kinesthetic feedback, requires more time in the haptic exploration of shape, probably because of the need of constantly keeping the contact of the finger with the surface.

The hypothesis of multisensory integration according to a Bayesian model is confirmed by the results for the small distance $d_1$. At the high distance $d_2$, when the difference between performances in C and K condition is bigger, the Bayesian model is not accurate enough for predicting the discrimination threshold in the KC condition.

In both cases the combined sensory stimulation (KC) always performs better than single modalities alone (C and K).

Conflict of interest

The authors declare that they have no competing financial interests.

Acknowledgement

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References

[13] G. Jansson, L. Monaci, Identification of real objects under conditions similar to those in haptic displays: providing spatially distributed information at the contact areas is more important than increasing the number of areas, Virtual Reality 9 (4) (2006) 243–249.

![Fig. 8.](image-url) Rightmost bars represent the predicted performance by the Bayesian bimodal estimate for the two distances (distance $d_1$ left, distance $d_2$ right): (a) low distance and (b) high distance.