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Integration of Length and Curvature in Haptic Perception

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We investigated if and how length and curvature information are integrated when an object is explored in one hand. Subjects were asked to explore four types of objects between thumb and index finger. Objects differed in either length, curvature, both length and curvature correlated as in a circle, or anti-correlated. We found that when both length and curvature are present, performance is significantly better than when only one of the two cues is available. Therefore, we conclude that there is integration of length and curvature. Moreover, if the two cues are correlated in a circular cross-section instead of in an anti-correlated way, performance is better than predicted by a combination of two independent cues. We conclude that integration of curvature and length is highly efficient when the cues in the object are combined as in a circle, which is the most common combination of curvature and length in daily life.

The integration of cues from different modalities or from different sources of information is a topic of growing interest, because it teaches us about the way information is processed by the sensory system. In this study, we investigated how length and curvature are integrated in unimanual haptic exploration. We know that in unimanual exploration, the presence of curvature improves the ability to distinguish the oblongness of stimuli: the threshold for distinguishing cylindrical objects with circular and elliptical cross-sections is smaller than that for distinguishing between blocks with square and rectangular cross-sections[1]. This is illustrated in Figure 1. Furthermore, we know that in bimanual exploration, length and curvature can be combined into a total percept of a cylinder with a circular cross-section[2,3]. However, unimanual perception is different from bimanual perception. It is still unclear whether the improved detection of oblongness in unimanual exploration is due to some form of integration of two cues or only due to a higher sensitivity for differences in curvature compared to length.

We discuss three possible explanations for the increased performance for cylinders over blocks. Firstly, it could be that curvature provides more precise information than length. In the case when both length and curvature are present in an object, subjects could be more sensitive in detecting the difference based on curvature and therefore select that cue to base their judgement on. This is called the winner-take-all model, in which subjects are more sensitive to one of the cues present and base the combined percept on the cue they are most sensitive to. In this model, if subjects are more sensitive to, for instance, the curvature cue, they would be able to distinguish objects which contain both curvature and length cues as well as they can distinguish objects which contain only curvature cues. This would be irrespective of how the length and curvature are combined, i.e. whether curvature and length form a circle or are not correlated at all.

Secondly, subjects could perceive both length and curvature simultaneously but due to stochastic fluctuations, one cue might be more precise on a specific trial. Subjects then change the cue on which they base their judgement accordingly. In this way, the combined chance of perceiving the distinction becomes larger than the chance of perceiving a difference in either cue individually. This we call independent combination, in which two uncorrelated cues give rise to a higher detection probability[4]. It is important to note here that although two cues can be correlated in the stimuli, it remains to be seen whether they are also correlated in the perception by subjects. In objects that have both length and curvature cues, it might depend on the way these two cues are combined whether they are treated as correlated in the perception.

Thirdly, subjects could combine the information from the length and curvature cues in a way that surpasses simple cue combination. An example is a combination according to the maximum-likelihood-estimator paradigm[5,6], in which cues are weighted with their statistical reliability. In this way, the perception of an object with two cues would be more accurate than when the cues are combined in an uncorrelated way.

We designed four stimulus sets with which we tested these three possible explanations. These stimuli were felt between the thumb and index finger. In condition 1, we used stimuli that differ only in length and have a flat surface. In condition 2, the stimuli differ only in curvature, which is defined as the reciprocal of the radius

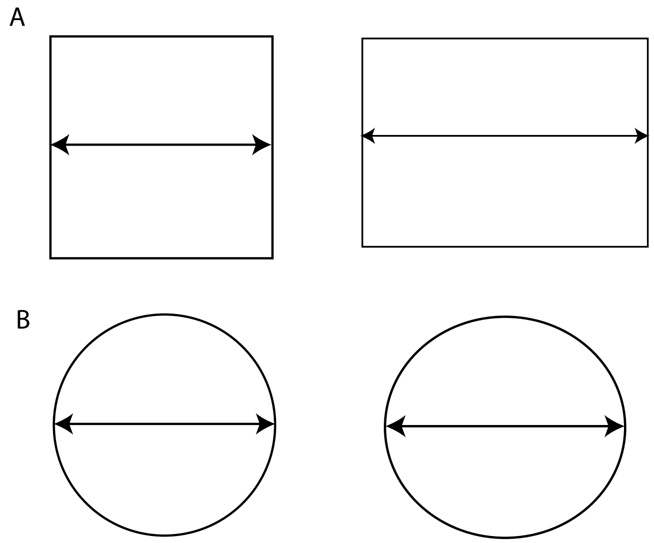

Figure 1 | Subjects are less sensitive in distinguishing objects with a square cross-section from objects with a rectangular cross-section (A) than they are in distinguishing objects with a circular cross-section from objects with an elliptical cross-section (B), due to the absence of curvature information in the former case.

($curvature = \frac{1}{R}$), and have the same maximum distance between the two surfaces. In condition 3, we used stimuli that differ both in length and curvature and these two cues are correlated as in a circle. In condition 4, we used stimuli that have the same lengths and curvatures as in condition 3, but the curvature and length are correlated in reverse order. This means that, for instance, the smallest length from condition 1 is combined with the smallest curvature from condition 2. This we will call anti-correlated with respect to a circle.

We compared the ability to discriminate *length only* (condition 1) and the ability to discriminate *curvature only* (condition 2) with the ability to discriminate circular cylinders (condition 3) and the ability to discriminate anti-correlated cylinders (condition 4). If the two cues in conditions 3 and 4 are processed by the subjects in a winner-take-all fashion, then we expect conditions 3 and 4 not to differ significantly from the best of conditions 1 or 2. If both condition 1 and condition 2 differ significantly from condition 3 we can exclude the winner-take-all model as a possible explanation in case they are combined in a circular way. The same conclusion can be drawn for the comparison with condition 4, where curvature and length are anti-correlated.

From the results of the *length only* and the *curvature only* conditions, we can predict what the results should be if the two cues are uncorrelated in the perception of subjects. We compared these predictions to the measured values of both condition 3 and condition 4. If the two cues are truly integrated, then performance in condition 3 should be better than predicted. In condition 4, the two cues are technically correlated, but this is not a combination often felt in daily life as opposed to the circular cylinders of condition 3. If integration is independent of the way these two cues are combined in the object, performance in condition 4 should be better than predicted. However, if both cues are used in the perception, but are not perceived to be correlated, we do not expect a difference between the results of condition 4 and the predicted results.

Results

Figure 2 shows the mean sensitivity index, d' (as explained in more detail in the analysis section), of 12 subjects for the four conditions for all differences from reference. A 4 (condition) by 5 (difference from reference) repeated measures ANOVA shows an effect of condition ($F(3, 33) = 22$, $p = 4.5 \times 10^{-8}$), difference from reference ($F(4, 44) = 16$, $p = 1.6 \times 10^{-14}$) and an interaction effect ($F(4.3, 47) = 6.5$, $p = 2.5 \times 10^{-4}$). The values for d' of both condition 1 (*length only*) and condition 2 (*curvature only*) are significantly lower than those of condition 3 where these two cues are combined in circular cross-sections ($p = 2.0 \times 10^{-3}$ and $p = 1.5 \times 10^{-6}$, respectively). Comparing the values for d' of these two conditions to condition 4, in which length and curvature correlate in the opposite way compared to condition 3, we see that condition 1 (*length only*) is not significantly different from condition 4 ($p = 0.19$), whereas condition 2 (*curvature only*) is ($p = 6.4 \times 10^{-5}$). Finally, we find that the values for d' of condition 3 are significantly higher than those of condition 4 ($p = 0.046$).

In Figure 3 the predicted values are shown with the values for conditions 3 and 4 for comparison. A 2 (condition) by 5 (difference from reference) repeated measures ANOVA shows an effect of condition ($F(1, 11) = 9.9$, $p = 0.0092$) and difference from reference ($F(4, 44) = 73$, $p = 7.2 \times 10^{-19}$) and no significant interaction effect. Since the effect of difference from reference is trivial, namely with increasing difference the d' increases, we only look into the effect of condition in more detail. Two paired t-tests show that the values for condition 3 are significantly larger than the predicted values for differences from reference of 1.0, 1.5 and 2.0 mm ($t(11) = 3.0$, $p = 0.012$, $t(11) = 3.5$, $p = 0.0050$ and $t(11) = 4.8$, $p = 5.9 \times 10^{-4}$, respectively). In contrast, the values of condition 4 are never significantly different from the predicted values ($t(11) = -2.0$, $p = 0.076$, $t(11) = 0.53$, $p = 0.61$, $t(11) = 1.3$, $p = 0.21$, $t(11) = 2.1$, $p = 0.064$ and $t(11) = 0.28$, $p = 0.78$, respectively).

Discussion

From Figure 2 it can be clearly seen that if both curvature and length are present in the object, subjects can distinguish the test stimulus from the reference much better than when only one of the cues is present. If one looks in more detail one can see that the d' for both *length only* and *curvature only* remain low until 2.5 mm difference. In contrast, if both cues are present the d' is already high at 1.0 mm difference. This means that with either of the cues by itself it is much harder to distinguish a difference smaller than 2.5 mm, but when both cues are combined already a very small difference is easily distinguished. Therefore, we conclude that there must be some form of integration of length and curvature and we can exclude the winner-take-all model.

The question that remains is whether the integration we find is due to an independent combination or due to subjects correlating the length and curvature cues in a more complex manner. From Figure 3 we can see that when length and curvature are combined in a circular cylinder, the predictions based on the assumption that the length and curvature cue are uncorrelated are significantly lower than the values for d' measured in condition 3. Thus, independent combination is insufficient to explain the better performance in condition 3. In contrast, the values of condition 4 are not significantly different from the predicted values, which means that in this condition the perception of length and curvature is probably independent and the increase in performance can be ascribed to independent combination.

Comparing condition 3 with condition 4, we can say that apparently, we are more sensitive to the length and curvature of objects if they are combined in a circular cross-section. Plaisier and Ernst[9] showed that a strongly curved local surface leads to an overestimation of the length, whereas a weakly curved local surface leads to an underestimation. To explain their results, they suggested that subjects assume that local curvature is related to the length. This assumption by subjects would also explain the better performance on objects with circular cross-sections that we find when comparing condition 3 with condition 4. Whether subjects assume circularity or not, our results show that for integration of information in the brain

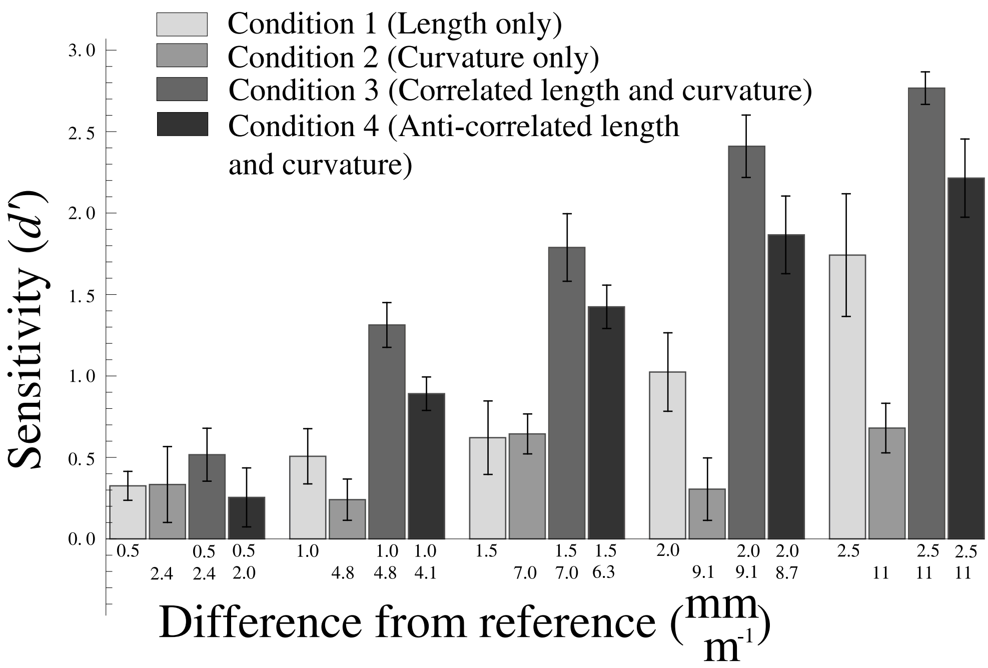

Figure 2 | Mean d' of 12 subjects for conditions 1 (*length only*), 2 (*curvature only*), 3 (correlated length and curvature) and 4 (anti-correlated length and curvature). For conditions 1, 3 and 4, the mean d' were plotted for differences from reference (diameter 20.0 mm) of 0.5, 1.0, 1.5, 2.0 and 2.5 mm. For conditions 2 and 3, the mean d' were plotted for differences from reference (diameter 20.0 mm, curvature 100 m^{-1}) of 2.4, 4.8, 7.0, 9.1 and 11 m^{-1} in curvature. The length of the stimuli for condition 2 were all 20.0 mm. Finally, the mean d' of condition 4 were plotted for differences from reference (diameter 20.0 mm, curvature 88.9 m^{-1}) of 2.0, 4.1, 6.3, 8.7 and 11 m^{-1} in curvature. Error bars indicate the standard error of the sample mean.

it is not only important which cues are available, but also how they are combined.

Methods

Subjects. Twelve paid subjects (mean age 21 ± 2 years, 4 male) participated in this experiment. All subjects reported to be right-handed. All subjects were naive as to the purpose of the experiment and gave their informed consent. None of the subjects reported any known hand deficits. The program under which these experiments were performed is approved by the Ethical Committee of the Faculty of Human Movement Sciences at the VU University in Amsterdam.

Stimuli and set-up. The stimuli were printed on a Z-Corp Z450 3D printer, by binding a plaster composite with an epoxy. The resolution of this printer is 300 by

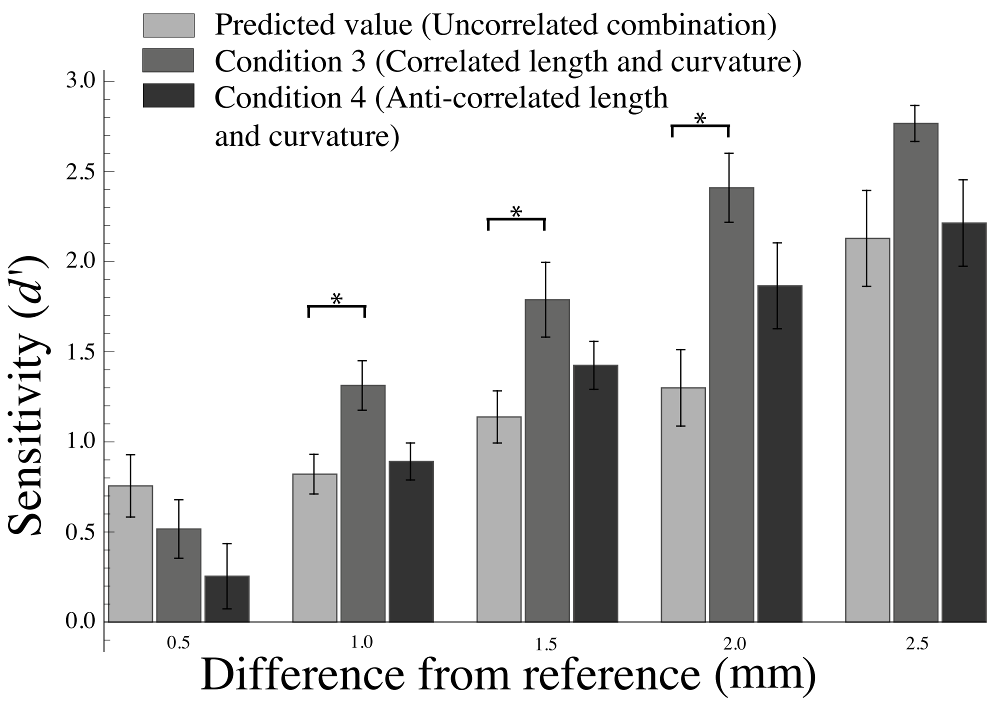

Figure 3 | The mean of the predicted values of d' if subjects use both length and curvature cues in an uncorrelated way. The mean values for conditions 3 and 4 are shown for comparison. The mean d' were plotted for differences from reference (diameter 20.0 mm) of 0.5, 1.0, 1.5, 2.0 and 2.5 mm. Error bars indicate the standard error of the sample mean.

450 dpi and the layer thickness is 0.089–0.102 mm. The cross-section of the stimuli, i.e. the curvature and the length, were printed in the horizontal plane and thus rendered with a resolution of 300 by 450 dpi. This is more than 10 dots per mm, which is sufficient for the purpose of measuring thresholds. The printed objects were made stronger by soaking them briefly in liquid superglue and then wiping them dry. Finally, the surfaces that were to be felt in the experiment were lightly sanded until they were smooth. All stimuli were 30 mm long and 20 mm high. The third dimension varied as described below. All stimuli had a square hole in order to put them on a stand. This ensured that the stimuli were fixed in place, but could be switched easily. All different stimuli can be seen in Figure 4.

We used four types of stimuli. In condition 1, the stimuli had flat surfaces which were 20.5, 21.0, 21.5, 22.0, and 22.5 mm apart for the test stimuli and 20.0 mm for the reference stimulus. In condition 2, the stimuli had curved surfaces with curvatures of 100 m^{-1} for the reference stimulus and 97.6, 95.2, 93.0, 90.9 and 88.9 m^{-1} for the test stimuli. In this condition, the stimuli had a constant maximum length of 20.0 mm. In condition 3, the stimuli were part of cylinders with circular cross-sections with the same diameters as the lengths in condition 1 for the test and reference stimuli. The curvatures are the same as in condition 2. For condition 4, we designed stimuli that had an anti-correlated length and curvature. This means that for a large length, the curvature was also large. This is the exact opposite of condition 3, where a small length is combined with a large curvature. This means that for the reference stimulus the length was 20.0 mm, but the curvature was equal to the curvature of a circular cylinder with a diameter of 22.5 cm, i.e. 88.9 m^{-1}. For the test stimuli we combined the lengths of 20.5, 21.0, 21.5, 22.0, 22.5 mm with curvatures of 90.9, 93.0, 95.2, 97.6 and 100 m^{-1}, respectively. The lengths of the stimuli described above differed less than 0.05 mm from the indicated length and the curvatures differed less than 0.5 m^{-1} from the indicated curvature. This accuracy is more than sufficient given the differences needed for measuring the thresholds. The exact method of verifying the dimensions of the stimuli is described in a supplementary document.

For each stimulus two instances were created. This ensured that subjects would not be able to use small differences in, for instance, texture to differentiate between two shapes, but could only use differences in shape.

Procedure. Subjects were blindfolded and seated on a chair. The stimulus to be felt was placed on a stand that was located 28 cm from the table edge at a 45 degree angle with the edge of the table (see Figure 5B). This ensured that subjects could comfortably grasp the stimulus without having to bend their wrist.

The following procedure of presenting subjects with the stimuli is based on the method used by Durlach et al.[7] to determine d' values for distinguishing small differences in length. In this method, we did not inform subjects what difference, for instance, length or curvature to focus on. This ensured that we could compare the performance of subjects between different conditions directly. This experiment was a one-interval forced-choice experiment and subjects were presented with two stimuli (reference and test) at the start of the experiment and the numbers 1 or 2 were assigned to the two stimuli. Whether number 1 was the test or the reference stimulus was randomized between blocks. Subjects were asked to feel the stimulus between their thumb and index finger and to focus only on the shape of the stimulus. They were given no further hints on how the shapes would differ. After feeling the two stimuli at the start of the experiment, subjects felt one stimulus at a time and had to indicate whether they thought it was number 1 or number 2. The experimenter provided feedback after every answer. Feedback in this type of experiment is important, because subjects easily lose their reference. Giving feedback ensures that subjects are constantly reminded which stimulus was named number 1 and which number 2. This was repeated 60 times for each pair of test and reference stimuli for each condition. The first 10 trials were practice trials and the final 50 trials were used for analysis. The subjects were not informed about this.

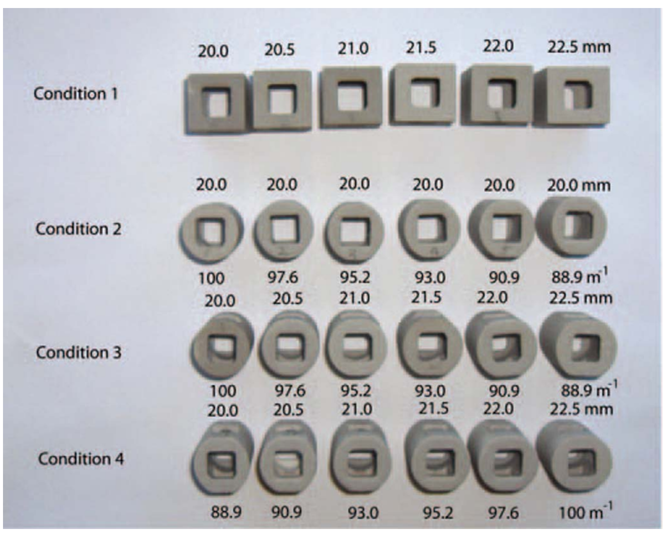

Figure 4 | Stimuli used in condition 1 (top) differ only in length. Stimuli used in condition 2 (second from top) differ only in curvature. Stimuli used in condition 3 (third from top) differ in both length and curvature as circular cylinders with increasing radii. Stimuli used in condition 4 (bottom) differ in both length and curvature with curvature in reverse order compared to condition 3. The lengths of the stimuli used in conditions 1, 3 and 4 are written above the stimuli. The curvatures of the stimuli used in conditions 2, 3 and 4 are written below the stimuli.

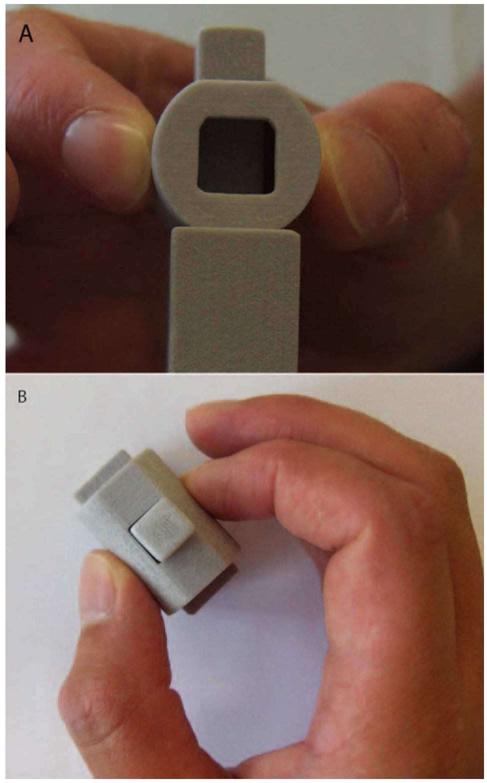

Figure 5 | (A): stimuli were grasped between the thumb and the index finger of the right hand. Stimuli were placed such that the axis was horizontal. (B): stimuli were placed on a stand at a 45 degree angle with the edge of the table.

We tested five differences between reference and test stimuli per condition. Each condition was tested in one session of one hour, giving a total of 4 hours per subject. The order of the conditions and the order of the test stimuli within a condition were counterbalanced as much as possible across participants by constructing a Latin rectangle. The rectangle was created by first creating a 4 by 4 Latin square. Another 2 Latin squares were constructed with the first line of the previous square shifted to the left. The same procedure was done for the five differences between reference and test stimuli. For the differences, a 5 by 5 Latin square was constructed and the last two rows of the last Latin square were left out.

In a run of 60 trials, subjects were presented with either one of the two duplicate reference stimuli (both of the same shape) or one of the two duplicate test stimuli. Which was to be presented was randomized. Each of the two identical stimuli was presented 15 times, which means that each shape was presented 30 times. Furthermore, in the first 10 trials, each shape was presented 5 times.

Analysis. For each run of 50 trials, we calculated the d' for each run. d' is a measure of sensitivity that takes into account the instances subjects indicate to detect a signal when there is no signal present (false alarm). In our case they indicate that they feel stimulus 1 while actually feeling stimulus 2. The d' values are calculated from the fraction of correct identifications of stimulus 1 and the fraction of incorrect identifications of stimulus 2 by the following equation[8]:

$$d' = Z(hit) - Z(false\ alarm), \tag{1}$$

where $Z(p), p \in [0, 1]$ is the inverse of the cumulative Gaussian distribution, *hit* is the fraction subjects indicate feeling stimulus 1 while feeling stimulus 1 and *false alarm* is the fraction subjects indicate feeling stimulus 1 while actually feeling stimulus 2. We plot the mean d' against the difference from reference for each condition. Statistical analysis was performed on the d' values. Firstly, we checked for sphericity. If sphericity was violated we used Greenhouse-Geisser corrected values. A 4 (condition) by 5 (difference from reference) repeated measures ANOVA was performed. Since the effect of difference from reference is trivial, namely with increasing length the d'

will increase, we only looked more closely at the effect of condition with Bonferroni corrected planned pairwise comparisons between the conditions 1–3, 2–3, 1–4, 2–4 and 3–4.

When the values of d' of length and of curvature are not correlated by the subjects when an object which contains both cues is felt, one can view these two cues as orthogonal[4]. In this case one can predict a d' for distinguishing two objects which contain both length and curvature by quadratically summing the values for d' of *length only* and *curvature only*[4]:

$$d_p'^2 = d_1'^2 + d_2'^2 \tag{2}$$

In this equation, d'_p stands for the predicted d' of an object that contains both length and curvature, d'_1 stands for the d' found in condition 1 (*length only*) and d'_2 stands for the d' found in condition 2 (*curvature only*). We calculated this d' for each subject per difference from reference. This leads to five mean values for the predicted d' which can be compared to the measured values of condition 3 and condition 4. In both conditions, the length and curvature are correlated within the stimulus. By comparing the predicted values to measured values we can check wether they are correlated in the perception of the subjects.

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Author contributions

V.P., W.M.B.T. and A.M.L.K. wrote the main manuscript text and V.P. prepared figures 1–5. All authors reviewed the manuscript.

Additional information

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