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Haptic shape constancy across distance

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Abstract. To explore haptic shape constancy across distance, we measured perceived curvature thresholds of cylindrical shapes, cut out of acetal resin blocks. On each trial, blindfolded observers used their bare finger to scan the surface of two of the shapes consecutively. One shape was close to the observer and the other positioned further away. This spatial displacement changes the available proprioceptive information about the object shape, and therefore the combined proprio-tactile information may signal different objects at the two distances. The results reveal a perceptual compensation for the change in proprioceptive information. However, two distinct patterns of distance compensation emerged: one groups' data are consistent with predictions from visual object constancy. The other group of observers demonstrate the reverse pattern of response such that objects further away need to have lower curvature to be perceived having equal curvature. We propose that perceived haptic curvature across distance depends on observers' differential weighting of the multiple available cues.

Keywords. Shape constancy; haptic exploration; distance; perceptual compensation.

1 Introduction

When reaching into your wallet for a €1 coin, it is easy enough to select a €2 coin by mistake. The size and shape of the coin are available from haptics: when we interact with the environment via touch, we can extract information about an object's shape, its size, its position, its surface texture and its weight, among other physical properties. If you visually compare the €1 and €2 coins, it is easy to discriminate the two. Many studies have explored the differences between visual and haptic estimates of object properties [1–3]. Spatial properties of objects in the environment, like the size of the coin, can be sensed by both modalities, but the constraints of each system predict different outcomes when our relationship to the object changes [4]. Haptically perceived shape of the coin, probed by the finger, involves tactile and proprioceptive sensing under the control of movement [5, 6]. Sensory feedback is generated from multiple sources, including mechanoreceptors in the skin and in deep structures (mus-

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cles, tendons and joints). In this instance, extraction of shape depends on integration of feedback from all sources of information. Therefore any compensation for distortions at the sensor level would have to account for all sources, related to proprioceptive changes and also cutaneous distortions. This raises the question of how our nervous system might compensate for changes in the available cues due to displacement of the coin. In vision it is obvious that we would perceive the same object independent of its location in space, because gaze shifts and eye movement perturbations can occur and produce exactly the same retinal input even when distance and orientation do not change [7–9]. This perceptual constancy allows the nervous system to maintain a coherent experience of the world despite being able to move its sensors independently to the environment.

1.1 Shape constancy

In vision, constancy refers to the stability of the perceived properties of an object over space and time which can be achieved by converting retinal signals into spatiotopic coordinates, allowing the observer to perceive space independently of his or her own eye movements [7, 10]. The problem would seem at least as important in haptic perception, where sensory surfaces undergo even more complex movements in space. It is known that an object's perceived haptic size is influenced by the extent of the arm, as well as local deformation of the probe [5, 11]. Any sensory system with the ability to move and explore the environment faces the problem of accounting for changes in proximal patterns of stimulation that are due to self-generated movement, and those that are not. Moreover, in order to experience objects in external space, these proximal patterns need to be converted into an external/spatiotopic frame of reference such that the object can be represented independently of the observer-generated perturbations. Consider the example of visual shape perception: the euro coin looks round both when viewed head on and when viewed from an acute angle, even though the area projected by the coin onto our retinae under these two conditions is very different. Size and shape constancy are achieved by adjusting the percept to compensate for distortions in the proximal stimulation due to changes in viewing angle. The first question we addressed is whether we can observe haptic shape constancy across distance.

1.2 Shape constancy in touch

In haptics it is unusual to have a field of view that remains constant. Therefore the question is whether haptic shape constancy is plausible for the kind of interactions the sensors have with the environment. That is, in touch the sensor, your finger, is often dramatically smaller than the explored object: as is commonly the case, the curvature of the finger is larger than that of the object, wherever it is touched. An estimate of shape must rely heavily on joint proprioceptive-tactile information. When we estimate the curvature of the €1, the configuration of the joint angles provided by arm, hand, and finger will impact upon the shape estimate derived. Therefore, when the object is displaced relative to the observer, the proprioceptive signals, coming from numerous

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joints and muscles, are dramatically different for the same finger kinematics [5]. Given the different cues available, why would we predict the object to be perceived as the same object across distance?

1.3 Aims

The aim of the study reported here is to investigate whether perceived curvature changes as a function of object displacement from the observer. Given perceived size is known to depend on the extension of the arm [12], it may be reasonable to assume that an haptic analogue to visual constancy across distance is not the most parsimonious option available to the nervous system. Maybe more useful is to reweight the proprio-tactile information to account for the displacement. Yet there is some evidence to suggest weak haptic constancy for direction of motion [13]. The question is therefore how local skin deformation at the fingertip and proprioceptive information will work together across object distance.

2 Method

2.1 Participants

Ten individuals (5 females, 2 left-handed, aged 20-35) participated in this experiment. Participants volunteered their time and were naïve to the purpose of the study.

2.2 Stimuli and set-up

The stimuli were 13 three-dimensional objects made from thermoplastic polyoxymethylene. Each object consisted of three-dimensional rectangular form with a circular hole. We manipulated the curvature of the circular hole, which is defined as reciprocal radius. That means that a cylinder with a radius of 0.5 m has a curvature of $1/0.5\ m^{-1} = 2\ m^{-1}$. Our standard shape curvature was set at $36\ m^{-1}$. To estimate perceived curvature twelve comparison stimuli were used, whose curvature ranged from $46\ m^{-1}$ to $26\ m^{-1}$ in steps of $2\ m^{-1}$ (see Fig. 1a). This included a comparison shape with equivalent dimensions to the standard object. The size of the embedding rectangular form changed slightly with the changes in cylindrical dimensions.

In each trial, the staircase-selected stimuli were manually slotted into placeholders that were attached to a table in front of the observer. The placeholders ensured that the objects were stable and did not vibrate randomly during the exploration phase. The placeholders were set at D1 and D2 (the near and far object locations as measured from the observer). D1 was 5cm from the torso of the observer, while D2 was 50 cm, with an angular offset. Participants sat at the table and rested their dominant hand on the tabletop. Prior to the commencement of the experiment, the distance was calibrated for each individual with D1 located directly in front of the participant when their arm was held at their side and D2 was defined by the extent of the arm outstretched in front of the participant.

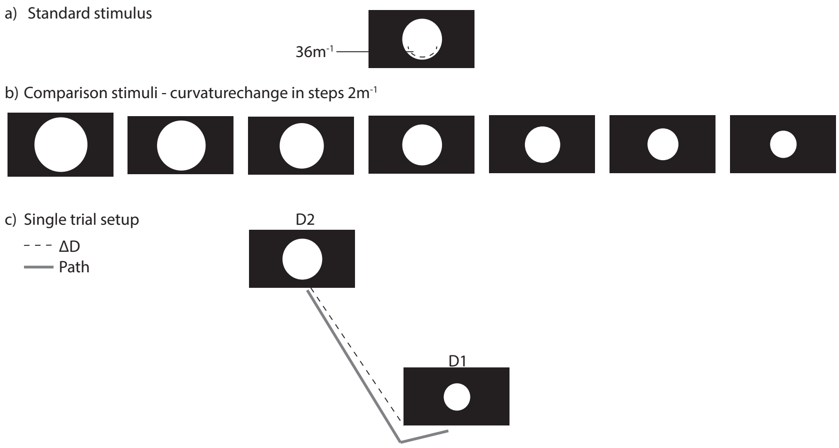

Fig. 1. Schematic representation of a) the standard stimulus and b) a subset of the comparison stimuli with changes in curvature by a step of 2 m^{-1}. b) Single trial setup for the 2AFC procedure in which participants compared the curvature of two objects: one located at D1 and the second positioned at D2. The exploration was done consecutively with one hand and to traverse ΔD (the distance between D2-D1), observers followed a line of tape on the tabletop to guide them to the second object.

2.3 Procedure

All observers were blindfolded throughout the entire experiment. Before each trial commenced two stimuli were manually slotted into the placeholders at D1 and D2 by the experimenter. In a two-interval, forced-choice procedure, observers used their bare index finger to explore two objects consecutively, one positioned at D1 and the other at D2. They reported which of the two objects had higher curvature. The curvature of one stimulus, the standard, was always 36 m^{-1}; the curvature of the other, the comparison, varied. During the inter-stimulus interval, participants traversed the space between the object at D1 and the object at D2 by following a line of tape on the tabletop. This way we avoided participants approaching the second object from a different elevation. He/she then explored the curvature of the objects with 6 sweeps per object. They indicated which of the two objects had higher curvature. The order of exploring the closer object first vs. exploring the more distant object first was randomized across trials. The participants were not told that the reference stimulus was used in all trials. They did not receive feedback on their performance.

2.4 Data analysis

We used interleaved staircases that tracked the standard stimulus at both D1 and D2, updating changes in curvature of the stimuli to estimate the curvature PSE for each distance separately. The data for the case when the standard object was at position D1 and the data for when it was at D2 were fit separately with a cumulative Gaussian function and the point of subjective equality (PSE) in curvature was extract-

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ed. The PSE (m^{-1}) indicates the curvature of the comparison object for which 50% of the time the comparison was perceived to have higher curvature than the 36 m^{-1} standard.

3 Results

As mentioned above, the standard object had a curvature of 36 m^{-1}. If participants were veridical (and assuming zero processing noise) then PSEs for both distances should be 36 m^{-1}. That is, there should be no difference between standard and comparison at either D1 or D2. Not only is this not what was found but it is clear from the data (see Figures 2 & 3) that observers compensated for distance using two distinct strategies: one for whom increasing the object distance increases the perceived curvature needed for equality and one for whom increasing object distance decreases the perceived curvature of the comparison. We ran a hierarchical cluster analysis to verify the existence of two distinct sub-groups. Two clusters emerged separated by a distance of 13.67.

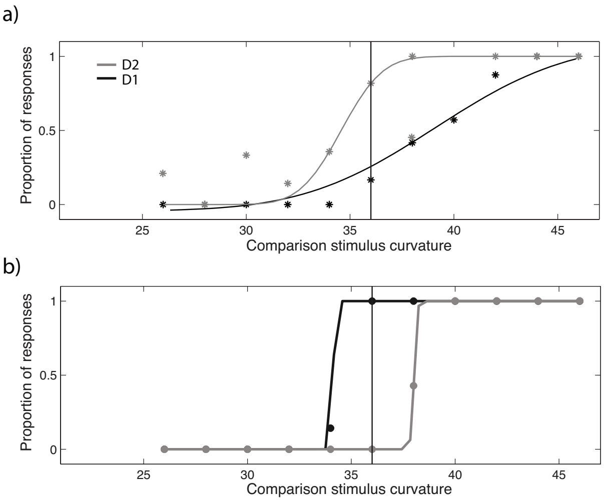

Fig. 2. Psychometric functions for estimated curvature as a function of distance: when the standard is close at D1 (grey) and then further from the observer at D2 (black). a) An example observer from group 1 for whom the function for the close object shifts towards high curvature while distant objects are more likely to be perceived as low curvature. b) An example observer from the subset showing the reverse pattern for near and far objects. Data points in the fitting procedure have been weighted according to the number of trials used to obtain them.

Fig. 2a shows the psychometric functions of an example observer from the first group of observers identified via the cluster analysis. The proportion of trials in which the comparison stimulus was judged as having higher curvature than the standard is plotted as a function of comparison curvature. In Fig. 2a) the psychometric functions are shifted toward higher curvature values for the near condition (black) and toward lower curvature values for the far object (D2) condition (grey). This indicates that for this observer to experience the same object size at the two distances, further objects need to have lower curvature to be perceived as equal to the closer standard. The pattern is consistent with visual shape constancy predictions. The example data from the second group of observers is shown in Fig. 2b. Here the response pattern is reversed: to experience the near and far objects as equally curved, the close object needs to have lower curvature and the far object, higher curvature to be perceptually equal. The PSE shifts in 2b are inconsistent with the expectation of shape constancy from vision. A second observation of the data in the two groups is that the precision of their estimates differs: the first group (vision-consistent) has noisier estimates (Fig. 2a) compared the estimation process of the second group (Fig. 2b).

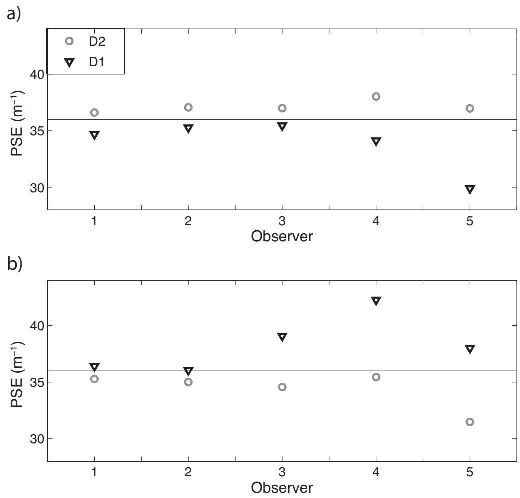

Fig. 3. The difference in curvature between the standard shape and the comparison shape necessary for participants to equate the curvature of the two at D1 and D2. a) For one group of observers, the distant object needed to have higher curvature for them to be perceived as equally curved. b) Whereas for the second group, curvature of the more distant object (D2) was under-estimated to arrive at perceptual equivalence.

Fig. 3a shows the PSE values for each observer when the standard was at closer (D1 - triangles) and when it was at the further position (D2 - circles). It can be seen that there is a relative difference in estimated PSE for all observers. However, whether the closer object (D1) or the further object (D2) needed to have a higher curvature to be perceived as equivalently curved as the standard depended on the observers themselves. The observers fall into two categories: Those whose haptic shape estimates across distance were consistent with visual-like compensation (i.e. closer shapes needed to have lower curvature to be perceived as the same shape as the standard at D2); and those for whom this pattern was reversed.

All observers demonstrate an effect of distance on their curvature estimates. However, the distinction between the two groups is vital in that they appear to have reversed perceptual compensation strategies.

4 Discussion

4.1 Haptic shape perception as a function of distance

In this study we show that the haptic shape depends on the object's distance from the observer. The exact nature of the dependence is complicated given that the data support two opposite compensation strategies. This may not be so surprising when we consider that the object surface available to the fingertip, at any moment in time, is larger than the sensor itself. Therefore unlike in visual processing there are multiple sources of information that can weigh in to account for the displacement.

One hypothesis for the difference observed is that one group relies more on local touch information, while the second group weights proprioceptive cues more highly. Previous results on haptic size across distance [12] suggests that proprioceptive feedback from arm extension, results in further objects being perceived as smaller. Other examples of haptic constancy include size perception [14,15] where the perceived size of a gap is experienced as smaller for more distant objects and larger for closer ones. In our data, most of the compensation occurs in the instance when the standard is close. In this case observers make larger perceptual (over/under) estimations for the far object than when the standard is at the more distant position (see Fig. 3).

If shape and size operate under the same priors then the visual-consistent group of observers may rely more on proprioceptive information while the second group might down-weight this source.

4.2 Shape constancy in vision – the result of regularities in the environment

In order to understand what causes displacement compensation strategies for vision, Knill exposed participants to different environments, manipulating the probability of different shapes [16]. When elliptical shapes occurred more often than circles, observers developed elliptical shape constancy. Therefore in vision it appears that shape constancy is the result of compensation mechanisms that account for the regularities in the environment and adjust the percept to maintain the most likely interpretation. Our data suggest that in haptic estimates across distance, perceived shape depends on the observer.

Why would the regularities in our haptic environment be different to those from vision? One possibility is that the plenhaptic function [4] shapes the kind of regularities we pick up on. As such it is possible for both sensory systems to select different regularities from the same environment. This could account for the difference in distance compensation observed between the two groups. Alternatively, the difference between the two groups is merely their interpretation of the concept of curvature or shape. The results suggest that two objects placed at different locations are incomparable for the brain. Instead, the brain chooses certain criteria and bases the comparison on them. In vision, the criterion of size is less arbitrary and compensation for distance only works with familiar objects [9]. It may be that for haptic shape, the function selected by participants is more arbitrary. This would account for the variance among observers.

Kappers et al. found similar inter-subject differences in curvature estimation when participants were asked to compare a haptic object to the cross-section of a visually sensed object [17]. Their data show haptic over-estimation of curvature and cross-modal comparison data suggest that mutually inconsistent representations of surface curvature coexist in a single observer in the haptic and visual modalities. Is it also possible that mutually inconsistent representations can be formed within haptics – via touch and proprioception [5]. Here we observe haptic compensation of distance in perceived shape. It remains to be seen what the underlying rule is that accounts for the emergence of opposite compensation strategies in our observers.

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