Haptic Figure-Ground Differentation via a Haptic Glance

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ABSTRACT

This study begins to address the nature of human haptic perceptual organization by examining "figure/ground" segmentation from a haptic perspective (i.e., differentiating an object from its supporting surface). The experiment focuses on the perception of the presence of an object via brief contact (i.e., a haptic glance) when both kinetic properties and geometric properties are manipulated. The results suggest that contact with objects that are moveable (cf. fixed) and tall (cf. short) greatly increases the perceived probability that an object is present. The effect of kinetics is further heightened when moveable objects have convexly curved bases.

KEYWORDS: Haptic figure-ground, perceptual organization, haptic glance

INDEX TERMS: H.1.2 Human information processing

1 INTRODUCTION

For all the human senses, a fundamental question for perception is: how do we progress from initial unconnected, potentially incomplete information from our sensory receptors to percepts of the physical world that are typically accurate, unambiguous and phenomenologically complete [1]? Three stages of sensory processing are commonly classified as occurring at low-, mid- or high-levels. Many haptic researchers have addressed "low-level" tactile processing for detecting perceptual primitives (e.g., material properties, edges) (e.g.,[2]), as well as for grasping and manipulating objects (e.g.,[3]) and for maintaining a stable posture (e.g.,[4]). Extensive research has also been devoted to relatively "high-level" haptic processing, as involved in manual exploration (e.g.,[5]), and in the identification of objects (e.g.,[6]) and their properties (e.g.,[7]).

In contrast, "mid-level" haptic processing, where basic primitives are perceptually grouped and organized into "objects" or their supporting surface (although the objects may not be identified at this stage) has received relatively little attention. However, the importance of this stage to haptic perception is particularly highlighted by the fact that, although haptic inputs about the environment are relatively sparse and slow to obtain (cf. vision), the system is remarkably fast and accurate when identifying 3-D common objects [8]. This would suggest that perceptual organization has a crucial role to play in grouping this sparse information into objects. Perceptual organization likely also serves an important role in manual dexterity inasmuch as people are capable of manipulating objects very effectively when only partial information is available, when the object has not yet been identified, and when visual feedback is not available.

Previous research on mid-level haptic perception has focused primarily on 2-D displays. [9] showed that given training, five blind children were capable of haptically differentiating 2-D figure from ground. More recently, [10-11] suggested and experimentally confirmed simple parallels between haptic and visual processing of 2-D layouts for computer displays with respect to several well-known visual grouping principles – similarity, proximity, and good continuation. To our knowledge, only one experiment [12] has used 3-D objects, that is, those with which the haptic system most commonly engages. The results of this fMRI study [12] suggest that the intraparietal and inferior parietal regions of the brain are involved in spatially integrating multiple discrete tactile contacts moving in temporal synchrony across the skin. These results demonstrate the organizational principle of common fate.

The theoretical approaches in the 2-D haptic studies above used current knowledge about visual and/or auditory perceptual organization. In contrast, we propose an approach that is more directly guided by current knowledge of how the haptic system inherently processes 3-D information. In our approach, we expect haptic perceptual organization to be derived from integrating cutaneous inputs from two or more discrete contacts on the hand, together with kinesthetic inputs that provide information about hand configuration and applied force. We anticipate that the integration process will critically depend upon determining *dynamic (i.e., kinetic), geometric and material consistencies* within a single object. Contact consistency across the hand should be contrasted with contact similarity, as the information can be different at the different contact pads as long as it stems from a common source (i.e., one object).

Here we focus on the contribution of these factors to solving the haptic "figure-ground" problem: How do we determine whether what we touch belongs to an object (i.e., figure) rather than to other parts of a scene, in particular the supporting structure (i.e., ground). This aspect of perceptual organization was chosen because it has long been considered one of the most basic and essential mid-level perceptual processing decisions for purposes of both cognition and action. We focus specifically on brief initial contact lasting only around 200 milliseconds (i.e., a haptic "glance" [13]). Despite its short duration, this type of contact has

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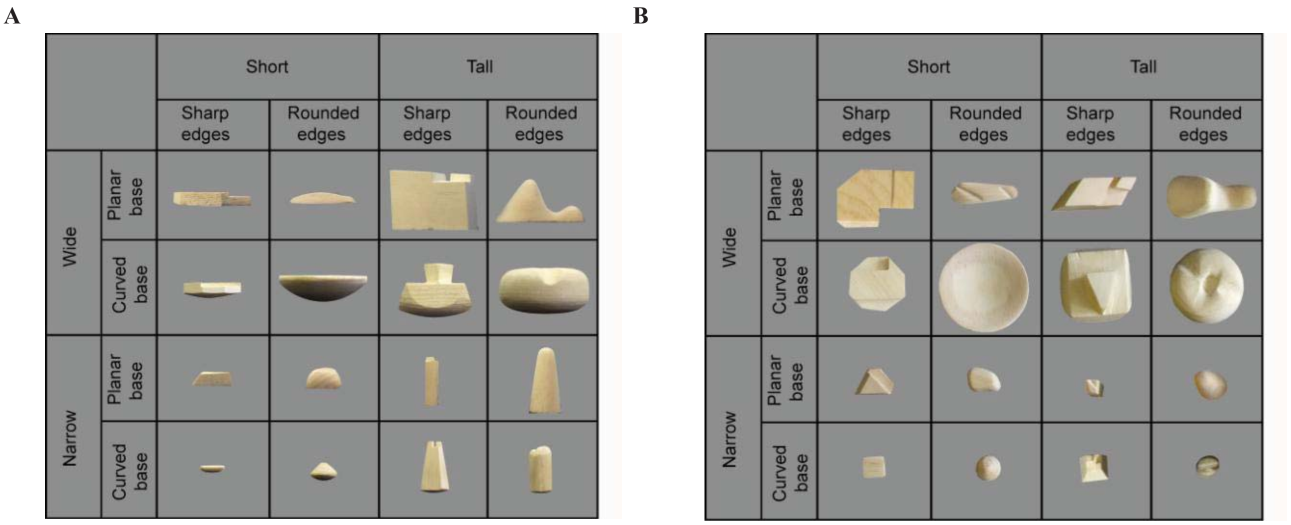

Figure 1. Stimulus set of 16 unique objects. A: side view; B: top view.

been shown to extract important information at both low and high levels of information processing. In this study we now address mid-level haptic processing.

2 EXPERIMENT

We were particularly interested in the potential contribution to *perception* of the interaction dynamics between the environment and the hand, which to our knowledge, has never before been recognized or systematically examined. We now propose that dynamics (and more specifically, kinetics) constitutes an integral aspect of haptic perception inasmuch as contact between the hand and the physical world is both inherent and unavoidable (cf. vision or audition). With respect to figure-ground segmentation via a haptic glance, we propose that the brief contact forces applied will typically produce micro-motions of an object (but not typically of a supporting surface) that are a significant contributing factor for purposes of separating an object from its supporting surface (and from other objects). Therefore, the main parameter addressed in this experiment was whether an object was moveable (able to produce micro-motions) vs. fixed to a background supporting surface (both immobile). We also considered the contribution of an object's geometric factors.

2.1 METHOD

2.1.1 PARTICIPANTS

A total of 32 paid participants (24 females, 8 males), ages 17-22 years (mean=18.2), participated. All participants were right-handed based on their performance on the Edinburgh Handedness Inventory [14].

2.1.2 MATERIALS

A considerable amount of pilot work was performed before deciding on the final set of stimulus objects and "background" supporting surfaces. Ultimately 16 unique objects of sanded pine were produced (Figure 1). These objects were parameterized by their maximum height, maximum width, the sharpness of their edges and the curvature of their base. The primary binary geometric dimensions that defined the objects were maximum height and maximum width: short vs. tall (0-2 vs. 4-6 cm) and narrow vs. wide (0-3 vs. 5-8 cm), respectively. All objects were constrained to be graspable with a single hand, with no axis (including the diagonal) greater than 8 cm [15]. To increase the variability of the object set, half the objects had sharp edges and the other half, rounded edges. Base curvature (never directly explored), was treated as an additional kinetic factor when objects were moveable. In this condition, the base was either flat or curved, the latter value serving to heighten the possibility that movement (i.e., wobble) would occur. In the fixed condition, because the base curvature was never manually contacted, all objects with curved bases were replaced by identical objects with planar bases to guarantee they were firmly attached to the supporting surface.

In addition, each object was presented on a planar vs. 3D background supporting structure, both made of sanded pine (Figure 2). The particular planar and 3-D supporting structures were chosen as they are commonly encountered in daily life (i.e., as tabletops, counters, etc., and as spatial organizers, respectively). The complexity of the 3-D supporting structure,

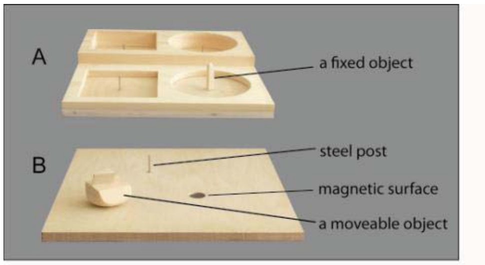

Figure 2. *A*: One of three versions of the 3D supporting structure. A tall, narrow object is shown in its proper fixed presentation position within the center of a recessed circular area. It is fixed in place by a metal pin projecting upward through its base. The second version of the structure uses magnets (to fix larger objects) and the third version has no attachments (for moveable objects). *B*: The planar supporting structure. A moveable object is shown in position, as well as the steel post and magnetic surface used to fix certain other objects. Participants never contacted the connector surfaces.

with variable heights and shapes, ensured that participants were not able to memorize the background (as they confirmed following the experiment).

2.1.3 PROCEDURE

Participants wore a blindfold and were seated at a table with the supporting surface centered in front of them. To eliminate sound cues, participants wore wax earplugs and headphones playing pink noise. Participants were trained to reproduce the desired "haptic glance" using all five fingers of their right hand. They were also reminded throughout the experiment that contact should be both quick and light. No attempt was made to ensure that participants' fingertips consistently contacted the objects in the same way on every trial, as we wished to emulate the stochastic changes that commonly occur in everyday life. Accordingly, on each trial the experimenter guided the hand to a random start position within the area of the object.

Participants were given one block of 10 practice trials, including two "blank" (no stimulus) trials. The practice objects were not used in the formal experiment. Participants numerically judged the likelihood that contact was with an "object" or with just the "supporting structure". A response scale of 0-100% was used where 0% indicated 0% probability that they did contact an object, and 100% indicated 100% probability that they did contact an object. The same judgment was required in the actual experiment.

2.1.4 EXPERIMENTAL DESIGN

Four crossed within-subject factors were included: Movement (2 levels: moveable, fixed), Background Supporting Surface (2 levels: flat, 3-D), Maximum Height (2 levels: short/tall), Maximum Width (2 levels: narrow/wide), with four objects per condition. In addition, for the moveable conditions, the four objects were randomly assigned to either planar or curved Base curvatures; for the fixed conditions, two repetitions of Base Curvature (planar) were assigned. An additional 12 blank (i.e., no stimulus) trials, with six per supporting structure, were presented. The 76 trials were randomly presented to each participant.

2.2 RESULTS

After confirming normality and homogeneity of variance assumptions across conditions, a 4-factor within-subject ANOVA was performed. The binary factors included Movement, Supporting Structure, Max Height and Max Width. As variation in base curvature was only expected to have an effect in the moveable condition, it was not included. Highly significant main effects with very large effect sizes (η_p^2) were obtained for Movement, $F(1, 31) = 52.3$, $p < .0001$, $\eta_p^2 = .63$, and Maximum Height, $F(1, 31) = 132.58$, $p < .0001$, $\eta_p^2 = .81$. Moveable objects produced higher probability estimates ($M_{Moveable} = 77.48$; $SEM_{Moveable} = 1.82$) than fixed objects ($M_{Fixed} = 64.88$; $SEM_{Fixed} = 2.04$). Taller objects yielded higher estimates ($M_{Tall} = 86.17$; $SEM_{Tall} = 1.80$) than shorter objects ($M_{Short} = 56.19$; $SEM_{Short} = 2.47$). No other main effects were significant.

The 2-way interaction, Movement x Max Height, was also highly significant, $F(1, 31) = 37.25$, $p < .0001$, $\eta_p^2 = .55$ (Figure 3). The effect of each variable was significant for both levels of the second variable; however, the Movement effect was greater for short than for tall objects, $t(31) = 6.1$, $p < .0001$. In addition, the probability that short, fixed stimuli were haptically perceived as objects was notably lower than for objects in the other three two-way combination of these two factors, (ts (31) = 12.19, 14.74, 8.11 , ps < .001 respectively),. Other statistically significant 2- and 3-way interactions had relatively small effect sizes (i.e., η_p^2s all approximately .15) and will thus not be considered.

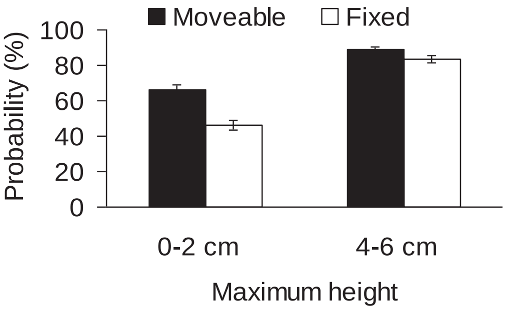

Figure 3. The 2-way interaction, Movement x Height

We next assessed whether the additional kinetic effect of Base Curvature further influenced probability estimates in the moveable condition. To this end, a 1-tailed paired-samples t-test was performed on the overall mean probability estimates for curved vs. planar object bases in this condition, with participant as the unit of observation. The mean probability estimate was statistically higher for convexly curved as opposed to planar bases: 81.7% (SEM = 1.7) and 73.3% (SEM = 2.3), respectively; $t(31) = 4.56$, $p_{\text{1-tailed}} < .0001$). Collectively, these results indicate that Base Curvature further enhanced the kinetic influence of Movement on participants' probability estimates.

The mean estimated probabilities for the blank trials (i.e., no object) that used planar or 3D supporting structures were both relatively low (mean ± SEM = 6.1± 2.9 % and 29.5 ± 4.5 %, respectively), compared to trials during which an object was actually presented. The results confirm that on trials in which no stimulus was presented, participants tended to believe they were feeling only the supporting structure. That the 3D estimates were statistically higher than the planar estimates, $t(31) = 6.6$, $p < .0001$) was expected because participants could mistakenly interpret contact with a higher portion of the 3D supporting structure as indicating the presence of an object.

3 GENERAL DISCUSSION

The current study addresses one of the most fundamental problems for human haptic perception, namely how people differentiate whether discrete contacts by multiple fingers belong to a 3-D object or its supporting surface. The study highlights the use of object contact dynamics and geometry via an initial brief contact. (In a more comprehensive publication, we further confirm the importance of material properties).

Although contact (and contact forces) is an inherent component of haptics, to our knowledge, the emphasis on object dynamics as a contributing factor to haptic perception is unique to our experiment. Our results confirmed our expectation that for even a single brief touch, the motions produced strongly influenced the nature of haptic perceptual organization. The estimated probability that participants were touching an object, as opposed to the supporting surface, was notably higher when objects were moveable as opposed to being fixed in place. Movement effects were further enhanced when touching objects with curved (cf. planar) bases, as the convex curvature (relative to the supporting base) served to increase object motions on contact.

The effect of the geometric property of maximum object height also very strongly influenced participants' probability estimates in that they assigned higher probability estimates to tall, as opposed to short, objects. This was likely due to the fact that tall objects are more likely than shorter objects to lie above supporting surfaces. In contrast, the object property of maximum width did not have a noticeable effect on predicting whether an object was present.

Although we made no attempt to match the magnitude of perceived variation across all manipulated factors, we note that the main effect of Max Height was greater than that for Movement. Brief contact with objects that were tall was apparently sufficient for segregating "figure" (object) from "ground" (supporting surface), despite the fact that kinetic information was also available. It is possible though that this may have been due to the height differences being a larger and more reliable effect than the effect of movement.

4 APPLICATIONS

The haptic differentiation of 3D figure and ground is but one aspect of the more general problem that pertains to how humans perceptually organize environmental interactions with multiple fingers into a percept of an "object". The results of such studies are directly applicable to the field of autonomous robotics, particularly for tasks that involve the haptic exploration of unknown environments. They are also highly relevant to those who design hardware or software for 3-D haptic interfaces for teleoperation (e.g., recovery of antiquities from murky waters) and/or virtual environments (e.g., rendering interior or exterior spaces for both sighted and visually impaired users).

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