Figure/Ground Segmentation via a Haptic Glance: Attributing Initial Finger Contacts to Objects or Their Supporting Surfaces

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Abstract—The current study addresses the well-known "figure/ground" problem in human perception, a fundamental topic that has received surprisingly little attention from touch scientists to date. Our approach is grounded in, and directly guided by, current knowledge concerning the nature of haptic processing. Given inherent figure/ground ambiguity in natural scenes and limited sensory inputs from first contact (a "haptic glance"), we consider first whether people are even capable of differentiating figure from ground (Experiments 1 and 2). Participants were required to estimate the strength of their subjective impression that they were feeling an object (i.e., figure) as opposed to just the supporting structure (i.e., ground). Second, we propose a tripartite factor classification scheme to further assess the influence of kinetic, geometric (Experiments 1 and 2), and material (Experiment 2) factors on haptic figure/ground segmentation, complemented by more open-ended subjective responses obtained at the end of the experiment. Collectively, the results indicate that under certain conditions it is possible to segment figure from ground via a single haptic glance with a reasonable degree of certainty, and that all three factor classes influence the estimated likelihood that brief, spatially distributed fingertip contacts represent contact with an object and/or its background supporting structure.

Index Terms—Human haptics, perception and psychophysics.

1 Introduction

Phenomenology, cognitive neuroscience, and computer science have long been challenged by the following question: 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]? *Figure/ground segmentation*, the topic of the current paper, constitutes a fundamental step in imposing perceptual order on the initial confusion of sensory inputs.

1.1 The Figure/Ground Problem

The reader is perhaps most familiar with the issue of figure/ground segmentation as it pertains to vision, where this topic has been studied more thoroughly than any of the other senses [2]. In keeping with the phenomenological conceptualization offered by Rubin [3], and supported empirically by Rock [4], we note that every contour (edge) in the visual field defines two regions that lie to either side of the edge. Peterson [5] has described the traditional view of figure/ground segmentation as follows: "Figures are regions of the visual field that appear to have a definite shape, a shape bestowed in part by their bounding contour (i.e., their edge). ... The region adjacent to the figure is locally shapeless near the edge it shares with the figure; this region is called the ground (short for background) because it often appears to complete amodally behind the figure" (p. 87). Separation of figure from ground has been called "figure/ground segmentation." Auditory scientists have also recently begun to address the figure/ground problem as it applies to complex acoustic scenes (e.g., [6]).

1.2 Figure/Ground Segmentation in Haptics

We now ask: Is figure/ground segmentation also relevant to the haptic domain? We begin by emphasizing that for the sense of touch, we normally operate in the 3D world. Therefore, "figure" is most commonly a real 3D object, that is, "a bounded volume of matter" [7]. "Ground" can be seen as the supporting structure on/in which the figure rests and which is completed amodally beneath it.

"Figure" objects are typically viewed against a variety of natural and artificial backgrounds ("ground"). We know from our daily interactions with objects that segmenting figure from ground haptically is likely to be relatively salient when manual exploration is unconstrained and the object rests on a simple planar surface (e.g., tabletop). However, the grounds of haptic scenes can range widely in complexity. For example, we also frequently encounter 3D supporting structures (e.g., natural rocky surfaces, artificially constructed holding containers, etc.). The presence of other "distractor" objects (e.g., keys among coins in a pocket; a large paper clip among others) can add still more

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complexity to a haptic scene [8], [9]. Traditionally, those interested in visual figure/ground segmentation allowed observers to freely explore relatively simple, high-contrast displays with little ambiguity. More recently, however, Fowlkes et al. [10] have highlighted the presence of figure/ground ambiguity in natural visual scenes. In this paper, we consider more ambiguous scenes as well.

In contrast to the sizeable literature on figure/ground segmentation in vision and audition, we could find only two disparate haptic publications related to haptic figure/ground segmentation. To our knowledge, Katz [11] was the first person to phenomenologically apply the figure/ground problem to touch, albeit in a somewhat puzzling way. In a section entitled "Figure and ground in vision and touch" (pp. 60-61), he used touching a brush with bristles as his primary example. He described the brush as a discontinuous space filled with points of the bristles, where the points act as a tactual figure, and the spaces between them as tactual ground. Katz' definition of ground seems somewhat atypical (cf. [3]) in that at least in this example, he does not consider "ground" as being completed amodally behind the figure.

More recently, Kennedy and Domander [12] showed that with training, five blind children aged 8-14 were capable of haptically differentiating figure from ground in 2D displays. Each display consisted of a single raised wavy contour with a dot (an imaginary "eye") appropriately positioned to the right or the left of the contour. The same contour could be interpreted as depicting one of the two different facial profiles that looked left or right, depending on the position of the "eye." To our knowledge, this clever study is the only one to experimentally demonstrate the existence of 2D haptic figure/ground organization, and no sighted blindfolded individuals were included.

1.3 The Nature of Haptic Processing

Although sensory information about the external world is considerably more sparse and sequential for haptics than for vision, these local haptic inputs can be effectively used to identify common objects quickly and accurately [13]. Thus, we anticipate that figure/ground segmentation also occurs quickly and plays a crucial role in the haptic perception of objects, their properties, and spatial layouts. It should also contribute to the considerable manual dexterity with which objects are manipulated when only partial information is available, when the object has not yet been identified, and when visual preview is not possible.

As outlined briefly in the next two sections, previous research in our lab has shown the importance for haptic perception of an initial brief contact, followed by a temporally more extended period of systematic manual exploration.

1.3.1 Initial Contact

Relative to free manual exploration, despite being constrained in both space and time, a brief initial contact ("haptic glance") lasting a couple of hundred milliseconds provides sensory inputs that contribute sufficient information to: detect initial contact and edges, differentiate relatively coarse differences in object material (e.g., rough versus smooth) and shape (e.g., curved versus flat) as opposed to more detailed geometric information, and to guide extended manual exploration to gain more precise information about an object property [14]. It may be used to classify or identify objects [15] as well, albeit with more limited success. Material and geometric contact properties also critically influence finger force control during a precision grip (e.g., [16], [17]).

Inasmuch as the haptic inputs available during initial contact are relatively limited, we ask first whether haptic observers are even capable of perceptually segmenting figure from ground under such temporally constrained conditions of exploration as a haptic glance.

1.3.2 Extended Manual Exploration

Depending on the contextual information gained from the initial haptic glance, the haptic explorer usually (but not always) proceeds to systematically execute a sequence of one or more stereotypical hand movement patterns ("exploratory procedures") that offer the most precise information about the identity of objects and their properties [18]. A number of studies have empirically confirmed the importance of both material and shape properties for haptic object recognition via extended manual exploration (e.g., [19], [20], [21], [22], [23], [24]. We propose that unconstrained manual exploration (e.g., executing a specific exploratory procedure to extract more precise information about some geometric or material feature at a contact site(s), or applying exploratory forces to determine the kinetic response at a contact site(s)) may help to resolve any perceptual ambiguities encountered during the initial haptic glance.

1.4 Factors Affecting Figure/Ground Segmentation

The two haptic studies in Section 1.2 used current knowledge of visual figure/ground segmentation to guide their approach to haptic figure/ground segmentation, using either phenomenology [11] or empirical research with 2D displays [12]. In contrast, our theoretical approach is grounded in, and thus, more directly guided by what is currently known about the nature of *haptic* processing as influenced by the haptic system's inherent strengths and weaknesses. Recognizing the critical importance of 3D objects for touch, we chose to use unfamiliar, custom-designed 3D objects as "figure" in our initial study on haptic figure/ground segmentation.

In addition, we propose a tripartite factor classification schema to guide our study. Two of the three factors which we propose are derived from our earlier research findings on differentiating objects haptically [15]. We anticipate from this work that the integration of sensory inputs from multiple fingers into a "figure" will critically depend upon determining both *material* and *geometric* consistencies within a single global shape, thereby differentiating figure (i.e., the object) from ground (i.e., a supporting surface).

We derive the third factor set, engineering *dynamics*[1] (consisting of both kinematics and kinetics [25]), from a critical aspect of haptic processing that fundamentally differs from either vision or audition, and that to our

1. Haptic "dynamic" properties are related but not identical to those addressed in the visual biological motion research, where the term is commonly used to address only kinematic factors (position, velocity, and acceleration). Haptics also involves the relationship between force, mass, and motion.

knowledge has not been previously emphasized in conjunction with the topic of haptic figure/ground segmentation. In the physical world, dynamics (both the engineering term and the lay meaning) only occurs if an object is active (i.e., imparts motion on itself or another object). For haptics, contact between the hand and the physical world is inherent and unavoidable. This means that the observer/actor will *always* apply contact forces to the physical world that will typically effect change. It also suggests that *kinetic* factors, the study of the relations among the forces acting on a body, its mass and its motion, may be functionally and uniquely important for haptic, as opposed to either visual or auditory, figure/ground segmentation. With respect to a haptic glance, the focus of the current study, applied contact forces typically produce micromotions of an object (but not typically of a supporting surface) that we propose will also be important for haptic figure/ground segmentation.[2]

In keeping with both material and geometric factor sets, we further predicted that haptic observers would be more likely to judge multiple discrete contact regions with consistent dynamics (based on the regions' relative location to each other) as belonging to the same object, as opposed to its supporting structure.

1.5 The Current Study

Initial pilot work for this study indicated that figure and ground percepts can vary quite markedly in perceptual salience when exploration is limited to very brief, initial contact and when the combination of factors is not chosen for the maximum effect. In this study, we began by considering the extent to which haptic observers are capable of differentiating an object (i.e., figure) from its supporting surface (i.e., ground) when a brief, initial haptic glance is used. Second, we empirically evaluated our newly proposed tripartite factor-classification schema by assessing the influence of briefly sensed kinetic, geometric, and material factors on haptic figure/ground segmentation.

Participants were required to numerically estimate the strength of their subjective impression that they were feeling an object versus only its supporting surface to assess the influence of the different factors on figure/ground segmentation via a brief, unimanual haptic glance. We initially considered requiring a binary yes/no response, but concluded that asking subjects to judge the strength of their "object" percept (on a scale of 0-100) would reflect the level of ambiguity detected more precisely within fewer trials. A nonbinary response should prove additional value to those who may wish to adopt a Bayesian approach to computationally modeling the processes underlying figure/ground segmentation.

We were particularly interested in the role of forces serendipitously imparted by the observer/actor on contact because we viewed the kinetics of object(s) as likely to be a primary contributor to haptic figure/ground segmentation. To our knowledge, the potential perceptual contribution of kinetic factors has never before been systematically examined within this perceptual context. Thus, we assessed the contribution of kinetic factors in both Experiments 1 and 2. In Experiment 1, we focused additionally on the role of geometry. In Experiment 2, in addition to manipulating both kinetic and geometric factors, we further varied surface texture, a prominent property of object material that plays an important role in perceiving objects and their surfaces [18]. We explain our specific predictions for Experiments 1 and 2 in Sections 2 and 3, respectively.

2 EXPERIMENT 1

To assess the role of *kinetic* factors, we manipulated two potentially important variables: objects were either moveable when briefly contacted or firmly fixed to the supporting surface; furthermore, in the moveable condition, the base curvature of the objects was either planar or convex (relative to the supporting surface), the latter condition serving to potentially enhance the perceptual importance of kinetics by increasing object "wobble" on contact. To replicate everyday life, these kinetic variables were made to vary stochastically—on any trial, the object may or may not move, depending where on the object force is applied (e.g., the object will not move if the force passes vertically down through the center of mass). We would expect, however, that when a force is applied, objects with more prominent, nonstationary kinetics would be most definable as figure against a stationary, shapeless background.

We also considered the contribution of two *geometric* factors. Based on our approach grounded in what is currently known about haptic processing, we would expect that objects that are *both* tall and narrow would have less geometric consistency with the background, and hence, be determined as figure more often than short and wide objects. This prediction also follows from a traditional view of figure and ground, and considering a simple planar background. Geometrically, we would expect objects that are both tall and narrow to be perceived as figure because these objects would be most clearly perceived as having a *definite 3D shape*; in contrast, the background (support structure) would appear shapeless, *completing beneath* the figure. For this first study, we therefore chose to assess the effects of height (i.e., maximum object height) and width (i.e., maximum object width).

2.1 Method

2.1.1 Participants

A total of 32 participants (24 females, eight males) ranging in age from 17 to 22 years (mean $= 18.2$) participated. All participants were right-handed based on their performance on the Edinburgh Handedness Inventory [26]. Participants either received one credit toward their final grade in an introductory psychology class or were paid \$10 as compensation. The experiment lasted about 40 minutes.

2.1.2 Materials

A considerable amount of pilot work was performed before deciding on the final set of stimulus objects and supporting surfaces. Ultimately, 16 unique objects were chosen that

2. In the current paper, we focus on "dynamics" (and more specifically, kinetics) as the study of the explicit relation between application of a force to an object, its mass and its subsequent motion. It should not be equated with the term "active touch", which is used by Katz and other behavioral neuroscientists to refer to the execution of voluntary exploratory movements in relation to an object for purposes of determining its invariant features (e.g., shape, texture, weight, etc.)

varied in their geometric (maximum height, maximum width) and kinetic/geometric (base curvature) form. One-half of the objects had sharp edges while the other half had rounded edges, for reasons that will be explained in the section titled "Stimulus objects." Each unique object was free to move ("moveable") versus attached to a background supporting surface ("fixed"); in addition, each was presented on a simple planar versus a complex 3D supporting structure.

Stimulus objects. We initially determined a typical range of values for both geometric continua (maximum height, maximum width). The continuum for base curvature was similarly explored to create a secondary kinetic factor (the primary one being whether or not an object was attached to the base).[3] All objects were further constrained to being graspable with a single hand, with no axis (including the diagonal) greater than 8 cm [27]. As the preliminary psychophysical evaluation revealed that it was unlikely that participants would be able to differentiate more than two values per continuum in the current experiment, parameter variation was binary, yielding eight different stimulus conditions.

In order to minimize the possibility of absolute object recognition, we increased the variability of the object set by producing two different objects for each of the eight conditions, one with rounded edges and the other with sharp edges. We did not include edge as a factor in our statistical analyses because it was not of primary interest in the current study. We saw little reason to predict that the subjective impression of touching a rigid object would depend upon the type of edges present. With artificial objects, both sharp and rounded edges occur frequently; for natural objects (e.g., rocks), perhaps those with sharp edges may be found a little more often than those with rounded edges, but the difference is not notable; moreover, unlike the current stimulus object set, a single object often contains both types of edges.

Accordingly, the final object set for the moveable condition consisted of 16 unique objects reproduced in sanded pine (Fig. 1). Each object was assigned to one of two possible values for each of the following parameters: short/tall, narrow/wide, with curved/planar bases (e.g., one object was tall, narrow, and curved on the bottom).

A second duplicate set of these 16 objects was created for use under the fixed condition so that each object could be securely attached to a background supporting surface, yet easily replaced by the experimenter between trial conditions. Depending on its size, each object was either attached using a magnetic surface or a steel post embedded in the background supporting structure. To facilitate the effective attachment using a magnet, all objects with curved bases were replaced by identical objects with planar bases.[3] For the short objects (0-2 cm), a circular piece of metal was glued to the bottom of each object, to secure it to the magnet embedded in the support structure. Object height was also adjusted so that with the metal piece in place, height was equivalent for fixed and matching moveable objects. For tall objects (4-6 cm) that did not attach securely with the magnet, a hole was drilled into each base to permit the object to be firmly secured to the steel post.

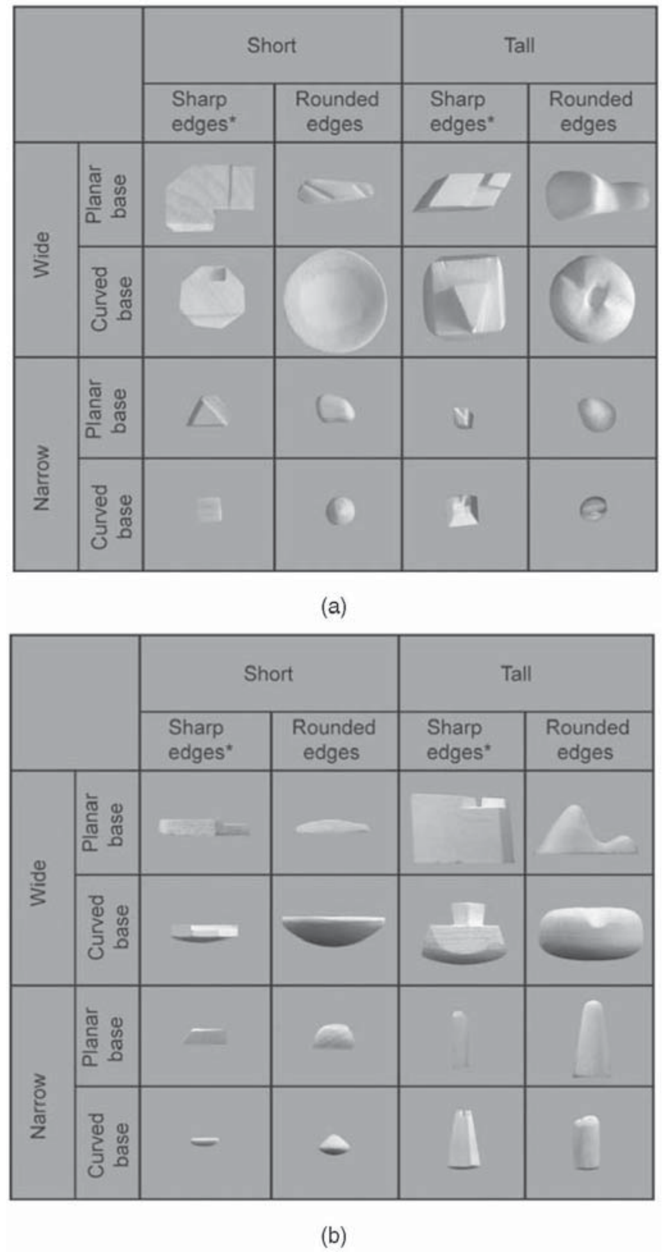

Fig. 1. Experiment 1: Stimulus set of 16 unique objects. (a) Top view, (b) side view. "*" indicates the eight smooth objects also used in Experiment 2.

Background supporting surfaces. Using only a simple planar supporting surface might have resulted in participants producing relatively uninformative ceiling and floor responses, inasmuch as local contact(s) with an object would consistently be above any local contact(s) with the supporting surface; in addition, if no object were present, all local contacts would occur at the same level. But in everyday life, other more complex supporting surfaces create perceptual ambiguities by being three dimensional. We attempted to capture some of this ecological spatial

3. In the current study, no geometric information about object base curvature was actually available in either moveable or fixed conditions because the fingers never contacted the base of the objects. Inasmuch as we were only interested in base curvature as a potential kinetic factor, it therefore seemed appropriate to limit variation of base curvature and its subsequent statistical assessment to the moveable (cf. fixed) condition, where it was directly relevant. This decision further allowed us to make the bases of all objects in the fixed conditions planar to meet the requirement that objects remain fully stationary when contacted.

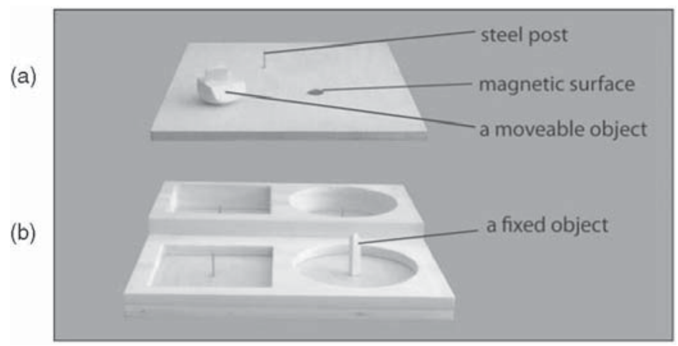

Fig. 2. (a) The planar supporting structure. A "moveable" object is shown in position. Both the steel post and the magnetic surface were used to firmly fix tall, narrow objects and all other objects, respectively. Note that objects were placed on the supporting structures with the latter oriented with respect to the participant such that no magnetic base or protruding post was ever touched. (b) The 3D supporting structure (with pin-attachment). 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 post projecting upward through its base.

variation in object backgrounds known to occur with both natural and artificial surfaces.

After considerable trial-and-error, we designed and constructed two types of supporting surfaces, one simple and the other relatively complex (Figs. 2a and 2b, respectively). Contact was allowed to randomly occur by placing stimulus objects of different heights and widths on/in the background structures such that across trials, the top of an object could be higher, lower, or at the same height as the supporting structure.

The simple supporting structure was a planar structure that was intended to simulate commonly encountered flat surfaces such as a table or counter top. The complex structure was a custom-designed, 3D varying structure in which sharp edges of different heights were spatially distributed. It was intended to simulate a version of a 3D spatial organizer into which objects are placed. With the variation in background structure, we anticipated that participants would be more likely to vary their numeric judgments of the strength of their "object" percepts across the full range, allowing for a more informative assessment of the three-factor classification system addressed in the current study.

The planar and custom-designed 3D supporting surfaces were made of pine, with outer lengths and widths of 31 and 34 cm, respectively. The thickness of the planar structure was 1.6 cm. The 3D surface was designed with two recessed circles ($\mathrm{diameter} = 13\ \mathrm{cm}$) and two recessed squares ($\mathrm{sides} = 12\ \mathrm{cm}$), with the top edges receding at 90 degrees to the base, as commonly occurs with artificial containers used in daily life. The sizes of the recessed shapes were selected to be large enough to accommodate the largest stimulus object together with a minimum of one finger on either side within the container. To further capture a raised "stepped" surface as occurs naturally with natural rock slabs, the 3D supporting surfaces included a 2 cm discontinuous step that bisected the top. However, the base of all four recessed shapes was equidistant (1.7 cm) from the tabletop below, resulting in recessed depths of holes of 1 and 3 cm across the step. (As the design of this first study was already highly complex, we made no attempt to additionally manipulate the relative depth or shape of the receding spaces, or the 3D step.)

A single planar supporting structure was produced with one magnetic area, one metal post, and the other areas free of both (Fig. 2a). For ease of storage and presentation, we produced three structurally identical versions of the 3D supporting structure, the only difference being the method of stimulus attachment employed, i.e., one with a post protruding from the base of each receding shape (for static tall objects, as shown in Fig. 2b), one with a circular magnetic surface in place of each post (for static short objects), and one with neither posts nor magnetic surfaces (for all moveable objects).

2.1.3 Procedure

Participants wore a blindfold and were seated at a table with the supporting surface for the experimental trial centered approximately 15 cm in front of them. To eliminate any sound cues produced by contact between the supporting structure and tabletop, a square section of nonslip material ($\sim 31 \times 31\ \mathrm{cm}^2$) was attached to the tabletop so that when changing the supporting structures, it would lie directly beneath the current supporting structure. To further eliminate any potential sound cues during manual contact, participants also wore wax earplugs and headphones through which pink noise was delivered. Between trials, the experimenter changed both the supporting structure and the stimulus object (all of which were stored on a compliant surface to eliminate potential sound cues).

To begin the formal experiment, participants read a set of written instructions. Then, the experimenter showed them how to produce a brief gentle contact using all five fingers of their right hand. Using five fingers maximizes the amount of information that can be obtained via a single one-handed haptic glance, and is commonly used in daily life. Participants were trained to reproduce the desired contact movement using the appropriate finger position, duration ($\sim 200\ \mathrm{ms}$),[4] and force. They were instructed to keep their forearm parallel to the table and to let their wrist drop in a relaxed and natural manner. They were taught to produce a gentle contact motion with the thumb and four fingers relaxed and moderately outstretched. When participants curled their fingers into the palm so that contact was made with the backs of their fingers, they were corrected. They were also corrected if they used a single finger to achieve contact by poking. Participants were reminded throughout the experiment that manual 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. To the contrary, we wished to emulate the stochastic changes in contact that commonly occur in everyday life when a person initially briefly contacts their

4. A total of 26 trials were videotaped for each of 8 participants (5 from Experiment 1 and 3 from Experiment 2). These were video digitized using Showbix, and subsequently analyzed using Max Traq to determine contact duration for each trial. Averaged over trials, participants, as well as experiments (because the mean durations for Experiments 1 and 2 were very similar —226 and 187 msec, respectively), the mean (SEM) contact duration was 211 (5) ms.

environment manually. Thus, there was no guarantee that on a given trial, an object that was free to move would actually do so. For example, there would be no torque, and thus, no resulting object micromotion, if the participant applied a vertical force precisely normal to the object through its center of mass. Conversely, when fingers contacted the object at a slight angle and/or away from the center of mass, the resulting forces and torques would serve to produce micromotions of the object. Slight differences in hand positioning could also alter the number of fingers that were in contact with a stimulus object and/or the supporting structure on any trial, and hence, how participants interpreted the spatially distributed haptic inputs.

Once the brief contact movement had been well learned, the formal experiment began. Participants were given one block of 10 practice trials, including two "blank" trials during which no object was presented. The practice objects were not used in the formal experiment. Blank trials were used to further assess the effectiveness of our custom-designed scenes. Participants should be less likely to believe they were feeling an object when trials were blank than when a stimulus object was actually present.

At the start of each experimental trial, participants placed their left hand on their lap and rested their right hand on the table in front of them. The experimenter stood across from them on the opposite side of the table. The background supporting structure (i.e., flat or 3D) was always placed on the square of padded material such that the stimulus object was approximately positioned over the center of this square. The planar orientation of the 3D supporting structure was randomly varied so that the step was aligned either parallel or at right angles to the participant; the structure was further translated so that the randomly chosen recessed shape was always closest to the participant's hand. Each object was placed in the middle of one of the four recessed bases. The planar orientation of each stimulus object on the supporting structures was randomly varied across trials.

After the stimulus was placed on the supporting structure, the experimenter tapped the participant's right hand, which he or she immediately raised ~ 25 cm above the tabletop. The experimenter then guided their hand to some random start position above the object such that the nature of the finger/object/supporting structure contact interactions was variable, mimicking the randomness of contact in ecological conditions. For example, the fingers were aligned so that on any trial the observer might contact the top edge of a recessed shape, the top flat surface of the supporting structure raised above the recessed areas, either of these together with the object, the object alone, or both the object and the base of the recessed shape. When the experimenter released the participant's hand, the participant vertically lowered it to produce a single brief contact between the five digit tips and the object and/or supporting structure beneath. Sometimes, their hand would descend at an angle; however, this was not considered a problem because it further enhanced the variability of contact interactions between fingers, object, and/or supporting structure.

Participants were instructed that on some trials, the experimenter would place an object on or in a supporting structure; on other trials, they would make contact solely with a supporting structure (no object presented). They were told to numerically estimate the strength of their subjective impression that they were touching an "object," as opposed to just the background supporting structure. They were instructed to respond by using a scale of 0-100, where 0 meant that they were absolutely certain that they did not contact an object and 100 meant that they were absolutely certain that they did contact an object. Increasing numbers meant that they judged it is increasingly likely that they had contacted an object.

They were also told that being uncertain was quite possible because contact would be so brief. Despite any uncertainty, however, it was vital that they make only one brief contact per trial, and that they do not attempt to extend or repeat the initial contact. Immediately following contact, participants verbally gave their scale estimate, as they raised their right hand above the contact location and returned it to the resting position on the table for the next trial.

At the end of the experiment, participants were asked three open-ended questions regarding the strength of their "object" percepts. The numeric results are presented and discussed in the Supplementary Materials, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/ToH.2010.25. (Table A1).

2.1.4 Experimental Design

Four completely crossed within-participant factors were included: Movement (two levels: moveable, fixed), Background Supporting Surface (two levels: flat, 3D), Maximum Height (two levels: 0-2 cm, 4-6 cm), and Maximum Width (two levels: 0-3 cm, 5-8 cm). Although we initially intended to cross the last two factors with Base Curvature (two levels: planar, curved), it was impossible to avoid some movement when objects with curved bases were contacted in the fixed condition (see the section titled "Stimulus objects"). Therefore, as previously explained, the bases of all stimuli used under the fixed conditions were made planar. The implications of this adjustment are further addressed in Footnote 3.

Each of the 16 geometrically unique stimuli described in the section titled "Stimulus objects" was presented once in each of the four conditions (two Movement levels $\times$ two Supporting Structures) in 64 trials. An additional 12 blank trials were presented in which no stimulus was present (six per supporting structure). Thus, each participant participated in a total of 76 trials. A different random order was used for each individual.

Within subgroups of four participants, each object was presented once within each of the four recessed shapes of the 3D supporting structure.

2.2 Results

We began our data analysis by addressing the main effects of kinetic (i.e., Movement) and geometric (Max Height, Max Width) factors, the primary factor classes of interest here, as well as of Supporting Structure (2D, 3D). For reasons previously explained, the additional kinetic effect of Base Curvature[3] was only varied in the moveable condition, and its influence will therefore be considered separately in a subsequent analysis. For purposes of the current analysis, the four corresponding estimates for objects with curved or planar bases and sharp or rounded edges were averaged within each participant.

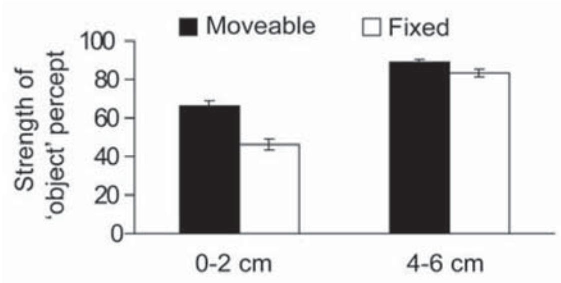

Fig. 3. Experiment 1: Two-way interaction, Movement × Height.

The resulting means served as input data to a four-factor within-participant ANOVA, after confirming that the data were normally distributed. The binary-level factors were Movement (moveable versus fixed), Max Height (short versus tall), Max Width (narrow versus wide), and Supporting Structure (2D versus 3D). Only statistically significant effects are reported in the current paper. Given the investigative nature of our initial empirical study on haptic figure/ground segmentation, we report but do not attempt to further interpret significant effects with relatively small effect sizes (i.e., partial eta square $[\eta_p^2] < 0.20$, all of which involved interaction terms.

As predicted, highly significant main effects with very large effect sizes were obtained for Movement, $F(1,31) = 52.3$, $p < .0001$, $\eta_p^2 = 0.63$, and for Maximum Height, $F(1,31) = 132.58, p < .0001, \eta_p^2 = 0.81$. Moveable objects produced higher numeric estimates regarding the perception of an "object" ($M_{Moveable} = 77.48; SEM_{Moveable} = 1.82$) 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 ($M_{Short} = 56.19; SEM_{Short} = 2.47$). By contrast, the main effect of Maximum Width was not significant.

The two-way interaction, $\text{Movement} \times \text{Max Height}$, was also highly significant, $F(1,31) = 37.25, p < 0.0001, \eta_p^2 = 0.55$. Paired t-test (two-tailed) comparisons showed that the effect of Movement was significant for both levels of Max Height ($ps < 0.002$); similarly, the effect of Max Height was significant for both levels of Movement ($ps < 0.00001$). However, the Movement effect was greater for short than for tall objects, $t(31) = 6.1, p < 0.0001$). The degree to which short, fixed stimuli were haptically perceived as objects was notably lower than for objects in the other three two-way combinations of these two factors, ($ts(31) = 12.19, 14.74, 8.11, ps < 0.001$, respectively), as evident in Fig. 3.

Other significant two-way and three-way interactions included $\text{Supporting Structure} \times \text{Max Height}$, $F(1,31) = 5.70, p < 0.05, \eta_p^2 = 0.16$, and $\text{Supporting Structure} \times \text{Max Width}$, $F(1,31) = 5.65$, $p < 0.05$, $\eta_p^2 = 0.15$; $\text{Movement} \times \text{Max Height} \times \text{Max Width}$, $F(1,31) = 5.63$, $p < .05, \eta_p^2 = 0.15$. All effect sizes (η_p^2) are relatively small, and the main effect patterns are evident within all higher level combinations of those factors.

Overall our primary predictions regarding the main effects of height and movement were confirmed, regardless of condition. The main effect of Maximum Width was not statistically significant. Several complex factor interactions were also noted, but their effect sizes were small compared to those of the main effects of interest.

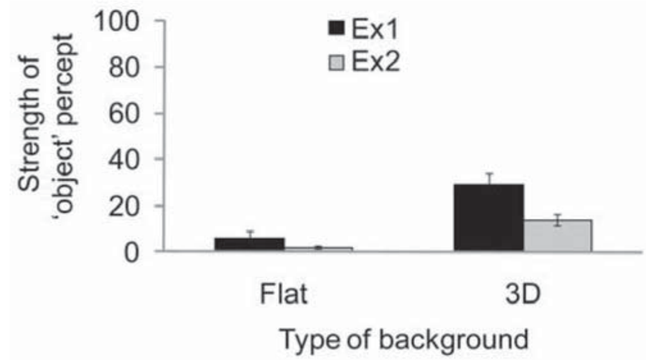

Fig. 4. Results for blank trials for Experiment 1 and Experiment 2.

As explained in Footnote 3, variations in the curvature of the base of the objects (curved versus planar) were only presented in the moveable condition, while two planar-base sets were presented in the fixed condition. Accordingly, we next assessed whether the additional kinetic effect of base curvature further influenced numeric estimates of the strength of the "object" percepts during brief contact in the moveable condition. To this end, a one-tailed paired-samples t-test was performed on the overall mean numeric estimates for curved versus planar object bases in the movement condition, with participant as the unit of observation. As predicted, the mean numeric estimate was statistically higher when the object bases were convexly curved as opposed to planar (relative to the supporting surface): 81.7 ($SEM = 1.7$) and 73.3 ($SEM = 2.3$), respectively; $t(31) = 4.56$, $p_{1\text{-tailed}} < 0.0001$). Collectively, these results indicate that the factor Base Curvature further enhanced the kinetic influence of movement on participants' numeric estimates of the strength of their "object" percepts.

The mean estimated "object"-percept strength for blank trials (i.e., no object) that used planar or 3D supporting structures were both relatively low ($\text{mean} \pm \text{SEM} = 6.1 \pm 2.9$ and 29.5 ± 4.5, respectively), compared to trials in which an object was actually presented (see Fig. 4). The results confirm that on trials in which no stimulus was presented, participants tended to believe that they were feeling only the supporting structure.

When asked at the end of the experiments how many/what kind of supporting structures there were, nine subjects responded that there was only a planar supporting structure. The remaining 23 subjects thought that there were either two or three structures, one planar and the other(s) 3D with protruding and/or receding regions.

3 EXPERIMENT 2

In Experiment 2, we altered the previous experimental design to assess the contribution of material cues, specifically, the objects' surface texture, as well as its interaction with both kinetic and geometric factors. While retaining both kinetic (Movement, Base Curvature) and geometric (Max Height, Max Width) factors, we added a binary Texture factor (rough versus smooth) to our analysis. Inasmuch as the number of stimulus conditions possible in any one haptic experiment is limited, in this first study on haptic figure/ground segmentation, the supporting structures were smooth (as opposed to being both smooth and

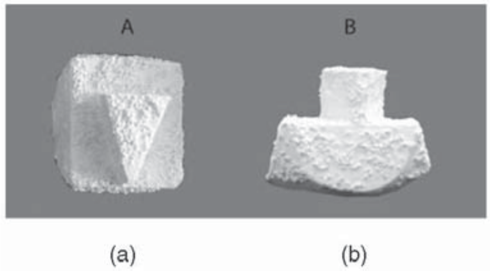

Fig. 5. An example of one of the rough objects used in Experiment 2 ((a) top view; (b) side view). The full set of eight objects is designated by an asterisk in Fig. 1. Rough and smooth versions of each object were presented in Experiment 2.

rough), while the surface texture of the 3D objects was either smooth or rough.

In addition to the predictions outlined in Experiment 1, we anticipated that the rough stimuli would have higher numeric estimates of "object" percept strength than smooth objects—for the sense of touch, roughness is highly salient [18]; moreover, artificial supporting structures (tabletops) are usually smooth, highlighting the texture contrast between object and supporting structure in this experiment.

3.1 Method

3.1.1 Participants

A total of 34 paid participants (six males, 28 females) participated. Their ages ranged from 18 to 22 years, with an average age of 19.7 years, and all were right handed [26]. The experiment lasted approximately 40 minutes.

3.1.2 Materials: Objects and Supporting Structures

In Experiment 2, in order to expand our focus to include binary variation of the objects' surface texture while maintaining the same number of trials as in Experiment 1, only objects with sharp (cf. rounded) edges were used.

We used four object sets, each consisting of eight of the original 16 unique wood-sanded stimulus objects from Experiment 1. All stimulus objects had sharp edges, and varied in Maximum Height, Maximum Width, and Base Curvature. Two of the object sets were perceptually smooth when initially contacted (see Fig. 1). The finish on the surfaces of the objects in the other two stimulus sets produced a rough percept on initial static contact. This textured surface was accomplished by coating the objects with latex paint embedded with galena crystals (diameter: +20 to +28 microns) that were naturally sharply edged. An example from the set of rough objects is shown in Fig. 5. The moveable and static movement conditions were achieved as in Experiment 1. Therefore, two of the four different stimulus sets consisted of moveable objects with smooth versus rough surfaces, while the remaining two sets consisted of objects that were fixed in place and had smooth versus rough surfaces.

Once again, the supporting structures were either planar or 3D (with two recessed circles and two recessed squares), as shown in Fig. 2.

3.1.3 Procedure

The procedure was the same as used in Experiment 1. The experiment took about 40 minutes.

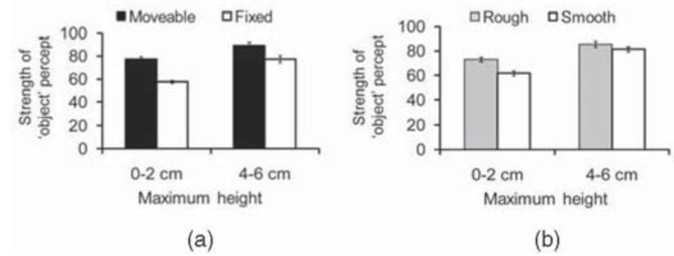

Fig. 6. Highly significant two-way interactions in Experiment 2. (a) Max Height × Movement. (b) Max Height × Texture.

3.1.4 Experimental Design

The design paralleled that for Experiment 1, with one additional factor, Texture (two levels: smooth and rough). Note that the background material for all support surfaces was sanded wood (i.e., smooth). The eight unique sharp edged objects were selected from the original set of 16 used in Experiment 1. This set was presented in each of the four $\mathrm{Movement} \times \mathrm{Texture}$ conditions. The treatment of Base Curvature was also the same as Experiment 1 (see the section titled "Stimulus objects," Footnote 3). Once again, 12 blank (i.e., no stimulus) trials (six per background) were included, for a total of 76 trials per participant. The order of presentation for each participant was random.

3.2 Results

The treatment of the data and statistical analyses were handled similarly to those in Experiment 1. For the primary analysis, after confirming that the data were normally distributed, the two corresponding estimates for objects with curved and planar bottoms were averaged, and the resulting means entered into a five-factor within-participant ANOVA. The binary-level factors included Movement (moveable versus fixed), Texture (smooth versus rough), Max Height (low versus high), Max Width (narrow versus wide), and Supporting Structure (2D versus 3D). Once again the second kinetic factor, Base Curvature, which only varied in the moveable condition, was separately addressed.

The following three main effects were statistically significant with very large effect sizes: Movement, $\mathrm{F}(1,33) = 55.86, \mathrm{p} < .0001, \eta_\mathrm{p}^2 = 0.63$, Max Height $\mathrm{F}(1,33) = 76.00, \mathrm{p} < 0.0001, \eta_\mathrm{p}^2 = 0.70$, and Texture $\mathrm{F}(1,33) = 46.69, \mathrm{p} < 0.0001, \eta_\mathrm{p}^2 = 0.59$. As in Experiment 1, the mean strength of the "object" percept was notably higher for moveable ($\mathrm{M}_\mathrm{moveable} = 83.3$; $\mathrm{SEM}_\mathrm{moveable} = 1.5$) than for fixed ($\mathrm{M}_\mathrm{fixed} = 67.3$; $\mathrm{SEM}_\mathrm{fixed} = 2.6$) movement conditions, and for taller ($\mathrm{M}_\mathrm{tall} = 83.3$; $\mathrm{SEM}_\mathrm{tall} = 2.0$) than for shorter objects ($\mathrm{M}_\mathrm{short} = 67.3$; $\mathrm{SEM}_\mathrm{short} = 2.1$). In addition, the mean strength of the "object" percept was higher for roughly textured ($\mathrm{M}_\mathrm{rough} = 79.1$; $\mathrm{SEM}_\mathrm{rough} = 1.6$) than for smoothly textured ($\mathrm{M}_\mathrm{smooth} = 71.5$; $\mathrm{SEM}_\mathrm{smooth} = 2.1$) objects. The effect of Max Width was also significant, $\mathrm{F}(1,33) = 5.43, \mathrm{p} < 0.05, \eta_\mathrm{p}^2 = 0.14$; however, its effect size was relatively small ($\mathrm{M}_\mathrm{narrow} = 73.5$; $\mathrm{SEM}_\mathrm{narrow} = 2.0$; $\mathrm{M}_\mathrm{wide} = 77.1$; $\mathrm{SEM}_\mathrm{wide} = 2.0$).

Significant two-way interactions with relatively sizable effect sizes ($\eta_\mathrm{p}^2 > 0.20$) include: $\mathrm{Max\ Height} \times \mathrm{Movement}$, $\mathrm{F}(1,33) = 10.48, \mathrm{p} < 0.0035, \eta_\mathrm{p}^2 = 0.24$, and $\mathrm{Max\ Height} \times \mathrm{Texture}$, $\mathrm{F}(1,33) = 15.50, \mathrm{p} < 0.0001, \eta_\mathrm{p}^2 = 0.32$. The two interaction terms are shown in Figs. 6a and 6b, respectively, the main effects being clearly evident. Paired t-test (two-tailed) comparisons showed that the effects of Texture and Height were significant for both levels of the other factor, i.e., Height and Texture, respectively (all $\mathrm{ps} < 0.0001$). The same can be said with respect to the effects of Movement and Height (all $\mathrm{ps} \leq 0.0001$). We further note that both Movement and Texture effects were larger when the objects were short as opposed to tall, $\mathrm{t}(33) = 3.23, \mathrm{p} < 0.005$, and $\mathrm{t}(33) = 3.93, \mathrm{p} < 0.0001$, respectively. In addition, the mean estimated strength of "object" percepts for both the short/smooth (Fig. 6b) and short/fixed objects (Fig. 6a) were statistically lower than the other three corresponding conditions (all $\mathrm{ps} < 0.00001$).

Finally, with only one exception, none of the three- and four way interaction terms reached statistical significance, with all effect sizes relatively small ($\eta_\mathrm{p}^2 < 0.20$).

As in Experiment 1, we performed a secondary analysis in which we asked whether a convexly curved object base enhanced the kinetic effect of object moveability during brief contact. A one-tailed paired-samples t-test was performed on the overall mean estimated strength of "object" percepts for curved versus planar object bases in the movement condition, with participant as the unit of observation. Once again, the mean numeric estimate was statistically higher for convexly curved, as opposed to planar, object bases: $\mathrm{M_{curved}} = 85.3\ (\mathrm{SEM_{curved}} = 0.5)$ and $\mathrm{M_{planar}} = 81.3\ (\mathrm{SEM_{planar}} = 0.9)$, respectively; $\mathrm{t}(33) = 2.89$, $\mathrm{p} < 0.008$. These results replicate those of Experiment 1 by suggesting that the factor, Base Curvature, further enhanced the kinetic influence of Movement on participants' numeric estimates.

The results of presenting blanks (i.e., no object) in conjunction with the planar and 3D supporting structures also showed the same pattern as observed in Experiment 1 (see Fig. 4). The mean numeric estimates for detecting an object were very low: $\mathrm{M_{planar}} = 2.0\ (\mathrm{SEM_{planar}} = 0.6)$ and $\mathrm{M_{3D}} = 0.9\ (\mathrm{SEM_{3D}} = 2.5)$. The results confirm that on trials in which no stimulus was presented, participants strongly believed they were feeling only the supporting structure. That the 3D estimates were statistically higher than the planar estimates, $\mathrm{t}(33) = 4.69, \mathrm{p} < 0.0001$, was to be expected if participants mistakenly interpreted contact with a higher portion of the 3D supporting structure as signifying the presence of an object. Note that the mean numeric estimates are consistently lower in Experiment 2 than Experiment 1 (6.1 for planer surfaces and 29.5 for 3D supporting structures). As the supporting surfaces in both experiments were made of sanded wood, the absence of any textured surfaces in the blank trials of Experiment 2 likely decreased the estimated probabilities that an object was actually present because participants would have known that some of the stimulus objects were textured.

When asked at the end of the experiments how many/what kind of supporting structures there were, four subjects responded there was only a planar supporting structure. The remaining 30 subjects thought there were either two or three structures, one planar and the other(s) 3D with protruding and/or receding regions.

4 General Discussion

Our study has focused on a fundamental question for human haptic object perception, namely if, and if so, how do observers manually differentiate whether multiple local contacts belong to a 3D object (figure) or to just the supporting surface (ground)? In this first study, we constrained exploration to an initial brief contact or "haptic glance," which has been shown to provide relatively coarse information about objects and their properties [15], [16].

4.1 Can People Haptically Segment an Object from Its Supporting Structure?

A variety of objects and two supporting structures were employed such that the height of local finger contact relative to the supporting structure was altered quasi-randomly across trials (above, level with, or below). This step was taken in an attempt to produce a variety of commonly experienced contacts with objects and/or their supporting surfaces. Inasmuch as the contact information provided by a haptic glance (cf. extended manual exploration) is relatively impoverished, it was not self-evident that observers would use the extremes (i.e., 0 and 100) of the numeric scale in estimating the strength of their subjective impression of feeling an "object" given the presence of figure/ground perceptual ambiguities. It is notable, therefore, that their mean estimates were close to zero for blank trials with the planar supporting structure, extending to > 80 (cf. a maximum of 100) under several conditions involving moveable and/or tall objects. We conclude that haptic segmentation of objects from their supporting structures using a single, one handed haptic glance can be perceptually salient under several different conditions.

4.2 The Tripartite Factor Classification Scheme

We have used what is known regarding the fundamental characteristics of haptic processing to both ground and guide our approach to haptic figure/ground segmentation. Both geometric and material cues have been shown to be critically important for the haptic recognition of surfaces, objects, and their properties (e.g., [13]; [18], [19], [20], [21], [22], [23], [24]).

We have also highlighted the fact that haptics clearly differs from both vision and audition in that the perceiver applies contact forces to surfaces and objects that, in turn, bring about change (i.e., dynamics, and more specifically, kinetics). Unlike vision or audition, even when objects are only briefly touched, forces produce micromotions that we propose strongly influence the nature of haptic figure/ground segmentation. Thus, our current approach is distinct from the earlier disparate haptics literature [11], [12], which emphasized visual principles in their approach to haptic figure/ground segmentation.

To assess our newly proposed tripartite factor-classification scheme, we empirically evaluated the effect of brief kinetic, geometric, and material contact parameters on the haptic differentiation of objects ("figure") from their supporting surfaces ("ground"). To this end, objects in Experiments 1 and 2 were either moveable as a result of brief contact or were fixed to a supporting surface. In addition, the base curvature of objects in the movement condition was either planar or convex (relative to the supporting surface), to increase the possibility that objects would wobble on contact, in this way further enhancing the perceptual consequences of kinetics. In Experiment 1, we also focused on the influence of geometric factors (i.e., object height and maximum object width). In Experiment 2, we further addressed the role of object texture (smooth versus rough).

4.2.1 Kinetic Properties

The results of Experiments 1 and 2 are unique to date in that they consistently highlight the value of kinetic cues when participants contacted objects and/or their supporting structure using only a brief, multifingered haptic glance. The numeric estimates of the strength of the "object" percept were notably higher when objects were free to move as opposed to being fixed in place. This kinetic difference was further enhanced when touching objects with convex (cf. planar) bases, the curvature serving to increase object micromotions on initial contact.

4.2.2 Geometric Properties

The effect of maximum object height also very strongly influenced participants' estimates of the strength of their "object" percepts in both experiments; more specifically, they assigned higher magnitudes to tall, as opposed to short, objects. To a considerably lesser extent, they assigned higher magnitudes to narrow, as opposed to wide, objects. However, the smaller effect size may, in part, be due to our desire to use ecological conditions. The contact of the participant's hand was random and may not have spanned the width of the whole object. In contrast, most objects were relatively constant in height, thus, contact with them would result in detecting the maximum height difference.

Although the effect sizes for Height and Movement factors were both considerable, the main effect of the former proved to be greater than the latter. It is possible that in our experiments, cues to height differences (cf. kinetic) may have been more reliably available because trials began with the observer's fingers positioned directly above each object (i.e., reducing the chance of movement). Moreover, the responses to open-ended questions (see Supplemental Materials, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/ToH.2010.25) indicate that when texture also varied (Experiment 2), the numeric estimates of the strength of the "object" percepts were attributed most to material, then kinetic, and finally geometric cues. Thus, further controlled investigation of higher-level interactions would seem valuable.

In regards to the effect of the type of supporting structure on the determination of a figure, we further note that the numeric estimates of the strength of the "object" percepts for blank trials associated with the 3D supporting structure were statistically higher than those for the planar supporting structure, $t(31) = 6.6, p < 0.0001$). These results suggest that participants were more likely to mistakenly interpret contact with the 3D supporting structure as contact with an object. This was particularly the case for the group of participants that believed there was just a planar background. The estimates were twice as high when participants thought there was only a planar background as compared to two or more structures (at least one being 3D): Experiment 1: $\mathrm{mean(SEM)} = 46.8$ (10.3) versus 22.7 (4.0); Experiment 2: 22.7(5.4) versus 12.7(2.7), respectively. (We did not statistically compare the relative differences because the number of subjects in the planar group was relatively low).

This interesting effect of support structure geometry suggests that haptic figure/ground segmentation is context-dependent, as has been previously demonstrated with vision (e.g., camouflage effects). That the main effect of supporting structure on perceived figure/ground segmentation judgments was not statistically significant was, therefore, somewhat puzzling. Further clarification and exploration of this geometric factor may be possible by more directly controlling the relative heights and widths of objects and their supporting structure (as suggested by the significant but small effects of Supporting Structure $\times$ Height and Supporting Structure $\times$ Width), and by examining hits and false-alarm data available when a two alternative-forced-choice, object-detection paradigm is used.

4.2.3 Material Properties

In Experiment 2, the surfaces of the stimulus objects were smooth versus rough when briefly contacted, whereas the surfaces of the background supporting structures were always smooth. The overall numeric estimates of the strength of participants' subjective impressions that they were feeling an "object," as opposed to the supporting background structure were higher for rough than for smooth objects. It is possible, however, that the most relevant aspect of the object surfaces was not whether or not they were textured, but rather whether the object and background surfaces were perceptually congruent or not.

On the basis of the current results, we conclude that figure/ground segmentation via a haptic glance is clearly influenced by kinetic, geometric, *and* material contact parameters, as proposed in our tripartite factor-classification scheme. Although we cannot directly compare the importance of these three factors, as we have not equated their subjective magnitude, both the effect of movement and the effect of texture appeared to be greater for shorter than for tall objects. This may be due to the fact that in this experiment, the height of tall objects was such a strong cue that it produced a ceiling effect on the data.

5 Haptic Perceptual Organization: Future Work and Applications

In future, we plan to extend our research on the role of manual exploration in figure/ground segmentation to investigate the use of multiple haptic glances, (which should allow preceding glances to create a context within which each current glance could be interpreted), and the role of more extended manual exploration (see Section 1.2.2). In addition, having affirmed the importance of all three primary factor classes, next we will investigate the nature and extent to which these three primary factor classes interact by deliberately equating perceptual magnitudes.

In addition, haptic differentiation of 3D figure and ground is but one aspect of the more general challenge that pertains to how humans perceptually organize multiple spatially distributed haptic inputs. We also plan to address the nature of haptic grouping: how we group inputs from multiple discrete contacts into one or more "objects." Here too, the literature to date is very sparse, the topic having only been addressed by one fMRI study with real 3D objects [28], and by a series of computer conference papers pertaining to the relevance of the visual Gestalt grouping principles for touch by Chang and her associates [29], [30], [31].

The results of studies on haptic figure/ground segmentation, and more generally, haptic perceptual organization, are highly relevant to those who design hardware or software for haptic/multisensory interfaces usable in a wide range of applications involving teleoperation (e.g., recovery of antiquities from murky waters, space repair) and/or virtual environments (e.g., rendering interior or exterior spaces for both sighted and visually impaired users or medical training systems for novice surgeons, gaming). They are also directly applicable to the field of robotics, particularly for tasks that involve haptic exploration of unknown environments.

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References

[1] J.R. Pomerantz and M. Kubovy, "Theoretical Approaches to Perceptual Organization: Simplicity and Likelihood Principles," *Handbook of Perception and Human Performance,* K.R. Boff, L. Kaufman, and J.P. Thomas, eds., pp. 1-46, Wiley, 1986.

[2] S.E. Palmer, *Vision Science: Photons to Phenomenology.* The MIT Press, 1999.

[3] E. Rubin, "Figure and Ground," *Readings in Perception* D. Beardslee and M. Wertheimer, ed. and tr., pp. 35-101, Van Nostrand, Original Work Published in 1915.

[4] I. Rock, , *The Logic of Perception.* MIT Press, 1983.

[5] M. Peterson, "On Figures, Grounds, and Varieties of Surface Completion," *Perceptual Organization in Vision,* R. Kimchi, M. Behrmann, and C. Olson, eds., pp 87-116, Lawrence Erlbaum & Assoc., 2003.

[6] A.S. Bregman, *Auditory Scene Analysis: The Perceptual Organization of Sound.* The MIT Press, 1990.

[7] P. Kellman, "Visual Perception of Objects and Boundaries" A Four-Dimensional Approach," *Perceptual Organization in Vision,* R. Kimchi, M. Behrmann, and C. Olson eds., pp. 155-201, Lawrence Erlbaum & Assoc., 2003.

[8] M.A. Plaisier, W.M. Bergmann Tiest, and A.M.L. Kappers, "Haptic Pop-Out in a Hand Sweep," *Acta Psychologica,* vol 128, pp. 368-377, 2008.

[9] M.A Plaisier, W.M. Bergmann Tiest, and A.M.L. Kappers, "One, Two, Three, Many-Subitizing in Active Touch," *Acta Psychologica,* vol. 131, pp. 163-170, 2009.

[10] C.C. Fowlkes, D.R. Martin, and J. Malik, "Local Figure-Ground Cues Are Valid for Natural Images," *J. Vision,* vol 7, nos. 8, 2, pp. 1-9, 2007.

[11] D. Katz, *The World of Touch,* L. Krueger, tr. Lawrence Erlbaum Assoc., Inc., 1989, Original Work Published in 1925.

[12] J. Kennedy and R. Domander, "Pictorial Foreground/Background Reversal Reduces Tactual Recognition by Blind Subjects," *J. Visual Impairment and Blindness,* vol. 78, pp. 215-216, 1984.

[13] R.L. Klatzky, S.J. Lederman, and V. Metzger, "Identifying Objects by Touch: An "Expert System," *Perception and Psychophysics,* vol. 37, no. 4, pp. 299-302, 1985.

[14] S.J. Lederman and R.L. Klatzky, "Relative Availability of Surface and Object Properties during Early Haptic Processing," *J. Experimental Psychology: Human Perception and Performance,* vol. 23, no. 6, pp. 1-28, 1997.

[15] R.L. Klatzky and S.J. Lederman, "Identifying Objects from a Haptic Glance," *Perception and Psychophysics,* vol. 57, no. 8, pp. 1111-1123, 1995.

[16] R.S. Johansson and G. Westling, "Roles of Glabrous Skin Receptors and Sensorimotor Memory in Automatic Control of Precision Grip when Lifting Rougher or More Slippery Objects," *Experimental Brain Research,* vol. 56, pp. 550-564, 1984.

[17] A.W. Goodwin, P. Jenmalm, and R.S. Johansson, "Control of Grip Force when Tilting Objects: Effect of Curvature of Grasped Surfaces and of Applied Tangential Torque," *J. Neuroscience,* vol. 18, pp. 10724-10734, 1998.

[18] S.J. Lederman and R.L. Klatzky, "Hand Movements: A Window into Haptic Object Recognition," *Cognitive Psychology,* vol. 19, no. 3, pp. 342-368, 1987.

[19] R.L. Klatzky, S.J. Lederman, and D. Matula, "Haptic Exploration in the Presence of Vision," *J. Experimental Psychology: Human Perception and Performance,* vol. 19, no. 4, pp. 726-743, 1993.

[20] R.L. Klatzky, S. Lederman, and C. Reed, "There's More to Touch than Meets the Eye: The Salience of Object Attributes for Haptics with and without Vision," *J. Experimental Psychology: General,* vol. 116, no. 4, pp. 356-369, 1987.

[21] S.J. Lederman and R.L. Klatzky, "Haptic Classification of Common Objects: Knowledge-Driven Exploration," *Cognitive Psychology,* vol. 22, pp. 421-459, 1990.

[22] S.J. Lederman, R.L. Klatzky, and C. Reed, "Constraints on Haptic Integration of Spatially Shared Object Dimensions," *Perception,* vol. 22, pp. 723-743, 1993.

[23] S. Lederman, C. Summers, and R. Klatzky, "Cognitive Salience of Haptic Object Properties: Role of Modality-Encoding Bias," *Perception,* vol. 25, no. 8, pp. 983-998, 1996.

[24] C. Reed, S.J. Lederman, and R.L. Klatzky, "Haptic Integration of Planar Size with Hardness, Texture, and Planar Contour," *Canadian J. Psychology,* vol. 44, no. 4, pp. 522-545, 1990.

[25] F.P. Beer and E.R. Johnston, Jr., "Vector Mechanics for Engineers," *Statics and Dynamics,* SI Metric ed., McGraw-Hill Ryerson Limited, 1977.

[26] R.C. Olfield, "The Assessment and Analysis of Handedness. The Edinburgh Inventory," *Neuropsychologia,* vol. 9, pp. 97-114, 1971.

[27] S.J. Lederman and A.M. Wing, "Perceptual Judgement, Grasp Point Selection and Object Symmetry," *Experimental Brain Research,* vol. 152, pp. 156-165, 2003.

[28] R. Kitada, T. Kochiyama, T. Hashimoto, E. Naito, and M. Matsumura, "Moving Tactile Stimuli of Fingers Are Integrated in the Intraparietal and Inferior Parietal Cortices," *NeuroReport,* vol. 14, pp. 719-724, 2003.

[29] D. Chang and K. Nesbitt, "Identifying Commonly Used Gestalt Principles as a Design Framework for Multi-Sensory Displays," *Proc. IEEE Int'l Conf. Systems, Man and Cybernetics,* pp. 2452-2457, 2006.

[30] D. Chang, K. Nesbitt, and K. Wilkins, "The Gestalt Principle of Continuation Applies to both the Haptic and Visual Grouping of Elements," *World Haptics Conf. Proc. Second Joint EuroHaptics Conf. and Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems,* pp. 15-20, 2007.

[31] D. Chang, K. Nesbitt, and K. Wilkins, "The Gestalt Principles of Similarity and Proximity Apply to both the Haptic and Visual Grouping of Elements," *Proc. Eighth Australasian User Interface Conf. (AUIC' 07),* vol. 64, pp. 79-86, 2007.

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