TACTILE PERCEPTION OF THREE-DIMENSIONAL SHAPES

by
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Abstract

Previous studies of three-dimensional shape perception showed that the tactile system is capable of perceiving a wide variety of shapes, ranging from small objects touched by a single finger to large objects touched by multiple fingers simultaneously. These studies, however, focused on only a limited range of perception at a time, rendering the comprehensive conclusion on general tactile shape perception impossible.

In the present study, we tested subjects' perception of both small curvature shapes presented locally on a single finger and large curvature shapes presented globally on two fingers concurrently. Systematic examination of local and global curvature perception revealed that local perception mainly relies on the detailed surface profile of the contacting curvatures, while global perception is influenced by the gross angle of contact on the stimulated fingers and the distance between them. Based on these findings, we hypothesized that tactile perception of three-dimensional shapes can be modeled as perceptual completion. Additional testing proved that both local and global shape perception in touch indeed follows the principle of completion. We conclude that global shape perception involves a completion process filling-in between the multiple contacting

fingers, whereas local shape perception entails an interference process from the neighboring non-stimulated finger based on the completion model.

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Chapter 1. Introduction

Our somatosensory system faces the daunting task of recognizing objects via touch only. However, we can recognize familiar objects haptically at surprisingly high accuracy of greater than 95% (Gibson 1962; Klatzky, Lederman et al. 1985). In fact, this recognition happens so rapidly and effortlessly that we often take our ability for granted. Yet, how the brain processes information from fingers and hands and recognizes objects is still largely unknown. Due to the difficulty in concurrent examination across multiple fingers, the exact mechanism of information integration across digits in tactile perception has not been studied systematically. Therefore, the present study aims to expand our understanding of how shape perception arises across multiple fingers in the somatosensory system.

Using three-dimensional curvature shapes, we first tested subjects' haptic perception channeled through a single finger as well as integrated across multiple fingers. Methodical examination of the pertinent parameters revealed that perception on a single finger mainly relies on the detailed surface profile of the contacting curvatures, while perception across multiple fingers is driven by the gross angle of contact on the stimulated fingers and the distance between them. Based on these findings, we conclude that tactile perception of three-dimensional shapes can be modeled as perceptual completion: shape perception across multiple fingers entails a completion process filling-in between the multiple contacting fingers, whereas perception on a single finger involves an interference process from the adjacent, non-contacted finger based on the completion model.

As an introduction to the current study, we will start this chapter with a general introduction to the somatosensory system, including how information flows within the system as well as what previous tactile studies have discovered about general shape perception in touch. Then, we will discuss details about our completion hypotheses and how it is related to the working model of tactile shape perception. The specific three-dimensional shape we examined was cylindrical curvature. Thus, we will follow with literature review on tactile curvature perception, and end with the outline for the rest of the thesis.

Introduction to Tactile Shape Perception

Information Flow in the Somatosensory System

When we grasp an object with the hand, the somatosensory system can perceive a vast variety of characteristics about the object: how big it is, what its overall shape is like, how sharp its edges are, how rough the surfaces are, etc. These object properties can be generally categorized into two families: local and global. Local features are the ones that we can feel within each fingertip purely based on the contact information from that finger, such as local curvature and edge orientation. On the other hand, global properties are recognized across multiple fingers based on integration of information from those fingers, such as global size and shape.

The first step of this local and global perception starts at the periphery. There are many peripheral receptors in the skin and joints, converting various physical features of objects into neural activities that are utilized by the tactile system for perception. Four types of mechanoreceptors in the glabrous skin, illustrated in Figure 1, and two types of proprioceptive receptors in the joints and muscles have been documented to be related to tactile perception. Detailed surface information, such as local edge orientation and surface pattern, is detected by Merkel discs that are associated with Slowly Adapting type I (SAI) fibers (Mountcastle 2005). Meissner's corpuscles respond to low frequency vibration and local motion, and carry the information to the brain via Rapidly Adapting type I (RAI) nerves. Pacinian corpuscles show sensitivity to high frequency, light vibration (Mountcastle 2005), which are associated with Rapidly Adapting type II (RA II) afferents. While these mechanoreceptors encode diverse characteristics of the surface that the skin makes contact with (i.e. cutaneous information), Ruffini endings are believed to relay positional information about the digits and hands (i.e. proprioceptive information) to the brain via Slowly Adapting type II (SA II) fibers (Mountcastle 2005). In addition, muscle spindles and joint receptors also detect muscle stretch and extreme joint movements, providing proprioceptive information to the central nervous system.

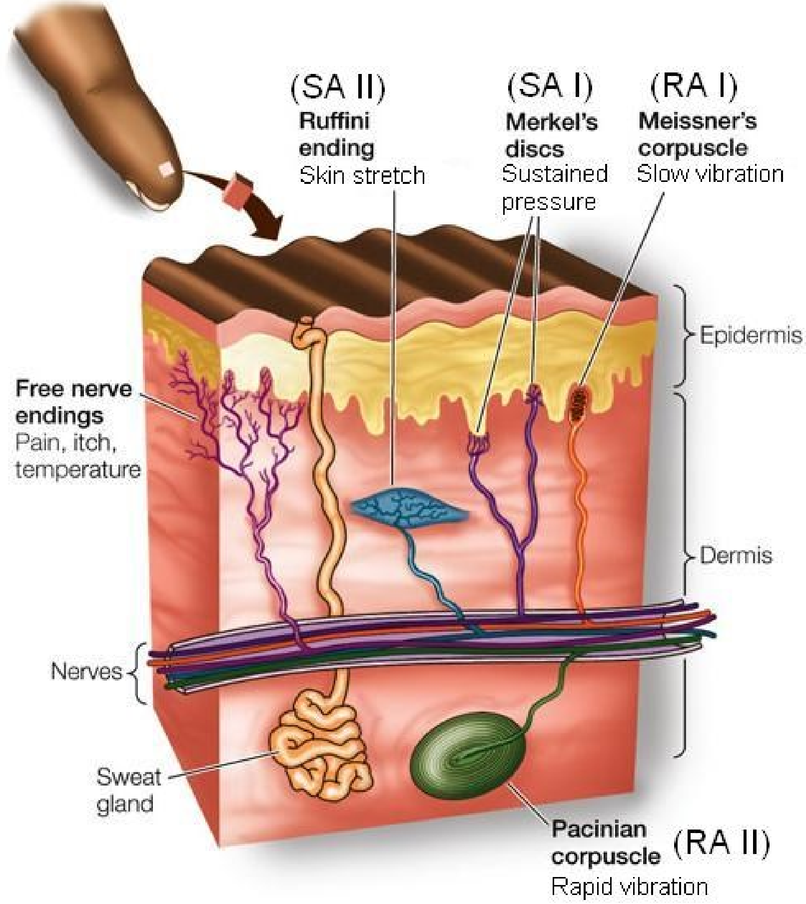

Figure 1. Sectional view of the glabrous skin. Four mechanoreceptors are shown in the dermis layer: Merkel's discs, Meissner's corpuscles, Pacinian corpuscles, and Ruffini endings.

These sensory afferents travel through various ascending spinal tracts, mostly via the medial lemniscus pathway, and reach the cortex where the different types of information are processed and integrated to evoke local and global perception of object properties (Mountcastle 2005).

Local Shape Perception

Perception of local characteristics presented on a single finger has been extensively investigated in the somatosensory field. One of the first local traits that were examined was recognition of alphabet letters (Johnson and Phillips 1981; Phillips, Johnson et al. 1983; Loomis 1985; Vega-Bermudez, Johnson et al. 1991). These researchers showed that, when the embossed letters were presented on a single finger, subjects could perceive these complex, yet familiar patterns purely based on cutaneous information from the contacted digit. Particularly, Johnson and Phillips (1981) tested various local features, such as gap detection and grating resolution, in addition to alphabet letters, and proposed that these detailed surface patterns are likely to be conveyed by the spatial code. Cho et al. (manuscript under review) further demonstrated that the tactile system is capable of recognizing not only familiar patterns like alphabet letters, but also novel complex patterns presented on a single finger. Other local qualities, such as local bar orientation and edge sharpness, have also been studied and shown to be perceived successfully by human subjects (Bensmaia, Hsiao et al. 2008; Skinner, Kent et al. 2013). These results, particularly of the complex pattern recognition studies, illustrated that the somatosensory system employs more than just a simple intensity of cutaneous inputs to perceive these complicated local features.

There have also been numerous neurophysiological studies that examined how local features are detected and perceived by the peripheral and central nervous systems. Phillips and Johnson (1981) studied peripheral afferents of pig-tailed macaques, and proved that the SA I fibers carry the detailed surface pattern information from the skin. Bensmaia et al. (Bensmaia, Denchev et al. 2008) recorded from neurons of the primary somatosensory cortex (SI) of rhesus macaques, and showed that these cortical neurons exhibit tuning curves to the orientation of a bar that is presented within the receptive field of the cells. These results, combined with the psychophysical findings, confirmed that the tactile system can perceive detailed local surface features presented on a single finger pad, using only cutaneous information from the contacted skin. Furthermore, these studies provided a general systematic layout on how different shape features, including curvatures, are perceived by the touch modality, at least within each finger pad.

While the majority of these tactile studies looked at processing from a single finger, little has been examined about perception across multiple digits. The mechanical complexity of proper stimulation across multiple digits makes it very challenging to study this topic. However, in real life, humans most often touch objects with multiple fingers. Thus, in order to truly understand how the somatosensory system functions in its most natural setting, it is essential to study global perception of object properties across multiple fingers.

Global Shape Perception

One of the most fascinating aspects of global perception in touch is the integration of information across digits and sub-modalities. In order to form a coherent percept of an object that is touched by multiple fingers simultaneously, both cutaneous and proprioceptive information from all the digits involved needs to be combined. A few neurophysiological studies provide a general insight into this integration of cutaneous and proprioceptive inputs in global perception. These studies found a set of neurons, named "haptic" neurons, in Brodmann area 2 of the primary somatosensory cortex of non-human primates (Iwamura and Tanaka 1978; Gardner 1988). These neurons respond only to a specific combination of cutaneous and proprioceptive inputs: in other words, these cells show increased activities when monkeys grasp a certain shape of objects in a particular way. These neurons are believed to integrate cutaneous and kinesthetic information from cortical areas 3a, 3b, and 1 of SI, and offer the possible neural basis for tactile global shape perception across multiple digits.

There were also psychophysical studies that demonstrated the integration of information from multiple fingers in forming percepts of various global properties. In the case of moving stimuli, for instance, perceived direction of motion across multiple fingers has been shown to be influenced by position of the digits (Evans and Craig 1991; Evans, Craig et al. 1992; Rinker and Craig 1994). Evans et al. (Evans, Craig et al. 1992) demonstrated that, when moving-bar stimuli are presented on different pairs of digits (e.g. a pair of index and little fingers or ring and little fingers), the degree of interference between the directions of the two moving bars varies with the distance between the stimulated fingers: the pair of ring and little digits shows a greater interference than that of index and little fingers. Rinker and Craig (1994) further supported this idea by showing that the pattern of interference between the moving stimuli on the two adjacent fingers modulates not only with the distance between them, but also with the spatial arrangement of the digits: when the directions of motion on the two fingers are compatible in the body-centered frame (e.g. the scanning direction on the thumb and index fingers are leftward and rightward, respectively, but overall it is perceived as one common direction of downward when the two fingers face each other), they tend to interfere with each other more than when they are not compatible. These results illustrated that, at least for moving stimuli, cutaneous and proprioceptive information is undeniably combined across multiple fingers, leading to a coherent global percept.

Moreover, Panday et al. (Panday, Tiest et al. 2014) found a similar result on perception of static shapes. When subjects grasp various shapes with their thumb and index fingers, the perceived shape of a stimulus is influenced by both the distance between the digits and the local curvatures touched by them. Specifically, when the local curvature and the distance are correlated (i.e. compatible in the body-centered frame), subjects exhibit increased sensitivity to changes in global shape of the stimuli.

These results of both neurophysiology and behavior studies clearly proved that integration of cutaneous and proprioceptive information is essential in perceiving global shape of moving as well as static stimuli across multiple digits. Particularly, these findings showed that shape perception through multiple fingers requires the cutaneous and proprioceptive inputs to be combined in very specific ways. This discovery led to more systematic modeling of the information integration in tactile perception.

Perception of Other Global Properties

Additionally, studies on global size perception exhibited integration of cutaneous and proprioceptive information across multiple fingers. Berryman et al. (Berryman, Yau et al. 2006) demonstrated that perceived distance between the thumb and index finger is influenced by cutaneous inputs, such as surface compliance and vibration on the fingertips. Plaisier and Ernst (2013) also examined judgment of distance between the thumb and index fingers, and found that perceived distance depends on local surface curvatures contacted by the fingers. Similar integration was observed in volume perception studies as well. Kahrimanovic et al. (Kahrimanovic, Bergmann Tiest et al. 2010; Kahrimanovic, Tiest et al. 2010) and Bergmann Tiest et al. (Bergmann Tiest, Kahrimanovic et al. 2012) showed that perceived volume of objects grasped by hands is significantly affected by cutaneous qualities, such as surface compliance and the area of contact. These results, in common, indicated that perception of finger distance (i.e. proprioception) is affected by cutaneous inputs.

The integration of cutaneous and proprioceptive information in haptic perception was further confirmed by object recognition studies. Klatzky et al. (Klatzky, Loomis et al. 1993) found that efficiency of haptic object recognition depends on the type of hand conformations, such as single digit, multiple digits, and the whole hand. Free exploration studies (Lederman and Klatzky 1987; Klatzky, Lederman et al. 1989; Reed, Klatzky et al. 1990; Thakur, Bastian et al. 2008) as well as haptic search projects (Overvliet, Smeets et al. 2007; Overvliet, Smeets et al. 2007; Morash, Pensky et al. 2013) provided additional support for this idea too.

Taken together, these diverse shape and size studies established that both cutaneous and proprioceptive inputs play a crucial role in perceiving various global properties of objects. Additionally, these findings led to the current model of tactile shape perception with those two inputs: proprioceptive cues influence how cutaneous information from multiple digits integrates in a given spatial arrangement to form a coherent perception across fingers. However, the exact mechanism of this information integration in haptic global perception calls for further investigation.

Models of Tactile Shape Perception

As illustrated in the studies mentioned above, the current model of haptic global perception focuses on the cutaneous and proprioceptive parameters of the touch modality. It hypothesizes that the cutaneous input is composed of local surface profiles detected on individual digits, and is integrated with spatial information from the digits to perceive the gross shape of objects (Hsiao 2008).

We propose that there are actually two different qualities to the cutaneous input. In addition to the surface profile, there is additional information about how the surface makes contact with the skin, resulting in a total of three parameters that affect perception of global shape: surface profile, relative digit position, and contact angle on fingertip. Surface profile includes the cutaneous features sensed on fingertips, such as surface curvature and local orientation. Relative digit position is the proprioceptive input. While these two are widely-accepted perceptual factors in tactile shape perception, the newly proposed parameter, contact angle on fingertips is described in more details below.

Newly Proposed Parameter

Contact angle is defined as a tangential angle that the cutaneous stimulus makes on the surface of the fingertip. For example, the tangential angle can be horizontal, when a surface touches the center of the finger pad that is in a supine position (i.e. palm facing upward), as illustrated in Figure 2. As the tangential angle deviates away from being horizontal, the surface can touch more to the side of the finger: a tangential angle of 45^o would correspond to the side of the fingertip. This tangential angle (i.e. local attitude on the fingertip) has been shown to be related to perception of shallow curvatures that are touched by multiple digits simultaneously (Pont, Kappers et al. 1999).

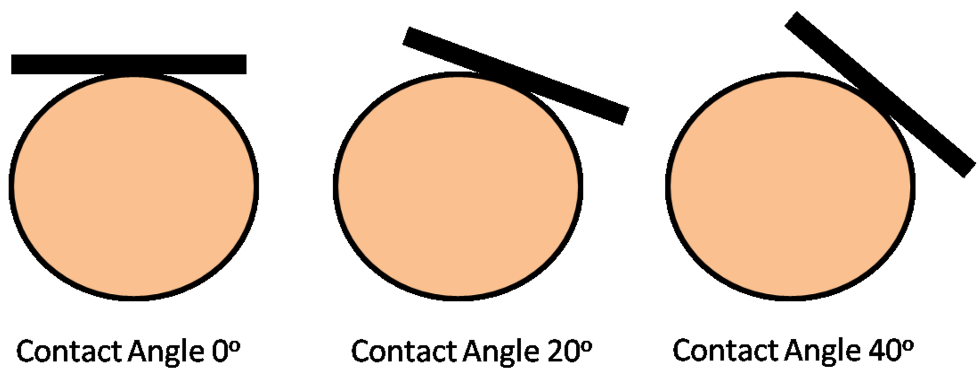

Figure 2. Definition of contact angle and its co-varying relationship with the location of contact on fingertips. The peach circles are the cross-sectional view of a supinated human finger and the black bar represents a contacting surface at different tangential angles.

Due to the circular nature of fingers, this contact angle co-varies with the location of contact within the finger pad that the stimulus surface is touching, and corresponds to only one contact location at a time, as seen in Figure 2. Thus, contact angle can provide information about the location of the cutaneous stimulus on individual fingertips, relative to the position of other digits (e.g. cutaneous stimulation on the middle finger is facing the index finger as opposed to the ring finger). Therefore, it is crucial information in global shape perception involving multiple fingers, and should be included as one of the relevant parameters.

Newly Proposed Model

Even when contact occurs across multiple digits, the tactile system has inherent limitation in how much information it can receive at once about the object touched. Our hands rarely make contact along the entire contour of the object and, often times, fingers and palms only touch limited part of the object. Then, the brain must figure out the overall shape of the object based on this incomplete information from the hand. This process is called perceptual completion where the brain produces a coherent percept of an object based on incomplete sensory inputs. Completion has been observed and widely studied in other sensory modalities, such as vision. Inspired by the visual completion model, we hypothesized that the tactile system might have a similar mechanism of completing across multiple contacting digits to perceive the overall shape of the object based on the relevant parameters, surface profile, relative digit position, and contact angle on fingertip.

Three-Dimensional Shape of Interest

With these new ideas in mind, we wanted to investigate how the different parameters contribute to the haptic perception of object shape and how it can be modeled as a perceptual process. The particular shape we decided to study in the current project was three-dimensional (3D) cylindrical curvatures. 3D curvatures allow both cutaneous and proprioceptive components of tactile stimuli to be projected into one curvature space, enabling systematic manipulation of the parameters. Specifically, we examined how curvature is coded using only cutaneous information (i.e. single-digit perception, denoted as local perception) or both cutaneous and proprioceptive inputs combined (i.e. multi-digit perception, denoted as global perception). The results provide understanding of how local and global shape perception arises in touch and what the underlying mechanism might contribute to it.

Introduction to Tactile Curvature Perception

Local Curvature Perception

There have been numerous studies that examined local perception of 3D curvatures and its interplay with other haptic functions on a single digit. Some researchers showed that local curvature is not only a salient shape feature but also a crucial factor in object manipulation (Goodwin, Jenmalm et al. 1998; Jenmalm, Goodwin et al. 1998; Jenmalm, Dahlstedt et al. 2000). For instance, object curvatures presented on individual fingers influence various components of the grasp, such as grip force with torsional loads and grasp kinematics. Other studies delved deeper into how shape of curvatures is sensed by a single finger. Particularly, Goodwin et al (Goodwin, John et al. 1991; Goodwin and Wheat 1992) demonstrated that when high curvatures (e.g. 600 m^{-1} or radius of 1.67 mm) are indented passively onto the index finger, human subjects can scale and discriminate the curvature stimuli with a Weber fraction of 0.1 (i.e. 10% difference in their curvature values), using only cutaneous information from that single finger pad.

In addition to the psychophysical studies, neurophysiological recordings from peripheral afferents of humans and monkeys examined perception of high curvatures presented on a single digit. These neurophysiological studies showed that SAI neurons, rather than RAI afferents, in fingertips can signal object curvature (LaMotte and Srinivasan 1993). They also demonstrated that a population of those SAI neurons can encode the shape of high curvature stimuli independent of amount or direction of contact force (Goodwin, Browning et al. 1995; Goodwin, Macefield et al. 1997; Birznieks, Jenmalm et al. 2001).

These results on perception of local curvatures confirmed that the somatosensory system is capable of perceiving a range of curvatures using a single finger, as well as coding reliable curvature information at the periphery. However, as hinted earlier, these previous studies tested only a limited range of very high curvatures (e.g. 600 m^{-1} or radius of 1.67 mm) that are small enough fit into a single fingertip, hence were not able to draw a comprehensive conclusion on the mechanism of curvature perception in touch.

Global Curvature Perception

There have been a small number of haptic studies that examined global perception of curvatures across digits. Kappers et al. (Kappers, Koenderink et al. 1994; Kappers, Koenderink et al. 1994) tested perception of hyperbolic shapes touched by the whole hand and found that humans can distinguish these curved shapes well above the chance level. Although qualitatively, another set of psychophysical studies examined global curvature perception using a limited range of low curvatures (e.g. 5 m^{-1} or radius of 20 cm) (Pont, Kappers et al. 1997; Pont, Kappers et al. 1999). They showed that in the case of low curvatures that expanded over multiple fingers, the change in local slope across fingers (i.e. difference in the tangential angles between contacted fingers) is sufficient to evoke perception of global curvature. However, their studies could not tease the effects of proprioception and contact angle apart in their stimulus design. As in other studies that tested global perception of curvatures with more than one finger (van der Horst and Kappers 2007; van der Horst and Kappers 2008; van der Horst and Kappers 2008; van der Horst, Willebrands et al. 2008; Wijntjes and Kappers 2009), there were many factors that were physically co-varying with one another (e.g. distance between the contacted digits and the stimulation angle on the fingers) due to the multiple fingers that were involved in contact. These studies on global perception of shapes failed to control for these various co-varying parameters and test their individual effects in an independent fashion.

In addition, global curvature perception has been examined using various haptic feedback devices in the virtual reality environment. Some researchers looked at how the contact angle information contributed to perception of curvatures of virtual objects (Robles-De-La-Torre and Hayward 2001; Drewing and Ernst 2006). By manipulating force and geometry parameters of the haptic feedback, these studies showed that the angle of force feedback on the contacted fingertip is crucial in perceiving shallow curvatures touched in the virtual environment. Provancher et al. (2005) further confirmed that, using their PHANToM device with the contact angle feedback on the fingertip, low curvatures can be perceived via contact angle information while high curvatures require the actual surface profile. Wijntjes et al. (2009), using a similar PHANToM device with contact feedback, also showed the importance of contact angle in low curvature perception when scanned in the virtual environment.

These findings, collectively, showed that different ranges of curvatures can be perceived with single or multiple digits; high curvatures can be perceived through cutaneous information from a single digit alone (i.e. local perception). On the other hand, low curvatures can be perceived through contact angle information across multiple digits (i.e. global perception). However, these previous studies did not examine a complete range of curvatures in one consistent platform that would include both very high curvatures perceived only locally and low ones perceived globally across digits. Furthermore, they did not perform fully independent and systematic manipulation of the relevant parameters. Thus, their results were not able to provide the comprehensive understanding on the precise and unbiased effects of local surface curvature, contact angle on fingertips, and proprioception of digit position in haptic shape perception.

Aims of Current Thesis

Therefore, the aim of this thesis is to investigate how these parameters influence and interact with one another to generate a consistent perception of 3D shapes. There are three objectives of this aim. First, we want to test how humans perceive a full range of curvatures in both local and global contacting conditions. Second, we want to investigate the differential effects of the cutaneous and proprioceptive parameters in local and global curvature perception. Third, we present a perceptual model on how the tactile system uses the pertinent factors to perceive three-dimensional shapes at both local and global levels.

Chapter 2 describes the general methods common to all the experiments described in this thesis: how the curvature stimuli were created, how they were delivered in a controlled way, the nature of the psychophysical task, and how the behavioral data was analyzed.

Chapter 3 presents the specific methods, results and discussion of the experiments that tested curvature perception over the complete range. It also shows how the relevant parameters affect local and global curvature perception differently through various experimental results.

Chapter 4 illustrates the perceptual completion model in haptic shape perception, and presents the behavioral data to support the model. The result shows that both local and global perception in touch follows the completion model.

Chapter 5 discusses what these results imply about the underlying mechanism of tactile shape perception, and how the somatosensory system integrates information from diverse receptors in the skin to produce a coherent perception of object shape.

Chapter 2. General Methods

This chapter describes general methods that are common to all the experiments in this thesis. Specific methods for each experiment are explained in more details in Chapters 3 and 4.

Parameters

We hypothesized that there are three parameters that affect perception of 3D curvatures: Surface Curvature, Hand Conformation and Digit Spread, and Contact Angle. As described in Chapter 1, Surface Curvature is the curvature of the stimulus surface sensed by fingertips. Hand Conformation and Digit Spread are proprioceptive inputs about relative digit position. Hand Conformation and Digit Spread are defined by the number of fingers stimulated and how they are arranged in space, respectively. Particularly, Digit Spread is defined as the angle between the two digits that are stimulated. Contact Angle is defined as a tangential angle that a stimulus surface makes on the surface of the stimulated fingertip. For example, Contact Angle is 0^o (defined to be horizontal) when a stimulus with certain Surface Curvature touches the center of the supinated finger pad (i.e. palm facing up). As Contact Angle increases, the curved surface touches more to the side of the finger, resulting in the stimulus facing the neighboring digit more.

Curvature Stimuli and Testing Conditions

Mathematical definition of curvature is an inverse of a radius. Thus, the lower the curvature value is, the flatter its surface is, and vice versa. Surface Curvature used in the current thesis follows this definition of curvature. The present study tested both low and high ranges of curvatures, starting from zero (infinite radius/flat) and low curvatures that span across multiple fingers to very high curvatures that could fit into a single fingertip (highest curvature tested is 512 m^{-1} with a radius of 1.95 mm). Since all the curvature stimuli were cylindrical, Surface Curvature was defined along the circumference of cross-sectional plane but constant along the length of the shape.

Contact Angle was derived from the tangential angles that the curvature stimuli would make with the fingertips in the given Digit Spread conditions (e.g. a shape with Surface Curvature of 5 m^{-1} presented in Digit Spread 0^o would make Contact Angle of 3.2^o with fingers). We measured the diameter of subjects' fingers and the distance between the centers of the fingers in 0^o and 30^o spread conditions. Assuming that the fingers are perfect cylinders, the subjects' average finger diameter of 15 mm and the average distance between the fingers of 23 and 68 mm were used to compute the Contact Angle values. Contact location was also modulated for different Contact Angles, due to the co-varying nature of contact location and angle. For example, Contact Angle close to

0^o would correspond to the center of the fingertip, whereas any angle away from it, such as 27.1^o, would contact the side of the fingertip (i.e. X1 in Figure 3 would be 0 mm for Contact Angle of 0^o but become greater than 0 mm as Contact Angle increases). All these contact locations are on the side of the finger that is facing the other testing digit.

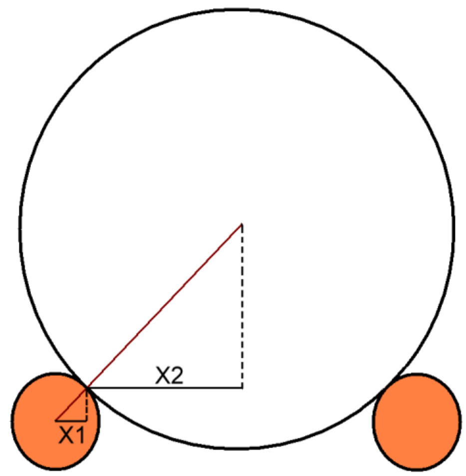

Figure 3. Contact Angle presentation. Due to the co-varying nature of contact angle and location, contact location was also varied to different contact angles accordingly. The black circle represents a curvature stimulus and the two peach circles are the two fingers touching the stimulus.

There were two types of stimuli used in this study: veridical and piecewise shapes. Veridical stimuli were the natural curvatures wherein all the parameters were coherent with each other without any manipulation. These veridical curvatures have a limitation that, when touched by more than one finger, they have Surface Curvature, Digit Spread, and Contact Angle co-varying with each other. For example, as fingers touch the sides of a curved surface with wider Digit Spread, Contact Angle also deviates more from horizontal, illustrated in Figure 4 (A). In order to achieve truly independent manipulation of these parameters, low curvatures that could be contacted by multiple digits simultaneously were broken into smaller pieces at different Contact Angles and called piecewise stimuli (Figure 4 (B)). These piecewise shapes were presented simultaneously on multiple digits with varying Digit Spread between them, enabling disjoining of Surface Curvature, Contact Angle and Digit Spread (Figure 4 (C)).

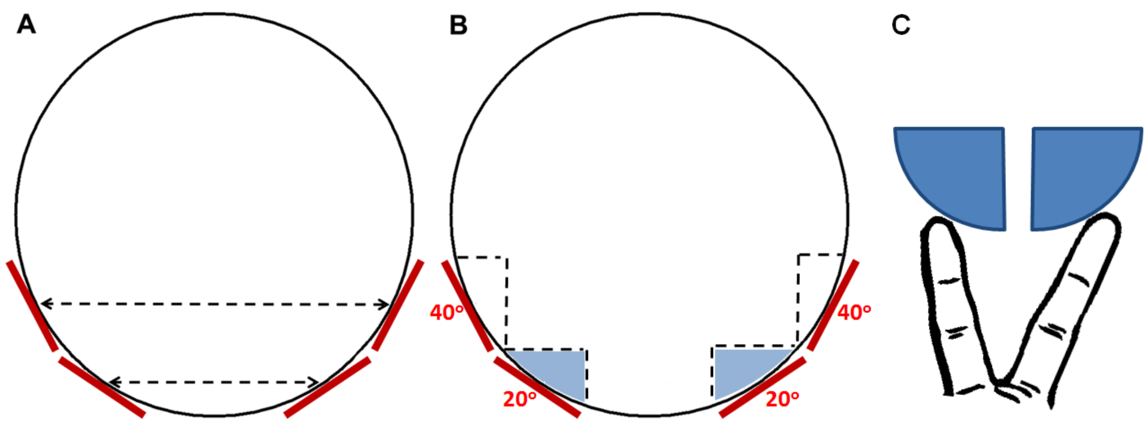

Figure 4. Illustration of piecewise curvature stimuli. (A) shows the co-varying nature of Contact Angle and Digit Spread in veridical curvatures. Black circles represent a curvature stimulus and red bars correspond to different tangential angles along the stimulus surface. (B) demonstrates how piecewise curvature stimuli were created for each Contact Angle and Surface Curvature combination. The example illustrates two piecewise shapes at Contact Angle 20^{o} and 40^{o} with the given Surface Curvature. (C) depicts how symmetric pairs of piecewise stimuli, as with the blue highlighted pieces in (B), were presented onto two fingers simultaneously in global conditions.

All the curvature stimuli were designed in SolidWorks (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA) and printed by Alaris30U 3D printer (Stratasys Eden Prairie, MN, USA). Since all the curvature stimuli had to be grasped and presented passively by a platen forcer system, in addition to the curvature surfaces, they were also equipped with forcer-compatible features (Figure 5). The first thing was the handle. On the opposite side of the curvature surface, an elongated cuboid was placed at the center to function as a handle for the forcer grippers. The second feature was the groove-fitting edges. In order for the forcers to grip the stimuli, the shapes were arranged in a grid format on a metal tray. On the tray, each shape was placed into an empty pocket with grooves on the four sides. The groove-fitting edges secured the shapes on the tray so that the forcers could grasp them reliably. The shapes were oriented such that the curvature surfaces faced down and the handles faced up so the forcers could grip from above.

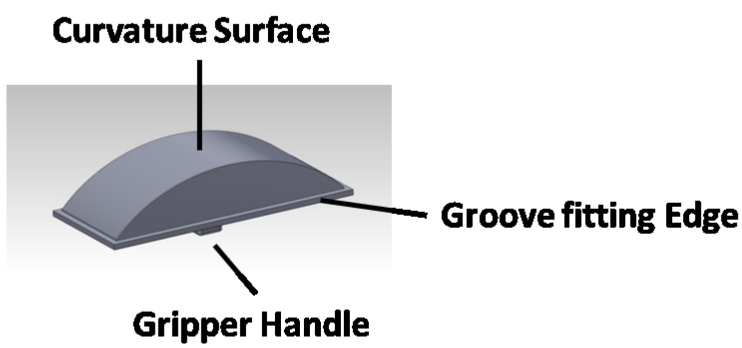

Figure 5. Example of curvature shapes. The curvature surface, groove-fitting edges, and the gripper handle are illustrated. The shape in the figure is shown upside down from its usual orientation.

There were two Hand Conformation conditions tested in this study: single-digit or local and multi-digit or global conditions. Single-digit cases were where all the curvature stimuli touched one finger at a time. In other words, only the cutaneous information collected locally from the contacted fingertip participated in curvature perception. These conditions are denoted as local perception cases. On the other hand, multi-digit conditions were where the curvatures touched two fingers simultaneously with varying Digit Spread between the digits. This enabled not only the cutaneous but also proprioceptive information and contact angle to contribute to overall perception of curvatures. These multi-digit cases are denoted as global perception conditions.

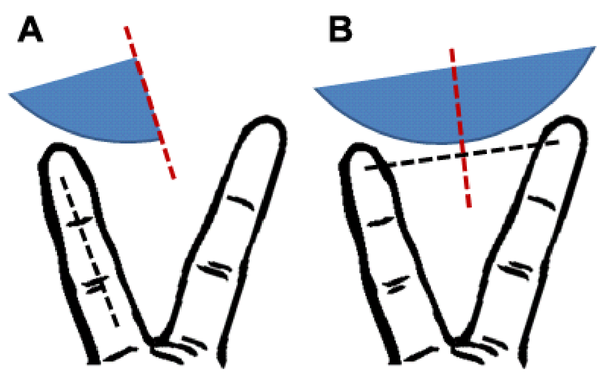

Figure 6. Alignment of curvature stimuli in single-digit/local (A) and multi-digit/global (B) conditions. In local cases, the axis of the curvature (red), was aligned parallel to the finger axis (black). In global cases, the axis of the curvature was aligned to the midpoint between the two fingers.

In single-digit/local conditions, all the curvature stimuli were aligned to the axis of the target digit so that the midline of the shapes and the stimulated finger axis were parallel to each other (Figure 6 (A)). In multi-digit cases, in contrast, the shapes were presented such that the midline of the curvatures would be aligned to the midpoint between the two finger centers (Figure 6 (B)).

Apparatus

All the stimuli were presented passively using a platen forcer system (IntelLiDrives, Philadelphia, PA, USA), pictured in Figure 7. The two platen forcers were hanging from the platform via magnetic force, as illustrated in the top photo of Figure 7, and their X-Y position was precisely controlled by a hydraulic pump (resolution of 100 μm). Each forcer was equipped with a gripper at the bottom tip such that it could grip any curvature stimuli and present them anywhere within the platform coordinate. The rotation angle of the gripper was controlled by a motor placed on top of the gripper. This rotation enabled the forcer to align the gripped shapes to any desired axis (e.g. parallel to the finger axis) as depicted in Figure 6. The Z-axis indentation along the forcer shaft was controlled by a motor and a displacement sensor (resolution of 100 μm). Using this system, we were able to completely control what shape was presented, where it was presented, at what indentation depth it was presented, and how the shape was aligned to the fingers. Using both forcers, we were able to stimulate up to two fingers simultaneously, as depicted in Figure 4 (C).

The position of subjects' fingers was accurately controlled by the motorized hand holder (in-house production), shown in the bottom left corner of Figure 7. Subjects' left hand was supinated with the back of the palm resting on the flat palm holder, labeled so in the figure. Two finger holders were linked to this palm holder, which were designed to resemble elongated cuboids with an opening on the top side, so that fingers (modeled with clay in the figure) could be placed inside along the major axis of the cuboids with the fingertips exposed through the openings. Placed within these holders, finger molds were created to fit each subject's two fingers using clay-like material, Extrude putty (Kerr Corporation, Romulus, MI, USA), in order to secure them to the finger holders and prevent slippage or involuntary movement of fingers during experiments. Two motors (Pacific Scientific Corporation, Washington, DC, USA) controlled the accurate position of the finger holders. This motorized hand holder provided us the full control over the precise position of subjects' two fingers.

The forcer and hand holder system was controlled by two QNX-running machines. QNX is a Unix-like operating system which enables precise, real-time operations. Since z-axis indentation involved both forcer motor control and displacement sensor reading, QNX1 was designated to supervise indentation of the two forcers. QNX2 was in charge of governing the rest of the system, including translational movement, rotation, and gripper function of the forcers as well as full control of the hand holder. Both QNX machines were ultimately managed by the main control computer, which oversaw the QNXs on the stimulation side and the display-and-response machine on the subject side.

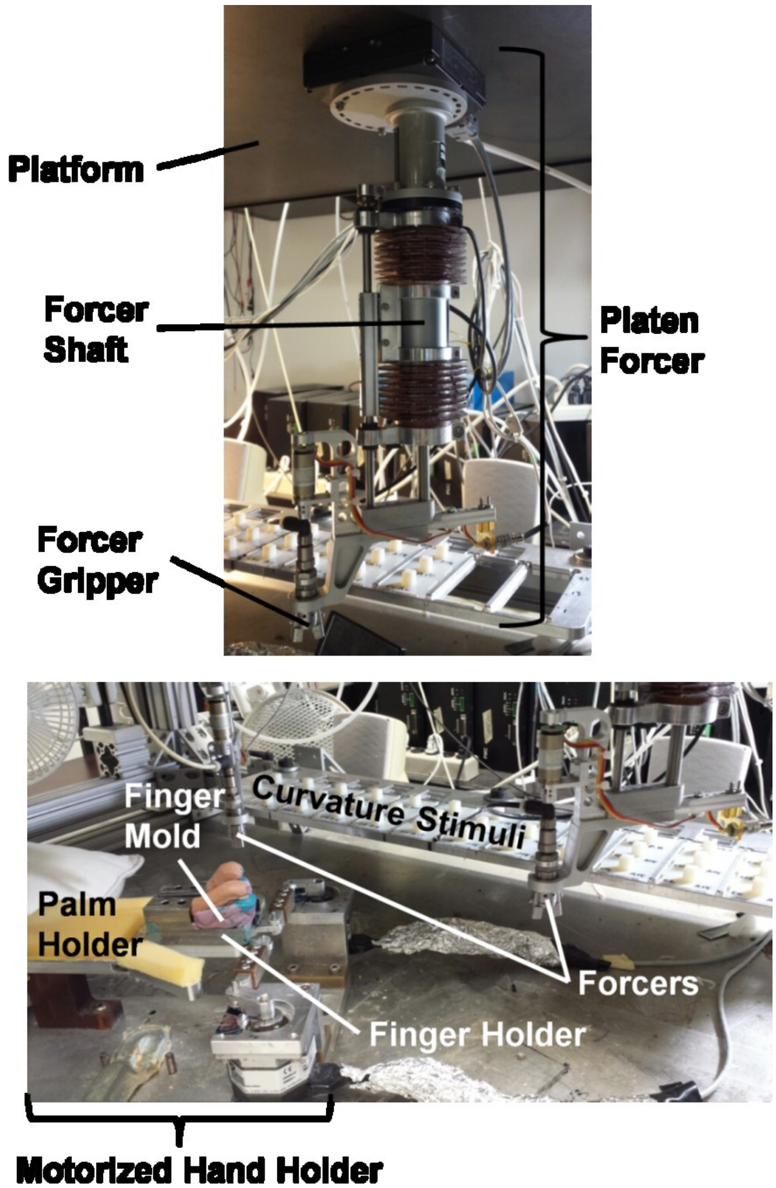

Figure 7. Platen forcer apparatus with motorized hand holder. Two forcers were hanging from the platform by magnetic force and were controlled by hydraulic pumps. One or both forcers (depending on the experimental procedure) traveled between the motorized hand holder with the finger holders and the tray that the curvature stimuli were sitting on. Human finger figures sitting on the finger molds were created with clay for the demonstration purpose.

General Experimental Design

There were four experiments in this study. EXPERIMENT 1 tested perception of both low and high curvatures in single- as well as multi-digit (i.e. local and global, respectively) conditions. In order to provide the general overview of curvature perception over the comprehensive range of natural curvatures, all the curvatures used were veridical shapes without any manipulation of the parameters. The results of this experiment also offered the guideline for the subsequent experiments.

EXPERIMENT 2 examined the systematic effects of Surface Curvature, Contact Angle and Digit Spread in both local and global perception cases. This was done by using two forcers and piecewise stimuli to manipulate the parameters in a completely independent fashion.

EXPERIMENT 3 investigated the differential effect of indentation depth in local and global perception conditions. Unlike EXPERIMENT 2, the curvature shapes used in this experiment were veridical shapes as in EXPERIMENT 1.

EXPERIMENT 4 was designed to test the perceptual model of 3D shape perception in touch, which was inspired by the results of earlier experiments as well as a similar model in vision. A range of curvatures, very low to mid, was presented using piecewise shapes in local perception conditions to confirm this suggested model.

The specific methods for these experiments are laid out in more details at the beginning of each corresponding section in Chapters 3 and 4.

Subjects

A total of 33 subjects participated in four experiments of this study and some of the subjects took part in more than one experiment. Ten (four males, ages of 19 to 32), eight (three males, ages of 18 to 28), seven (four males, ages of 18 to 30), six (six males, 19 to 32), seven (five males, 19 to 32), and eight subjects (four males, ages of 26 to 35) participated in EXPERIMENT 1, local and global conditions of EXPERIMENTS 2 and 3, and EXPERIMENT 4, respectively. The summary of subject information is listed below in Table 1. All the subjects gave informed consent to the procedures, which were approved by the Human Institutional Review Board of the Johns Hopkins University School of Medicine.

Table 1. Summary of subject information for the four experiments of this study. The number of subjects indicates the total number of subjects who were tested for the designated experiment. The number inside the parentheses represents the number of male subjects for each experiment.

	EXP 1	**EXP 2 (local)**	**EXP 2 (global)**	**EXP 3 (local)**	**EXP 3 (global)**	**EXP 4**
Number of Subjects	10 (4)	8 (3)	7 (4)	6 (6)	7 (5)	8 (4)

Behavioral Task

Subjects were seated behind a black curtain, thus were not able to see any curvature stimuli throughout the session. In front of the curtain, an 18-inch monitor and a keypad were placed to deliver trial cues (e.g. "START" signal) to the subjects and record their answers. Regardless of their handedness, subjects were tested on their left hand and typed in the answers with their right hand. Subjects were instructed to perform subjective magnitude estimate, where subjects selected a number that best represented how curved the stimulus felt. Before each experiment, subjects were presented with the lowest, highest and some of the randomly selected curvature stimuli without any feedback, to be familiarized with the range of the test curvatures. Once they were familiarized, they defined a numeric scale that they felt most comfortable to work with (adapted from Lederman and Taylor 1972 and Goodwin, John et al. 1991). Subjects were instructed that the lowest number should correspond to the flattest shape they felt, while the highest number should be the most curved one. They were also instructed to report a number that was twice as big if curvedness doubled.

In each trial during the experiment, the subjects were presented with one curvature stimulus (could be composed of one or two physical shapes depending on the experimental conditions) and assigned a number to it from the numeric scale they pre-selected. Right before a trial started, subject's proprioceptive sensation was reset by moving the fingers to the widest and then narrowest spreads. Once fingers were set to the right position for the trial, "START" signal was presented to the subject on the screen in front of him/her for the ready period of about 1.5 seconds. The exact length of the ready period was uniformly randomized between 1.2 and 1.8 seconds. Indentation of a curvature stimulus followed for one second, and the subject typed in a number that best represented the perceived curvature of the stimulus using a keypad. The order of the stimuli was completely randomized, and there was about a 20-second break between trials due to the forcer movements necessary for the following trial. The time sequence of events in each trial during experiments is visualized in Figure 8.

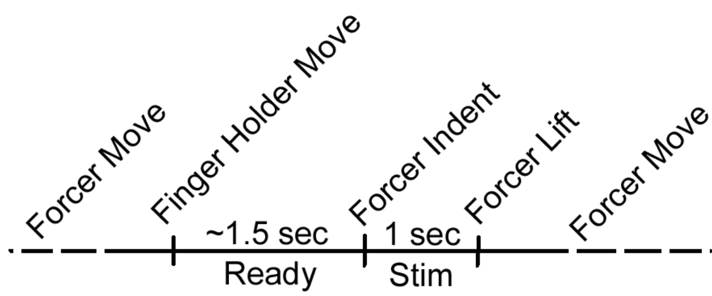

Figure 8. Time sequence of events during experiments. Forcers moved around on the platform to return the used stimulus to the shape tray and bring in the new shape for the upcoming trial. Once the forcers were ready, the finger holders moved to 30^{o} then 0^{o} spreads to reset the proprioceptive sense. Once the fingers were positioned to the correct spread, the ready period started when no apparatus moved. As soon as the ready period was over, the forcers lowered the shapes into subjects' fingers and stayed down for one second. After the forcers lifted off of the fingers, the entire cycle repeated.

Data Analysis and Interpretation

Since subjects were free to choose any numerical scale they wished, there was a vast difference among the scales that were used for reporting. In order to compensate for different ranges individual subjects selected, raw responses were first normalized. Once perceived curvature data for each subject was collected, it was centered to each subject's grand mean value and divided by each subject's response range for normalization (Equations 1 and 2). The rationale for this specific method of normalization is explained further in the Appendix. For each experimental condition, the normalized data points were tested for outliers. Any response that was two standard deviations away from each condition's mean was considered to be an outlier and discarded. The average magnitude estimates across all subjects were calculated by adding the normalized estimates of all subjects and dividing them by the total number of estimates. One subject's data in EXPERIMENT 1 was discarded since the subject did not show any sign of curvature perception at all in all testing conditions.

These normalized responses were interpreted as a measure of perceived curvature: the higher the number was, the more curved perceived shape felt. They were used to assess how different experimental conditions affected subjects' perceived curvature. In subsequent chapters, this relationship is used to explore how local and global perception of curvatures differs from each other (Chapter 3) and what underlying mechanism can explain this perception (Chapter 4).

$$\text{Normalized Responses} = \frac{Raw\ Responses - Grand\ Mean}{Range\ of\ Responses}, \quad \text{(Equation 1)}$$

$$\text{where Grand Mean} = \frac{\sum All\ Responses}{Total\ Number\ of\ Responses} \quad \text{(Equation 2)}$$

Chapter 3. Comparison between Local and Global Curvature Perception

This chapter describes experiments that examined both local and global perception of curvatures. As indicated in Chapter 1, previous curvature studies had limitations: 1) they tested only a limited range of curvatures; 2) they failed to employ fully independent manipulation of the parameters. We first tested subjects' local and global perception over a comprehensive range of curvatures. Systematic examination of individual parameters revealed that local and global curvature perception exhibits a significant difference in terms of how the brain utilizes the detailed surface information. All the local conditions point to single-digit perception of curvatures, while global indicates multi-digit cases.

EXPERIMENT 1: Overall 3D Curvature Perception

Since the previous tactile curvature studies focused on a limited range of curvatures at a time, the aim of EXPERIMENT 1 was to test the most comprehensive range of curvatures possible within one paradigm. We also wanted to test the widest variety of finger conditions in order to obtain the most generalized understanding of 3D curvature perception in tactile sensation.

Specific Methods

There were two parameters examined in this experiment: Surface Curvature is the numeric values of the testing curvatures and Hand Conformation is the finger stimulation conditions. A complete range of Surface Curvature that included both low (close to flat, 0, 2, 4, 8, 16 m^{-1} with radii of infinite, 500, 250, 125, and 62.5 mm) and high (very curved, 32, 64, 128, 256, 512 m^{-1} with radii of 31.25, 15.625, 7.8125, 3.9063, and 1.9531 mm) curvatures was tested. All the curvatures were real, veridical stimuli without any manipulation.

The five low curvatures were examined in six Hand Conformations: one finger alone at a time for the two test fingers (single-digit stimulation for local perception), and two fingers simultaneously with 0^o, 10^o, 20^o, and 30^o spreads between them (multi-digit stimulation for global perception). The spread between the fingers in single-digit conditions was fixed at 20^o.

In summary, in each trial, one of the ten curvatures was presented either on one finger alone or two fingers simultaneously if possible. All the stimuli were indented vertically 2 mm into the surface of the skin on the fingertips. All these experimental conditions were tested in two different digit pairs: index-and-middle (D2-and-D3) and middle-and-ring (D3-and-D4) fingers.

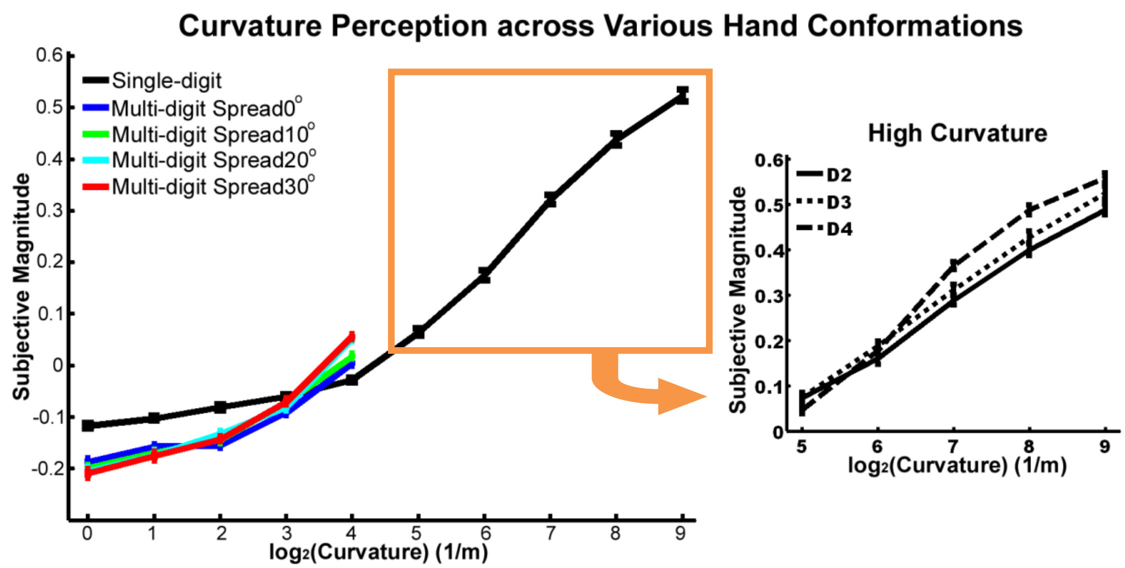

Figure 9. Results of EXPERIMENT 1. The x-axis on the main figure represents the ten curvatures tested in their log values with base of 2. The reason why the multi-digit plots in colors extend over only the first half of the x-axis is the physical size limitation of high curvature stimuli. Error bars are the standard error of means for the within-subject design. The inset figure on the right shows the individual plots for D2, D3, and D4 alone conditions for high curvatures.

Results and Discussion

Normalized subjects' responses for ten curvatures are plotted in Figure 9. As mentioned earlier, the low and high curvatures were tested in different Hand Conformation conditions due to the physical size limitation. The low curvature range (five curvatures of 0 through 4 in Figure 9) shows five plots for one-finger stimulation in black and four two-finger stimulations in colors, whereas the high curvature range inside the orange rectangle (5 through 9 in Figure 9) shows only one black plot for the one-finger stimulation case. These results of EXPERIMENT 1 were analyzed separately for each curvature range of low and high.

First, the high curvature data tested only in local conditions was analyzed through two-way repeated-measures ANOVA with curvature values (32 through 256 m^{-1} of Surface Curvatures) and stimulated fingers (three local conditions of D2, D3, and D4 alone). The results revealed the main effect of Surface Curvature [$F(1.46,11.683)=125.693$, Greenhouse-Geisser corrected $p<0.001$] and Hand Conformation [$F(2,16)=5.178$, $p<0.04$] in the local perception. Combined with the finding that the plot increases with the increasing curvature value in Figure 9, this result proved that humans can successfully perceive the high curvatures presented locally on a single finger using only cutaneous input from the stimulated finger, either D2, D3 or D4. This finding is in agreement with that of the previous curvature studies (Goodwin, John et al. 1991).

A detailed comparison between the stimulated fingers showed the significant difference between D2 and D4, and this dissimilarity was the main driving force for the effect of Hand Conformation found above [two-way repeated-measures ANOVA: $F(1,8)=8.968$, $p<0.02$]. The normalized responses for D2, D3, and D4 are plotted separately in the right inset of Figure 9. In order to maintain consistency among single-digit stimulation conditions across low and high ranges, only the pair of D2 and D3 was tested for all the subsequent experiments.

The responses for the five low curvatures were run through two-way repeated-measures ANOVA with the curvature values and finger stimulation conditions: five levels of low Surface Curvature and eleven levels of Hand Conformation (single-digit stimulation on D2, D3, and D4 alone; two-digit stimulation with Digit Spread 0^{o}, 10^{o}, 20^{o}, and 30^{o} for D2-and-D3 and D3-and-D4). The ANOVA revealed the main effect of Surface Curvature [$F(1.541,12.33)=60.953$, Greenhouse-Geisser corrected $p<0.001$] and the significant interaction between Surface Curvature and Hand Conformation [$F(4.868,38.943)=3.439$, Greenhouse-Geisser corrected $p<0.02$]. The main effect of the testing curvatures proved the subjects were able to perceive the low curvatures across all different finger conditions tested. The interesting part was the significant interaction found between Surface Curvature and Hand Conformation. This interaction suggested that perception of low curvatures was modulated by how many fingers were touching or how the fingers were arranged in space. We wanted to investigate more deeply this effect of finger conditions in perception of low curvatures. However, given a total of eleven Hand Conformation conditions, we wanted to first simplify the finger stimulation conditions in order to test systematic differences among them.

All the local responses from different digits were compared against to each other to test any disparity among stimulated fingers. A two-way repeated-measures ANOVA with curvatures and stimulated fingers showed no difference among D2, D3, and D4 perception of the low curvatures [$F(2,16)=0.31$, $p>0.7$ for the main effect of finger;

$F(2.997,23.976)=0.922$, Greenhouse-Geisser corrected $p>0.4$ for the interaction with the curvature]. Thus, D2, D3, and D4 responses were all combined as the single-digit stimulation data, plotted in black in Figure 9.

All the global responses from the D2-and-D3 and D3-and-D4 cases were also compared against each other to check any finger-pair disparity. A series of two-way repeated-measures ANOVA with curvatures and digit pairs was performed for all Digit Spread conditions (0^o, 10^o, 20^o, and 30^o). The results exhibited no difference between D2-and-D3 and D3-and-D4 for all levels of Digit Spread [$F(1,8)=0.554$, $p>0.4$ for Spread 0^o; $F(1,8)=0.263$, $p>0.6$ for Spread 10^o; $F(1,8)=0.407$, $p>0.5$ for Spread 20^o; $F(1,8)=0.62$, $p>0.4$ for Spread 30^o]. Hence, D2-and-D3 and D3-and-D4 data were combined for all the spread conditions, and plotted in four colors in Figure 9.

Once finger stimulation conditions in the low curvature data were simplified to five levels, we compared between local and global responses: in other words, between the black and the colored plots in Figure 9. The ANOVA results revealed a significant interaction between Surface Curvature and the local and global responses. [two-way repeated-measures ANOVA: $F(1.495,11.963)=17.150$, Greenhouse-Geisser corrected $p<0.005$]. This significant interaction indicated that the perception of low curvatures was modulated by how many fingers were touching the curvatures.

We wanted to investigate further the four levels of global conditions (Digit Spread of 0^o, 10^o, 20^o, and 30^o). Thus, two-way repeated-measures ANOVA with the curvatures and the global finger conditions was performed. The results demonstrated the main effect of Surface Curvature [$F(1.437,11.498)=66.426$, Greenhouse-Geisser corrected $p<0.001$]

and the significant interaction between Surface Curvature and Digit Spread [$F(12,96)=2.212$, $p<0.02$]. A series of follow-up ANOVA tests revealed that, among the four Digit Spread conditions, only Digit Spread 0^{o} and 30^{o} exhibited the significant interaction between Surface Curvature and Digit Spread [two-way repeated-measures ANOVA: $F(4,32)=3.856$, $p<0.02$]. The significant interaction, indicated by the different slopes between the blue and red plots in Figure 9, suggested that perception of low curvatures is modulated by the spread between the contacting fingers. Together with the previous finding, these low curvature results proved that the perception of low curvatures is influenced by the number of contacting fingers as well as the distance between them.

In order to investigate the difference among the three key finger stimulation conditions (i.e. all single-digit combined, and Digit Spread 0^{o} and 30^{o} of multi-digit in the black, blue, and red plots of the figure, respectively) more systematically, 1^{st} order linear regression with Surface Curvature as a regressor was performed, and the resultant slopes are plotted in Figure 10. The fitted slopes showed a significant increase in the order of single-digit, multi-digit Digit Spread 0^{o}, and 30^{o} [one-way repeated-measures ANOVA: $F(2,16)=23.459$, $p<0.001$; post-hoc linear contrast: $F(1,8)=35.472$, $p<0.001$]. This result demonstrated that when a range of low curvatures were touched by two fingers, as opposed to one finger, subjects felt greater difference between curvatures. Additionally, as the two fingers spread out wider, subjects felt even greater difference between the curvatures.

Comprehensive testing of curvatures in this experiment demonstrated that perception of curvatures is influenced by both what the finger pads feel and how the contacting fingers are arranged in space. Particularly, subjects felt greater difference between low curvatures when touching with two fingers spread out, as opposed to two fingers together or just one finger.

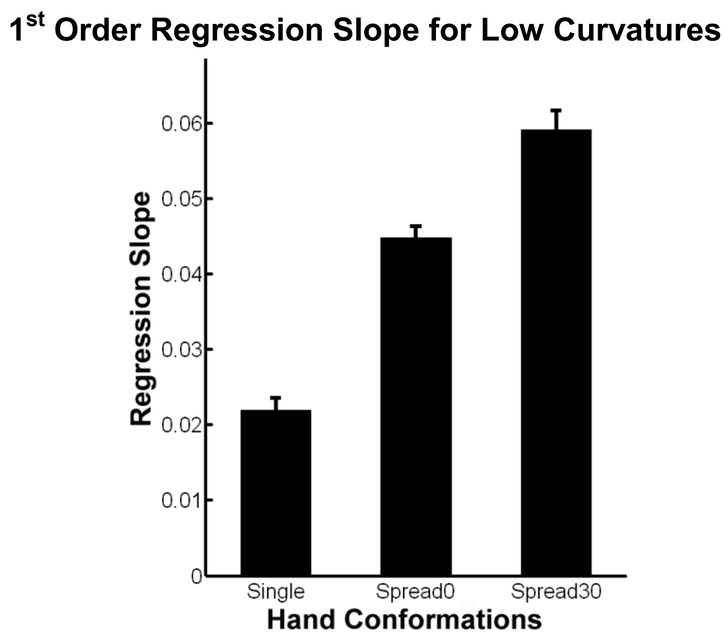

Figure 10. Slopes from 1st order regression for low curvatures. Three key Hand Conformations, shown in the x-axis, were considered for the analysis. The error bars represent the standard error of means for the within-subject design.

Although the importance of multiple-digit contact for global shape perception was verified, what exact aspect of multiple-digit stimulation caused this augmented perception was not clear due to the natural limitation of veridical curvatures used in this experiment. More specifically, the veridical curvatures exhibited co-varying of Surface

Curvature, Contact Angle, and Digit Spread when more than one finger was touching the shapes. For example, as Digit Spread increased from 0^{o} to 30^{o} for any given curvature, the tangential Contact Angle also increased, rendering the independent manipulation of these parameters impossible. Hence, the aim of the next experiment was to test the influence of the individual parameters on local and global curvature perception in a fully controlled, systematic way.

EXPERIMENT 2: Systematic Testing of Curvature Perception

The greatest limitation of findings from EXPERIMENT 1 was that various factors were co-varying. In order to disentangle the pertinent parameters, the piecewise stimuli, along with two platen forcers, were utilized to achieve systematic variation of the parameters. This enabled us to examine the individual as well as interactive effects of Surface Curvature, Contact Angle and Digit Spread in local and global curvature perception.

Specific Methods

A set of Contact Angles was first determined based on selected Surface Curvature and Digit Spread values for multi-digit, low curvature cases. Surface Curvatures of 5, 15, and 25 m^{-1} were chosen, since EXPERIMENT 1 results showed that these curvatures were perceived differently when touched by two fingers compared to when touched by one finger: therefore, these Surface Curvatures were prime candidates to test the influence of Digit Spread and Contact Angle in global conditions. Based on these three curvatures and Digit Spread of 0^o and 30^o in multi-digit conditions, six Contact Angles were computed: 3.2^o, 8.8^o, 9.4^o, 13.9^o, 27.1^o, and 45.1^o with 0^o being horizontal. In each trial of multi-digit cases, a pair of piecewise shapes with one of the three low Surface Curvature values at one of the five Contact Angles, 3.2^o, 8.8^o, 9.4^o, 13.9^o, and 27.1^o, was presented simultaneously on D2 and D3, while Digit Spread was also varied between 0^o and 30^o. The highest Contact Angle of 45.1^o was not tested in multi-digit conditions due to physical limitation.

For single-digit conditions, three Surface Curvatures within the high curvature range from EXPERIMENT 1 were chosen: 35, 105, and 175 m^{-1}. Human subjects were able to perceive difference between these curvatures easily (i.e. produced very different magnitude estimates in Figure 9). The piecewise stimuli at all six Contact Angles, 3.2^o, 8.8^o, 9.4^o, 13.9^o, 27.1^o, and 45.1^o with 0^o being horizontal were used. In each trial of single-digit cases, one piecewise shape with one of the three Surface Curvatures and one of the six Contact Angles was presented onto D2 or D3 alone. Digit Spread in this case was fixed at 20^o to ensure that shapes did not accidently touch the unintended neighboring digit.

In both single- and multi-digit cases, all the stimuli were indented 2 mm vertically into the surface of subjects' fingertips. Only the pair of D2 and D3 was tested in this experiment.

Results and Discussion

In order to investigate the individual effects of Digit Spread and Contact Angle in global perception of low curvatures, three low curvatures were presented in two-finger stimulation conditions with independent manipulation of Surface Curvature, Digit Spread, and Contact Angle. The results are presented in the left panel of Figure 11. This data was analyzed through three-way repeated-measures ANOVA with Surface Curvature (5, 15 and 25 m^{-1}), Digit Spread (0^o and 30^o) and Contact Angle (3.2^o, 8.8^o, 9.4^o, 13.9^o, and 27.1^o). The ANOVA results revealed the main effects of Digit Spread and Contact Angle [$F(1,6)=14.887$, $p<0.01$ and $F(4,24)=29.4332$, $p<0.001$, respectively] but no effect of Surface Curvature [$F(2,12)=1.913$, $p>0.15$]. The main effect of Contact Angle is shown in the figure as the reported curvature increases with increasing angle. The effect of Digit Spread is indicated by the solid lines above the dotted lines across all Contact Angles. The interesting result was found with Surface Curvature. Unexpectedly, there was no significant effect of Surface Curvature, shown by the overlap of the three color plots in the figure.

As shown in the left panel of Figure 11, there was also a significant interaction between Digit Spread and Contact Angle [$F(4,24)=6.33$, $p<0.002$] but no interaction between Surface Curvature and other factors [$F(2,12)=0.116$, $p>0.8$ for interaction with Digit Spread; $F(2.426,14.556)=0.832$, Greenhouse-Geisser corrected $p>0.4$ for that with Contact Angle]. This interaction between Digit Spread and Contact Angle was found to be linear via post-hoc contrast analysis [$F(1,6)=27.522$, $p<0.003$], demonstrating that the difference in perceived curvature between Spread 30^o and 0^o increased linearly as the angle of cutaneous stimulation on the two adjacent digits became steeper. This is illustrated in the figure by the difference between the solid and dotted lines increasing linearly as the angle increases towards right.

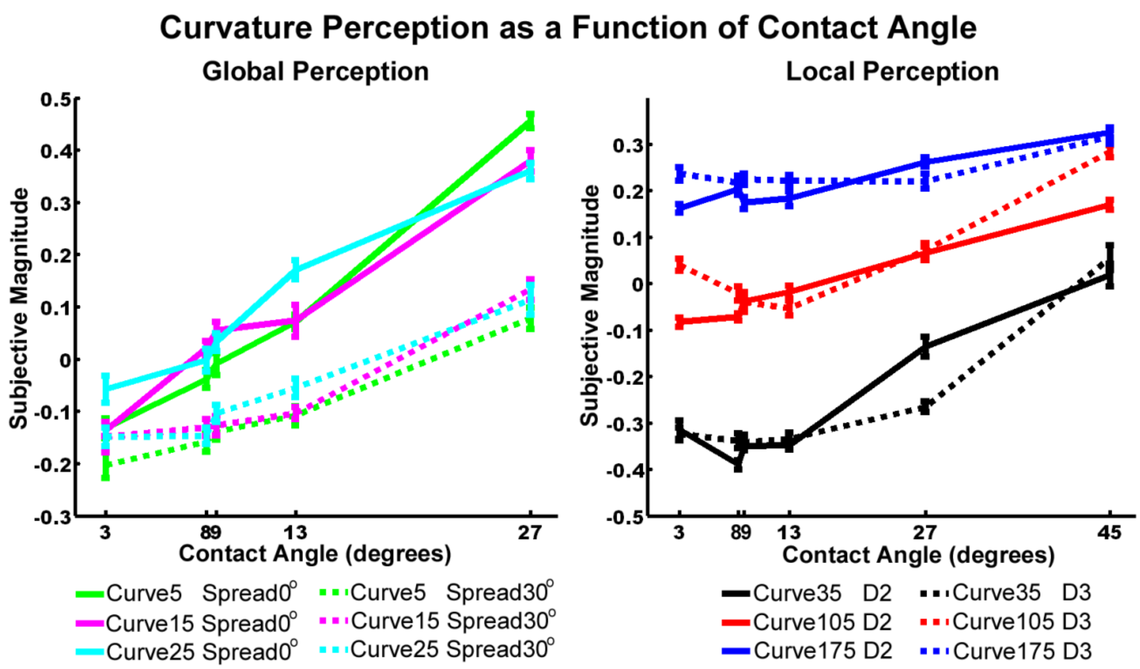

Figure 11. Results of EXPERIMENT 2. The left panel depicts the responses in global perception conditions. As the three Surface Curvature levels show no significant difference among them, the three colored plots statistically overlap with each other. On the other hand, the local responses in the right panel show significant difference among the three high Surface Curvature levels as they are clearly separated from each other. The error bars represent the standard error of means.

These results showed that, when multiple fingers touch an object together, the brain focuses on the gross angle information on the contacting fingers and the distance between them, rather than the detailed surface features. The curvatures used in this global experiment were, in fact, discernable in local conditions of EXPERIMENT 1. This established that the detailed surface information is taken over by the gross contact angle information when multiple fingers touch an object. This suggested that the brain attends to different aspects of the inputs depending on how many fingers are touching the object.

The three high curvatures (35, 105, and 175 m^{-1}) were tested in local conditions (D2 and D3 alone) with six contact angles (3.2^o, 8.8^o, 9.4^o, 13.9^o, 27.1^o, and 45.1^o). The results are presented in the right panel of Figure 11, and the responses were analyzed through three-way repeated-measures ANOVA. The results showed the main effect of Surface Curvature and Contact Angle but not single-digit Hand Conformation, similar to what was found in EXPERIMENT 1 [$F(1.101,7.709)=267.182$, Greenhouse-Geisser corrected $p<0.001$ for Surface Curvature; $F(2.024,14.166)=37.013$, Greenhouse-Geisser corrected $p<0.001$ for Contact Angle; $F(1,7)=0.290$, $p>0.6$ for single-digit condition]. Post-hoc contrast analysis also revealed linearly increasing perceived curvature with Surface Curvature [$F(1,7)=281.2$, $p<0.001$]. These results confirmed that the cutaneous information from the fingertips was sufficient to perceive high curvatures, as previously established by Goodwin et al. (1991) and others.

There was a significant interaction between the Surface Curvature and Contact Angle [$F(2.361,16.525)=6.152$, Greenhouse-Geisser corrected $p<0.01$]. As seen in the right panel of Figure 11, there was a greater effect of Contact Angle as Surface Curvature approached the low curvature range. Perception of the highest curvature exhibited a minimal effect of Contact Angle [one-way repeated-measures ANOVA: $F(5,35)=5.693$, $p<0.05$ for D2 but $F(2.323,16.264)=1.324$, Greenhouse-Geisser corrected $p>0.2$ for D3].

This was further examined by post-hoc contrast analysis, which exhibited the linearly diminishing effect of Contact Angle as Surface Curvature increased [$F(1,7)=15.783$, $p<0.006$]. This significant interaction, along with its main effect, of Contact Angle was an unexpected finding, and suggested that the neighboring, non-contacted finger might have affected the perception on the contacted finger. This discovery led to the inception of tactile perceptual grouping model, inspired by the visual completion phenomenon.

Comparing the results of global and local experiments, the biggest difference between global and local curvature perception was found to be the differential effect of the detailed surface information. When a single finger touches an object, the brain focuses on the detailed surface features purely based on cutaneous information. To the contrary, when multiple fingers touch an object, the brain only utilizes the gross angle information of the cutaneous input and the spatial information through proprioceptive sensation, overlooking the detailed surface features of the object.

EXPERIMENT 3: Effect of Indentation in Curvature Perception

As the results of EXPERIMENT 2 demonstrated the difference between global and local perception of curvatures, a follow-up experiment was designed to test additional disparity between local and global curvature perception. One of the parameters that have been tested in single-digit perception of high curvatures was the varying levels of contact force (Goodwin, John et al. 1991). We wanted to examine if we could replicate the previously observed effect of contact force in terms of indentation depth, and if the effect of indentation depth might or might not be different in the case of global curvature perception.

Specific Methods

Low Surface Curvatures of 5, 15, and 25 m^{-1}, veridical curvature shapes without any manipulation of Contact Angle, were presented at three levels of Indentation Depth, 0.5, 1.25, and 2 mm, in multi-digit conditions with D2 and D3. Digit Spread was also varied between 0^o and 30^o. High Surface Curvatures of 35, 105, and 175 m^{-1}, also without any Contact Angle manipulation, were presented in single-digit conditions on the center of D2 or D3 at three indentation depths, 0.5, 1.25, and 2 mm. Only the pair of D2 and D3 was tested in this experiment as well.

Results and Discussion

Three veridical low curvatures were tested with varying Indentation Depth levels in multi-digit conditions on D2 and D3 together, and the result are shown in the left panel of Figure 12. When three-way repeated-measures ANOVA with Surface Curvature (5, 15, and 25 m^{-1}), Digit Spread (0^o and 30^o), and Indentation (0.5, 1.25 and 2 mm) was performed, there was the main effect of Surface Curvature [$F(2,12)=197.002$, $p<0.001$], Digit Spread [$F(1,6)=34.068$, $p<0.002$], and their interaction [$F(2,12)=5.283$, $p<0.03$], as expected from the low curvature results of EXPERIMENT 1. However, there was no effect of Indentation on global perception of low curvatures [$F(2,12)=0.340$, $p>0.7$], indicated by the three color plots overlapping with each other in the left panel of the figure. This was opposite of what was reported by the previous studies in local curvature perception, thus unexpected.

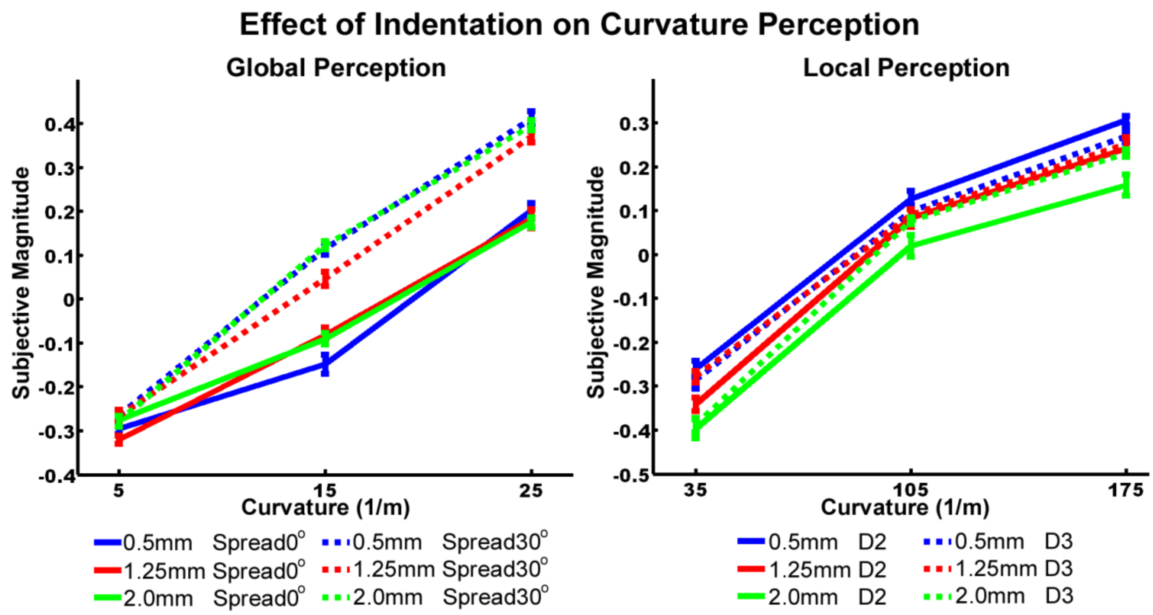

Figure 12. Results of EXPERIMENT 3. The left panel illustrates the responses in global perception conditions. As the three Indentation Depth levels show no significant difference among them, the three colored plots statistically overlap with each other. On the other hand, the local responses in the right panel show significant difference among the three Indentation Depth levels as they are clearly separated from each other. The error bars represent the standard error of means.

The results of local perception are illustrated in the right panel of Figure 12. When three high curvatures (35, 105, and 175 m^{-1}) were tested with the same varying Indentation Depths in two single-digit conditions (D2 and D3 alone), there was the main effect of Surface Curvature [three-way repeated-measures ANOVA: $F(2,10)=196.017$, $p<0.001$] and no effect of single-digit Hand Conformation [$F(1,5)=0.195$, $p>0.6$], similar to the high curvature data of EXPERIMENT 1. The interesting result was found with the effect of Indentation Depth. Unlike the global perception data above, there was the significant main effect of Indentation Depth in local curvature perception [$F(2,10)=8.206$, $p<0.009$], as the three color plots are separated from each other in the figure. When further analyzed, the effect of Indentation Depth was found with D2 but not with D3 [two-way repeated-measures ANOVA: $F(2,10)=4.926$, $p<0.04$ for D2; $F(2,10)=3.108$, $p>0.08$ for D3]. The finding of D2 showing the effect of indentation depth in single-digit conditions concurs with the previous results from Goodwin et al. (1991). In addition, we found that D3 does not respond as readily to changes in indentation depth. These results are in agreement with those of previous studies showing higher sensitivity of D2 than that of D3 (Vega-Bermudez and Johnson 2001).

The results of this experiment further confirmed the differential effect of detailed surface information found in the prior experiment. When touched by multiple fingers, the level of indentation or contact force does not exhibit any influence on the perception across the fingers. However, when touched by a single finger, perception is significantly modulated by the level of indentation. Since indentation or contact force manipulates the details of the contact profile that the fingertips feel, this finding also supported the disparate contribution of the detailed surface information between local and global perception in touch.

General Discussion

The overall take-home message of the experiments presented in this chapter is how local (i.e. single-digit) and global (i.e. multi-digit) perception of curvatures differs from each other. The gist of findings from EXPERIMENT 1 is that perception of low curvatures is influenced by the number of contacting fingers and the spatial arrangement of those fingers. The regression result of the low curvatures more clearly demonstrates that the range of perceived curvature becomes larger as more fingers contact the curvatures. In addition, the range of curvature perception increases even more when the two fingers are spread apart than when they are together. Although the importance of multiple-digit contact for global shape perception is verified through this result, what exact aspect of multiple-digit contact causes this augmented perception is still not clear due to the co-varying nature of the relevant parameters in this experimental design.

The results from EXPERIMENT 2 demonstrate that in perceiving global shape of objects across multiple digits, detailed surface information plays a very minor role while proprioception, gross contact information (e.g. tangential angle) on finger pads, and their interaction deliver the majority of the necessary information. This suggests that the significant effect of Hand Conformation and its interaction with Surface Curvature observed in the global case of EXPERIMENT 1 were, in fact, driven by the effects of Contact Angle and Digit Spread and their interaction: when the contacting fingers were apart, they touched more to the side of the curved shapes with steeper contacting angles, due to the co-varying nature of the veridical curvatures used in EXPERIMENT 1, and resulted in increased perceived curvature.

The lack of a significant Surface Curvature effect in global conditions of this experiment initially may seem to conflict with the results of EXPERIMENT 1, where even single-digit perception of low curvatures showed the main effect of Surface Curvature. However, these results actually corroborate our hypothesis about global shape perception: the brain focuses more on the distance between the multiple contact digits and the gross contact information on those fingers to make out the global shape of a large object spanning across digits, rather than the detailed cutaneous surface profile from each finger pad; to the contrary, when the same object is touched by a single finger, the brain needs to rely on the local surface information, which is the only available input to the brain, to perceive its shape. These results also concur with the previous results by Pont et al. (Pont, Kappers et al. 1999), which showed that the local attitude or angle information is more crucial than the actual surface details in perceiving low curvatures contacting multiple fingers.

What we further discover in this study via systematic variation of the pertinent parameters is the exact effect of the contacting angle and how it interacts with other parameters. In the case of global perception, the contrast analysis of the interaction between Contact Angle and Digit Spread reveals that as the angle of cutaneous stimulation becomes steeper, there is a greater difference in perceived curvature between the two spreads: the subjects perceive the shape to be more curved as the object touches more to the side of fingers, and this trend becomes more exaggerated when the fingers are together than when they are spread apart. This finding hints at that the brain must have a mechanism integrating these two parameters across the two contacted fingers to make out the overall curvature, as represented by the blue dotted lines in Figure 13. This mechanism could also explain the witnessed effects of Contact Angle, illustrated in (A) and (B) of the figure, and Digit Spread, depicted in (B) and (C) of the figure.

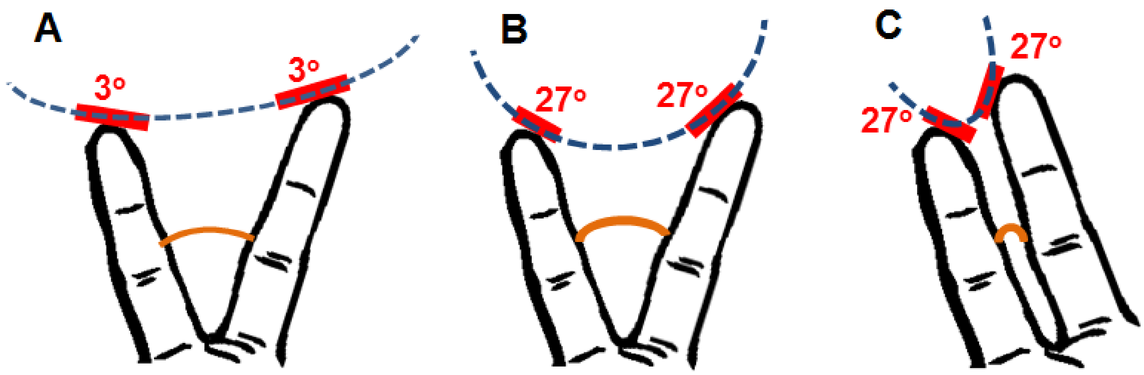

Figure 13. Illustrations to show how perceived curvature changes with Contact Angle and Digit Spread in global perception. The red segments symbolize parts of an object that touch the fingers at certain angle. The blue dotted lines show the suggested shape of the object the brain is likely to make out across the contacted fingers. (A) and (B) show that, in a given Digit Spread condition, the perceived shape becomes more curved as the angle becomes steeper on the stimulated fingers. This tendency becomes more inflated as the fingers move closer to each other, depicted in (C).

The effect of the stimulation angle in perceived curvature was also observed in local trials with high curvatures. Analogous to what was found in global perception, the perceived curvature in the local case also increases with increasing Contact Angle. In this local perception, the stimulation angle exhibits interaction with the actual surface curvature, instead of the distance between the fingers: the effect of stimulation angle diminishes as the curvature increases. The effect of the angle and its interaction with the curvature suggest that the perception on the contacted finger might be influenced by the existence of the adjacent, non-contacted digit. Since D2 and D3 stimulations were completely randomly presented in this experiment, both fingers were always placed on the apparatus although only one of them was stimulated with a curvature in each trial. This non-stimulated, neighboring finger might interfere with the mechanism that is similar to the integration across fingers proposed in the global case, as depicted in Figure 14. This scenario could explain the effect of Contact Angle, illustrated in (A) and (B) of the figure, as well as its interaction with the curvature, shown in (B) and (C) of the figure.

The results of EXPERIMENT 3 add another aspect to the difference between local and global shape perception in touch. Since the brain focuses on the gross contact information when multiple fingers touch an object, not the detailed surface profile, it is anticipated that varying indentation depth that affects the detailed profile of the contacting surface does not influence the global perception. On the other hand, local shape perception that mainly relies on the detailed surface information is significantly affected by the changes in indentation depth. Thus, these results are not only in agreement with the findings of EXPERIMENT 2, but also further strengthen them.

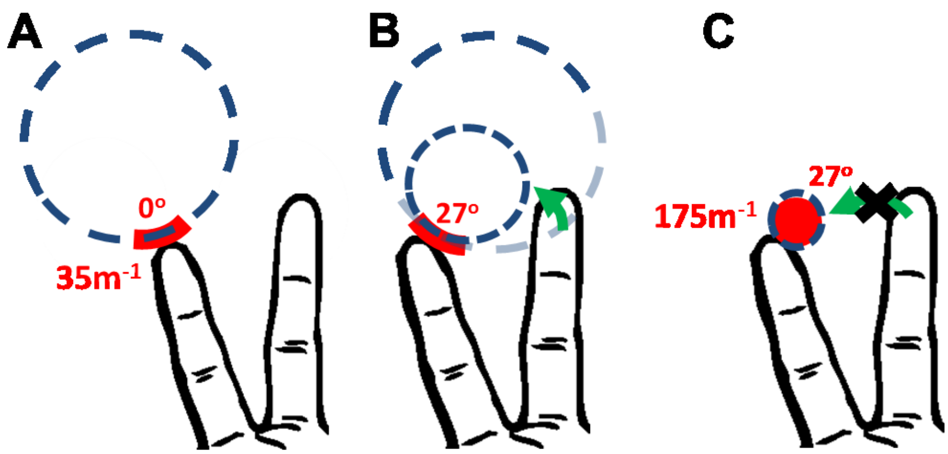

Figure 14. Illustration to show how perceived curvature changes with Surface Curvature and Contact Angle in local perception. As in Figure 13, the red segments and circle symbolize parts of an object that touch the fingers at certain angle. The blue dotted lines show the suggested shape of the object the brain is likely to perceive on the contacted digit. The green arrows represent interference from the non-stimulated finger. (A) illustrates that, when a medium curvature is presented at a low angle, the neighboring digit does not interfere with the contacted digit. As the angle becomes steeper, the neighboring digit starts interfering with the across-digit integration process, resulting in higher perceived curvature, shown in (B). When a very high curvature is presented, as in (C), this interference does not occur.

Summary

Taken together, the results of this chapter prove that large shapes, touched by multiple digits simultaneously, are perceived by integrating the distance between the contacting digits and how the shapes make contact with the fingers, not the detailed surface features individual digits feel. To the contrary, small shapes, contacted by a single finger at a time, are perceived through the actual surface profile of those shapes. This differential effect of the detailed surface profile between local and global perception, as well as the unexpected finding on the effect of contact angle in local perception demand further investigation on the underlying mechanism and fundamental model of tactile 3D shape perception.

Chapter 4. Perceptual Completion in Tactile Shape Perception

The results of previous experiments suggest an across-digit integration process that could explain how the brain utilizes given inputs to perceive the overall shape of the object across fingers. In this chapter, a perceptual model, inspired by a similar process in visual completion, is proposed to explain the across-digit integration in both local and global 3D shape perception of tactile sensation. This model is proved through an experiment testing all the relevant parameters in extreme conditions. The result of this experiment establishes that tactile shape perception is fully modeled by perceptual completion process.

Introduction to Perceptual Completion

Completion in Vision

Unlike vision where our eyes often have access to the entire shape of an object at once, touch has intrinsic constraints in how much of shape information it can receive at once. Hands rarely make contact along the entire contour of an object and, often times, fingers and palms only touch limited part of the object. Then, it becomes the brain's job to infer the overall shape of the object based on this incomplete information from the hand. However, the visual system too needs to rely on incomplete contour information to perceive the entire shape of the object in certain occasions. Visual completion is the phenomenon where the brain perceives objects that only have partial contour information available due to occlusion.

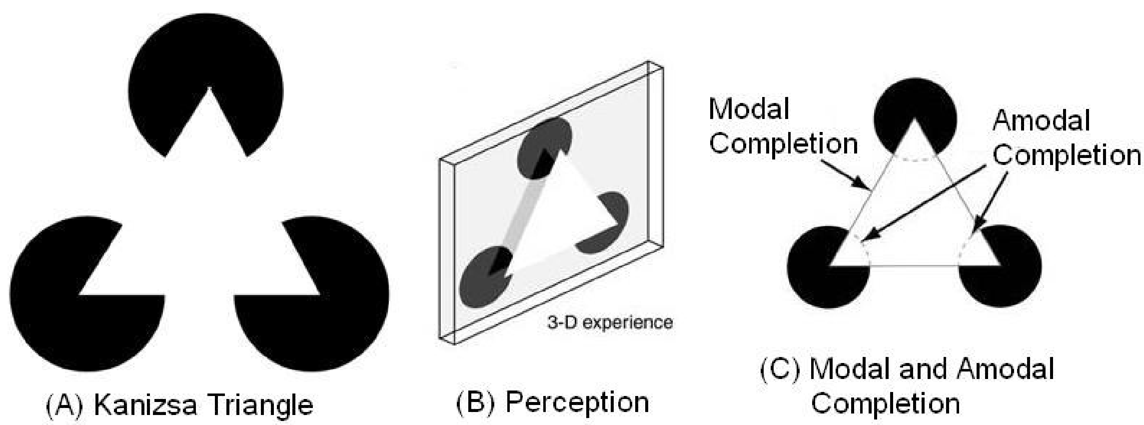

Figure 15. Kanizsa triangle. (A) shows Kanizsa triangle with illusory contours; (B) illustrates how the brain perceives the shapes in 3D space; (C) demonstrates how modal and amodal completion contributes to the perception of Kanizsa triangle.

There have been many neurophysiological, behavioral, and imaging studies on how this completion process happens in visual perception (Kanizsa, 1955; vonder Heydt, Peterhans et al. 1984; Palmer and Neff 1996; Feldman 1999; Tse 1999; Murray, Foxe et al. 2004). One of the most seminal examples of visual completion is the famous "Kanizsa Triangle" (Figure 15 (A)). This example illustrates both modal and amodal completion: the triangle at the center demonstrates modal completion where the foreground object without physical contours is perceived via illusory contours; the black circles depict amodal completion where objects in the background that are occluded by a foreground object are perceived by extending its partial contours (Figure 15 (B) and (C)).

The modally completed triangle is perceived through the illusory contours interpolated between the vertices located on top of the circles. Amodally completed circles are perceived by interpolating the rest of the circle contours. One of the prominent differences between modal and amodal completion is that the amodally completed circles do not exhibit any illusory contours, while the modally completed triangle does. Despite these differences, both modal and amodal completion enables the brain to perceive objects that have only incomplete shape information available to the eyes.

Proposed Completion in Touch

Due to the perceptual similarity between tactile shape perception and visual completion, we propose that a similar completion process to that of vision might be able to explain how perception of 3D shapes arises in touch. As in visual completion where the partial contours are interpolated to close the gaps between them, tactile completion also interpolates the contacted surfaces on individual digits to connect the gaps between the fingers (Figure 16).

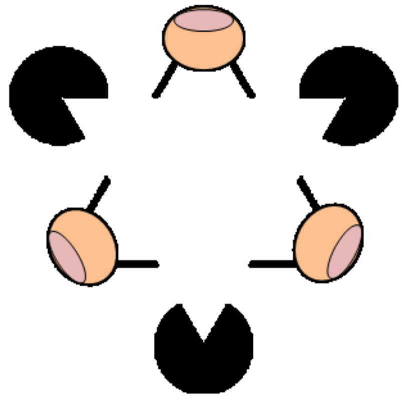

Figure 16. Illustration of how tactile completion compares to visual completion. As the eyes see only pieces of contours in visual completion, the fingers only contact certain parts of the object in touch. Thus, in both modalities, the brain needs to complete between those detected contours/surfaces.

We hypothesize that this completion model might be the underlying mechanism for both global and local shape perception discussed in Chapter 3. In global conditions where multiple fingers touch an object simultaneously, we propose that the brain “fills-in” between those contact digits to perceive the overall shape of the object, as depicted by the blue dotted lines in Figure 17. We believe that this global completion process is influenced by two parameters: the angle of contact on the multiple contacting fingers, and the distance between them. As described briefly in Chapter 3, the steeper angle of contact causes the completed curvature across the stimulated fingers to become more curved, illustrated in Figure 17 (A) and (B). The completed shape also becomes more curved as the distance between the contact fingers decreases, depicted in (B) and (C) of the figure.

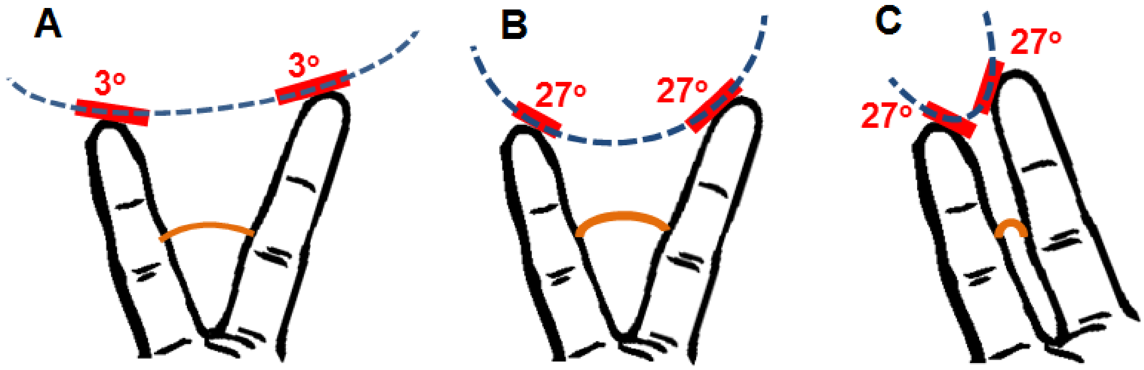

Figure 17. Illustration of global completion in touch. The red segments denote parts of an object that touch the fingers at certain angle. The blue dotted lines show the suggested shape of the object the brain is likely to make out across the contacted fingers. (A) and (B) show that perceived curvature increases as Contact Angle increases from 3^{o} to 27^{o}. When Digit Spread decreases from (B) to (C), perceived curvature also increases.

This model fully accounts for the global perception results of our previous experiments, particularly those of EXPERIMENT 2. The global results are shown in Figure 18 with cartoon visualizations illustrating the completion process involving two contacted fingers. The filled-in (i.e. completed) curvature across the two contact digits becomes more curved as the angle of contact becomes steeper, as visualized in (A) and (B) or (C) and (D) of Figure 18. This is the reason why, regardless of the distance between the fingers, the reported curvature plot exhibits a positive slope in the figure. Even with the same contact angles, the completed curvature becomes more curved when the fingers are close to each other than when they are apart, as visualized in (A) and (C) or (B) and (D) of Figure 18. This explains why the solid lines are above the dotted lines in the figure.

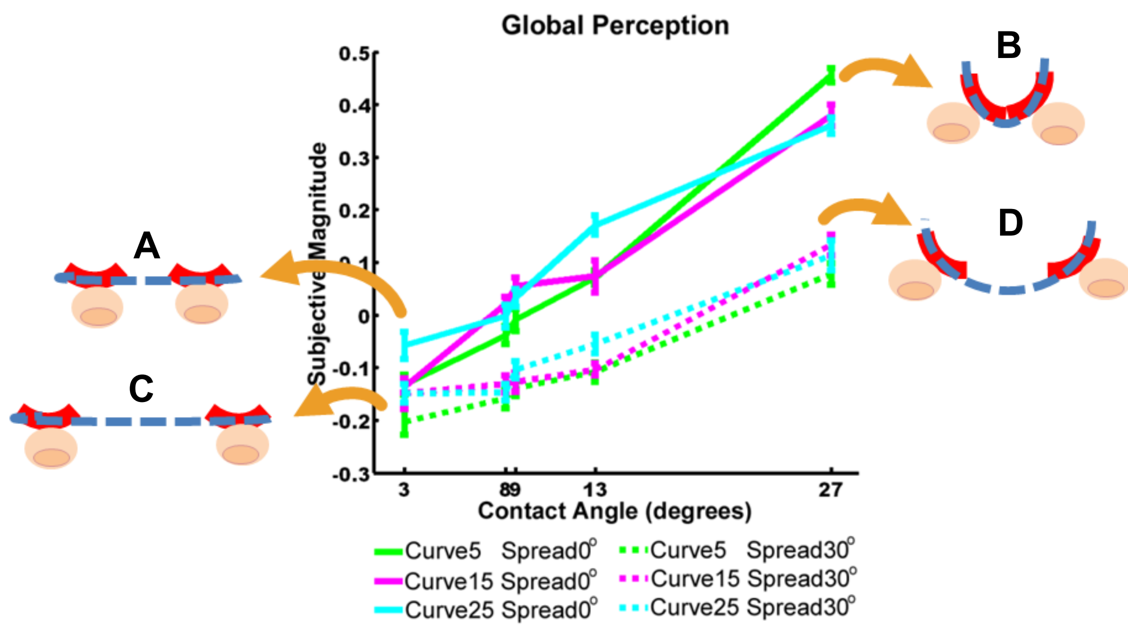

Figure 18. The result of global perception from EXPERIMENT 2 and visualization of how tactile completion induces perceived curvature in different circumstances of (A) through (D). The peach circles represent the subjects' fingers, the rec segments indicate the surfaces of piecewise curvature stimuli, and the blue dotted lines denote the completed curvatures the brain is likely to perceive.

The interaction between the contacting angle and the spread between the fingers observed in Figure 18 can be explained by this model as well: when the stimulation angle is low, the completed curvature is not much affected by the distance between the fingers, as illustrated on the left side of the figure. However, when the angle is steeper, the completed curvature across fingers becomes much more curved when fingers are together than when they are spread apart, as depicted on the right side of the figure.

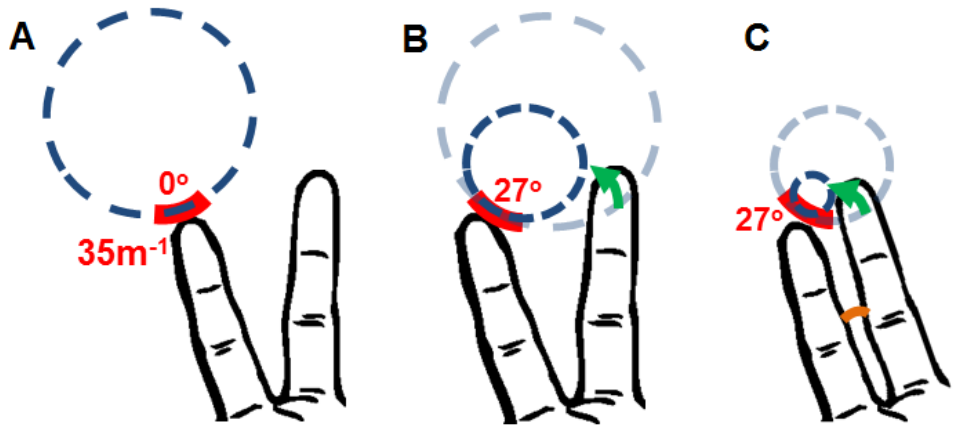

Figure 19. Illustration of local completion in touch. As in Figure 17, the red segments symbolize parts of an object that touch the fingers at certain angle. The blue dotted lines show the suggested shape of the object the brain is likely to perceive on the contacted finger. The green arrows represent interference from the non-stimulated, neighboring digit. The brain bases its perception on the profile of the contacting surface when the angle of contact is low as in (A). (B) shows that, as the angle increases and touches more to the side of the finger, the adjacent non-contact finger starts interfering with the base curvature and results in increased perceived curvature. The distance between the two fingers would also affect the interference and could cause the perceived curvature to increase as the fingers come close to each other, depicted in (C).

Local shape perception where only one finger touches an object can also be modeled by the completion mechanism. In this case, completion can be viewed as an “interference” process between the neighboring contact and non-contact fingers: perceived curvature is first determined by the profile of the contact surface, as illustrated in Figure 19 (A). Depending on the angle of contact and the distance between fingers, the non-contacted digit could act as a perceptual stop and interfere with the originally completed curvature. As the angle becomes steeper touching more to the side of the finger, the non-stimulated finger starts interfering with what is perceived on the contacted finger and causes the perceived curvature to become more curved, as depicted in Figure 19 (B). Similarly, as the non-contacted digit comes closer to the stimulated digit, the degree of interference increases and also causes the perceived shape to be more curved, shown in Figure 19 (C). Thus, we believe that this tactile completion is influenced by three shape parameters: the profile of contact surface, the angle of contact, and the distance between the contact and non-contact digits.

This interference model supports both the effect of the contacting angle and its interaction with the actual surface profile, observed in the local perception data of EXPERIMENT 2. The results are shown in Figure 20 with cartoon visualizations illustrating the local completion process. When the angle of contact is low so the object contacts near the center of the finger, the adjacent non-contact digit is less likely to interfere and the perceived curvature is purely based on the profile of the contacting surface, as seen in (A) and (C) of Figure 20. When the curvature is not so curved, as the angle becomes steeper, the neighboring non-contact finger starts interfering with the curvature on the contact finger and results in an increased perceived curvature, illustrated in (C) and (D) of Figure 20. However, when the surface is highly curved, interference from the adjacent non-contact digit is not possible anymore and the influence of the contacting angle on the perceived curvature diminishes, depicted in (A) and (B) of Figure 20. This is the reason why the slope of the blue plot is less positive, close to zero, than that of the black plot in the figure.

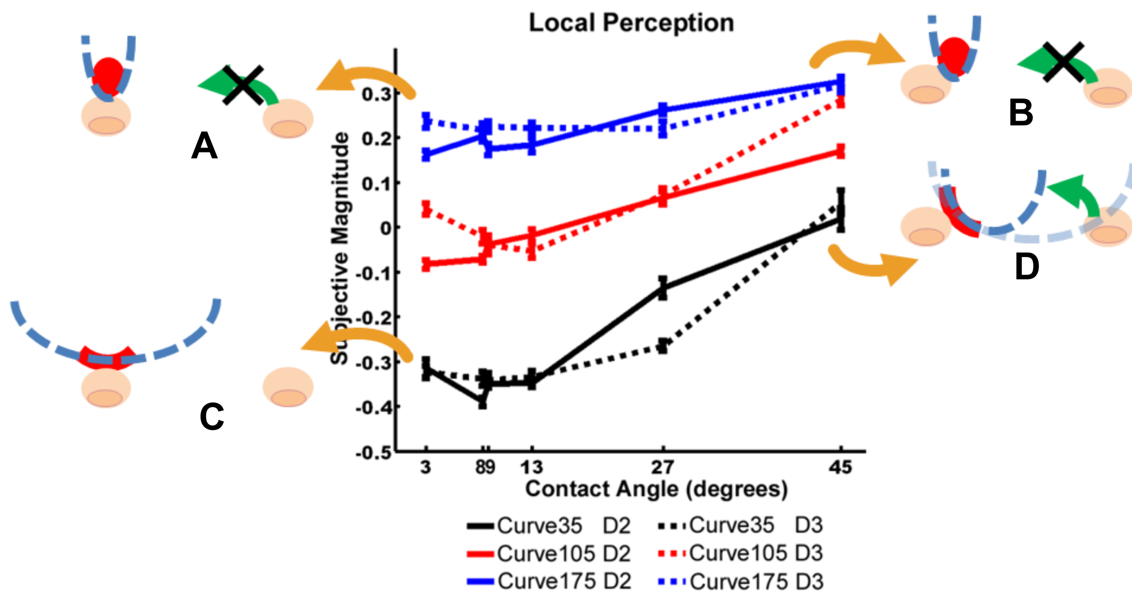

Figure 20. The result of local perception from EXPERIMENT 2 and visualization of how tactile completion induces perceived curvature in difference circumstances of (A) through (D). As in Figure 18, the peach circles represent the subjects' fingers, the red segments or circles indicate the surfaces of piecewise curvature stimuli, and the blue dotted lines denote the completed curvatures the brain is likely to perceive. The green arrows represent the interference from the non-stimulated digit.

In addition to the profile of contacting surfaces and the angel of contact, this interference model also predicts the distance between contact and non-contact digits to affect the local perception. As illustrated in Figure 19 (C), the spread between fingers could also cause the interference from the neighboring non-contact digit. When the fingers are close to each other, this interference would result in increased perceived curvature. This aspect of the completion model was, unfortunately, never tested in any of our previous experiments. Therefore, the aim of the last experiment was to test this very hypothesis.

EXPERIMENT 4: Completion in Curvature Perception

Predictions based on Completion Model

This experiment was designed to test if the completion model we proposed was indeed applicable in local and global shape perception of touch. Since the global perception data of EXPERIMENT 2 already verified our tactile completion model in the global case, we wanted to further test this model in local perception. Particularly, we wanted to examine if the distance between the fingers, in addition to the profile of contact surfaces and the angle of contact, would affect the locally perceived curvature. More specifically, Digit Spread must exhibit an interaction with Contact Angle: in the case of Contact Angle 0^o, for instance, Digit Spread would not have any effect since there could not be any interference from the neighboring finger. However, at higher Contact Angle, such as 27^o as in Figure 19 (C), decreasing Digit Spread would cause the perceived curvature to increase due to a greater degree of interference from the non-contacted finger.

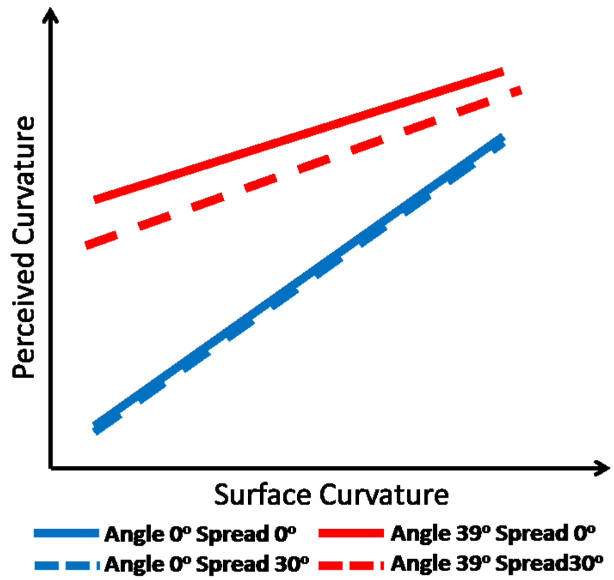

Figure 21. Predicted results of EXPERIMENT 4 based on local completion model. Contact Angle of 0^{o} is in blue while 39^{o} in red. Digit Spread of 0^{o} is in solid lines whereas 30^{o} in dotted lines. Digit Spread was predicted to have an effect on perceived curvature at high Contact Angle, but not at low ones.

These predictions are plotted in Figure 21. First, the model predicted that the perceived curvature would increase with higher Contact Angle. This is illustrated by the red plots being above the blue ones in the figure. Second, Contact Angle was anticipated to interact with Surface Curvature as its effect would diminish with increasing Surface Curvature. This is depicted by the decreasing difference between the red and blue plots.

These two predictions were in fact already witnessed in the local perception data of EXPERIMENT 2, thus were to be confirmed again in the following experiment. The newly tested predictions involving Digit Spread were the essence of this experiment. Increasing Digit Spread would cause the perceived curvature to decrease at high Contact Angle, as the red solid line is above the red dotted one in the figure. To the contrary, Digit Spread would not have any effect on perceived curvature at low Contact Angle, illustrated by the two blue plots overlapping.

Specific Methods

All three parameters that were hypothesized as inputs to the local completion model were tested: Surface Curvature, Contact Angle, and Digit Spread. The specific range of Surface Curvatures used in this experiment focused on low to middle ranges of curvatures. A total of three Surface Curvatures was tested: 12, 35, and 105 m^{-1}. 12 m^{-1} was a low curvature defined in earlier experiments, while 35 and 105 m^{-1} were in the middle range. Two extreme Contact Angle conditions, 0^o and 39^o, and two extreme Digit Spread levels, 0^o and 30^o, were also tested. All three of these parameters were factorially crossed with each other and resulted in a total of 12 experimental conditions. All of these conditions were tested in local stimulation of D2, since D2 has been proved to be most sensitive (results of EXPERIMENT 3 in Chapter 3; Vega-Bermudez and Johnson 2001). However, D3 was also secured onto the finger holder in order to properly examine the effect of Digit Spread in interference from the non-contact digit. All the curvature stimuli were indented vertically 2 mm into the surface of the skin on D2.

Results

In Figure 22, the results showed significant effects of Surface Curvature, Contact Angle, Digit Spread and their interactions, as the model predicted [three-way repeated-measures ANOVA: $F(2,14)=109.934$, $p<0.001$ for Surface Curvature; $F(1,7)=16.904$, $p<0.006$ for Contact Angle; $F(1,7)=9.406$, $p<0.019$ for Digit Spread; $F(2,14)=17.011$, $p<0.001$ for the two-way interaction between Surface Curvature and Contact Angle; $F(1,7)=7.205$, $p<0.032$; $F(1,7)=7.205$, $p<0.032$ for the two-way interaction between Contact Angle and Digit Spread; $F(2,14)=5.011$, $p<0.023$ for the three-way interaction among Surface Curvature, Contact Angle, and Digit Spread].

More detailed examination of the data for each Contact Angle or Digit Spread condition was performed through two-way repeated-measures ANOVA. The results showed a significant effect of Digit Spread in the case of Contact Angle 39^{o} but none for Contact Angle 0^{o} [$F(1,7)=9.504$, $p<0.019$ and $F(1,7)=0.964$, $p>0.35$, respectively]. On the other hand, there were significant effects of Contact Angle as well as its interaction with Surface Curvature in both Digit Spread 0^{o} and 30^{o} cases [$F(1,7)=26.959$, $p<0.002$ and $F(2,14)=20.482$, $p<0.004$ for Digit Spread 0^{o}; $F(1,7)=10.058$, $p<0.017$ and $F(2,14)=12.635$, $p<0.002$ for Digit Spread 30^{o}].

In both three-way and two-way ANOVA analyses, there was no significant interaction found between Surface Curvature and Digit Spread [three-way repeated-measures ANOVA:$F(2,14)=0.214$, $p>0.8$; two-way repeated-measures ANOVA:

$F(2,14)=1.973$, $p>0.175$ for Contact Angle 39°; $F(2,14)=0.584$, $p>0.57$ for Contact Angle 0°].

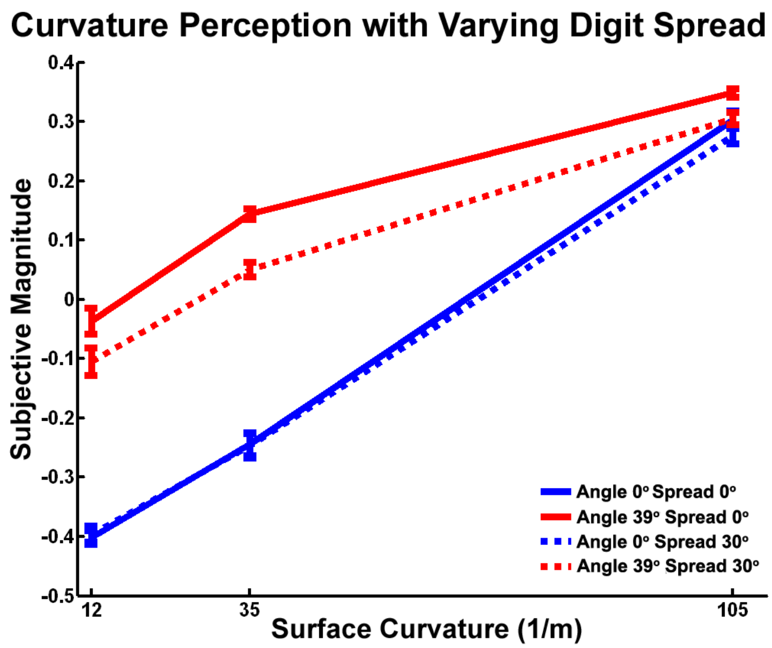

Figure 22. Results of EXPERIMENT 4. The same color and line codes are employed as in Figure 21. As predicted by the model, decreased perceived curvature was observed with increasing Digit Spread at Contact Angle of 39°. However, at Contact Angle of 0°, no effect of Digit Spread was witnessed. The error bars represent the standard error of means.

These results confirmed that all the predictions based on the local completion model were indeed true. The main effects of Surface Curvature and Contact Angle were precisely in the direction the model predicted in Figure 21. The significant interactions between Surface Curvature and Contact Angle, as well as Contact Angle and Digit

Spread were perfectly in line with the predictions. Particularly, the differential effect of Digit Spread at low and high Contact Angle cases fully proved the tactile completion model in local perception.

Discussion

The results of this experiment demonstrated that 3D shape perception in the case of local stimulation indeed follows the principle of perceptual completion. The model predicted that, due to the "interference" from the neighboring non-contact finger, perception on the contact digit would exhibit increased perceived curvature with increasing Contact Angle as well as decreasing Digit Spread. Since the effect of Contact Angle was already witnessed in the local perception case of EXPERIMENT 2, EXPERIMENT 4 focused on testing the effect of Digit Spread in the interference conditions.

This prediction was verified by the two- and three-way repeated-measures ANOVA analyses. The interaction found between Contact Angle and Digit Spread alluded to a differential effect of Digit Spread at different Contact Angles, as the model predicted. Moreover, the two-way ANOVA results proved that in the case of Contact Angle 39^o where the interference from the adjacent digit was feasible, there was a significant increase in perceived curvature as Digit Spread decreased from 30^o to 0^o. However, this increase was not observed for Contact Angle 0^o where no interference from the adjacent digit was possible. Given these results, the main effect of Digit Spread found in the three-way ANOVA must have been driven by the significant effect of Digit Spread in the case of Contact Angle 39^{o}.

In addition, the results of this experiment revealed the significant effect of Contact Angle in both cases of Digit Spread. This was in agreement with the previous findings from the local perception data of EXPERIMENT 2, and re-confirmed our predictions based on the local completion model. Collectively, the local stimulation results of EXPERIMENTS 2 and 4 clearly demonstrated that tactile 3D shape perception in the local case indeed occurs through the completion mechanism.

Summary

The tactile completion model proposes two processes for global and local perception: filling-in and interference. The global perception data of EXPERIMENT 2 verify the filling-in model in terms of both Contact Angle and Digit Spread. The local perception results of EXPERIMENT 2 corroborate the interference model with only regard to Surface Curvature and Contact Angle, overlooking Digit Spread. By adding the final piece of the puzzle with Digit Spread, EXPERIMENT 4 successfully proves the full interference model in local shape perception: due to the perceptual interference from the adjacent non-contacting finger, the perceived curvature on the contact finger increases with increasing Surface Curvature and Contact Angle as well as decreasing Digit Spread. Taken together, these experiments demonstrate that tactile 3D shape perception, either in global or local conditions, follows the mechanism of perceptual completion.

Chapter 5. General Conclusion

This thesis attempts to provide a systematic understanding of how the somatosensory system processes a variety of information from the hand to perceive three-dimensional shapes. Since the majority of prior tactile studies either focused on a limited aspect of shape perception or lacked well-controlled methodical experimental design, failing to offer a generalized conclusion, the current study puts emphasis on two points: 1) testing as comprehensive ranges of stimuli and conditions as possible, and 2) systematic and independently-controlled manipulation of the relevant parameters. Using three-dimensional curvature shapes, we first test subjects' haptic perception channeled locally through a single finger as well as integrated globally across multiple fingers. Through careful examination of the results, we discover significant differences between local and global perception of curvatures. Based on these findings, we conclude that tactile perception of three-dimensional shapes can be modeled as perceptual completion.

Local versus Global Shape Perception

The current study is an attempt to understand how 3D shapes, particularly 3D cylindrical curvatures, are perceived by the tactile system. In order to obtain the general understanding on 3D curvature perception, we initially test the most comprehensive range of curvatures that has ever been tested in the somatosensory field. Additionally, we also examine both local and global perception of those curvatures within one paradigm. The results suggest a significant difference between local and global perception of curvatures. When touching with multiple fingers (i.e. global perception), the subjects perceive greater difference between curvatures, compared to when touching with only one finger (i.e. local perception). However, due to the physical limitation of natural curvature stimuli, which was also present in previous curvature studies, this result cannot pinpoint exactly what parameter is responsible for this significant dissimilarity between local and global perception of curvatures.

The systematic and independent examination of individual parameters, using the newly invented curvature stimuli and tactile stimulator, reveals that this discrepancy is mainly driven by the differential effect of detailed surface information. When multiple fingers touch an object, the detailed surface information does not contribute to perception, whereas gross angle information on those contacting digits and the distance between them do. On the contrary, the detailed surface features influence the perception when a single finger touches an object. This finding establishes that the greater difference in reported curvature when touching with multiple fingers, mentioned above, is primarily caused by the contacting angle and the distance between the fingers, not the surface curvature of the stimuli. The fact that subjects are capable of discerning those curvature stimuli in local conditions shows that the brain has the ability to utilize the detailed surface information, but focuses more on the gross angle of contact and the finger spatial information when multiple fingers touch the object.

These results of local and global shape perception are in agreement with those of previous tactile studies. First, the finding that perception of curvatures is modulated by finger conditions agrees with that of haptic object recognition studies. Klaztky and other researchers proved that perception of 3D shapes is affected by the number of the contacting fingers and how they are arranged in space (Klatzky, Loomis et al. 1993). They found that, analogous to what we did, shape perception is significantly altered between when subjects use only one finger, all five fingers tied together, or all five fingers spread out.

The local and global curvature perception data also concurs with what Provancher et al. (2005) found with their haptic feedback device. They specifically found that low curvatures can be perceived via contact angle information on the fingertip, while high curvatures require the actual surface curvature. Although this study focused on the utility of tactile feedback in virtual reality environment, their finding in tactile curvature perception resonates with our result of local and global curvature perception.

Our global perception data not only agrees with what Pont et al. (Pont, Kappers et al. 1997; Pont, Kappers et al. 1999) showed with low curvatures, but also augments it. They proposed that the local attitude (i.e. contact angle) is the key in perceiving low curvatures across multiple fingers, not the actual surface of the contacting curvatures that the fingers feel. However, their experimental design had a weakness that the local attitude and the distance between the contact fingers co-varied with each other, rendering a definite conclusion on the topic impossible. In the present study, we verify the individual effects of contact angle and finger distance in global curvature perception through fully controlled, systematic testing. In addition to this, we further demonstrate that global curvature perception is entirely explained by the angle on the contact fingers, the distance between them, and their interaction.

The local perception results of the current study successfully replicate the previous findings of Goodwin et al. (Goodwin, John et al. 1991; Goodwin and Wheat 1992). In both studies, high curvatures are effectively perceived by a single finger. However, what we further discover in this study is the effects of contacting angle and the distance between the neighboring fingers in local conditions: when there is a non-contacted finger present next to the stimulated finger, the perceived shape becomes more curved, as the shape touches more to the side of the contacted finger and the distance between the two fingers narrows. These findings hint at that the brain might still employ an integration strategy across adjacent fingers even when only one finger actually comes in contact with the object. At first, this may seem counterintuitive, but it eventually leads to the inception of perceptual completion model in tactile shape perception.

Collectively, the current findings on local and global shape perception enhance previous understanding on the topic. The substantial difference between local and global perception of curvatures found here seems to be induced by what aspect of peripheral inputs the brain focuses on in order to produce perception of 3D shapes in a given contact condition. Despite this difference, the results suggest that the brain might utilize the same integration process to evoke both local and global perception of 3D shapes in touch.

Tactile Completion Model

The local and global results of this study provide the foundation for the perceptual model that explains how shape perception occurs in touch. In both local and global cases, the somatosensory system seems to employ a similar mechanism that integrates incomplete peripheral inputs across fingers. Therefore, inspired by visual completion, tactile completion model is proposed as the underlying mechanism to describe the across-digit integration. Tactile completion is a process where the somatosensory system interpolates between the fingers contacting the object to perceive its overall shape, as in visual completion where the visual system interpolates between the partial contours to perceive the overall object.

The global results of this study confirm the tactile model in the global case. When multiple fingers touch an object simultaneously, the brain fills in the gaps (i.e. completes) between the contacting digits, and perceives the overall shape of the object based on the gross contact angle information on the touched fingers and the distance between them. This model, summarized in Table 2, perfectly predicts our global curvature perception results. The reported curvature increases as the angle of contact increases and the distance between the stimulated fingers decreases. Furthermore, the significant interaction between the angle and the finger distance is seamlessly in line with what the model predicts.

Table 2. Summary of tactile completion model. Both global and local shape perception can be explained by the tactile completion model, yet via different processes of the model.

	Global Perception	Local Perception
Parameters	Contact Angle and Digit Spread, but not Surface Curvature	Surface Curvature, Contact Angle, and Digit Spread
Perceptual Process	Filling-in between contact digits	Interference from adjacent non-contact digit
Completion Model	Completion between multiple contact digits	Completion between contact and non-contact digits

The local data too corroborates the tactile completion model. When only a single finger touches an object, the brain perceives the shape of the object based on the detailed surface input from the contacting finger. However, depending on the angle of contact and the distance from the neighboring non-stimulated digit, the brain could sense a perceptual interference between what is being sensed by the contacting finger and what the shape should be, and alter the perceived shape. This is exactly what is observed in our local data. Perceived curvature increases with increasing degree of interference from the adjacent digit, as the shape touches more to the side of the finger and the distance between the contacted and non-contacted fingers diminishes. Particularly, the reduced effect of the angle for highly curved shapes, which cannot readily interfere with the adjacent non-stimulated digit, is fully accounted for by the model. Moreover, the fact that the effect of the finger distance is only witnessed at high contact angles, where interference is feasible unlike at low angles, provides undeniable support for our model.

Tactile completion can be viewed as part of perceptual grouping witnessed in other sensory modalities. Perceptual grouping has been described and extensively investigated by Gestalt psychologists (Koffka, 1935). They examined many of the factors that govern perceptual grouping in diverse sensory situations, including similarity, continuity, simultaneity, etc. When these conditions are satisfied, the brain "groups" certain components together to belong to one common object.

In vision, many psychophysics and neurophysiology studies have shown perceptual grouping in a form of visual completion and border-ownership (Kanizsa 1955; von der Heydt et al. 1984; Palmer et al. 1996; Feldman 1999; Tse 1999; Murray et al. 2004). Similar to what we have observed in our somatosensory data, the visual system fills in the gaps between partial contours that it believes belong to one object, and perceives them as one coherent object. Perceptual grouping also has been studied in audition (Bregman and Dannenbring 1973; Darwin and Bethell-Fox 1977; Bregman and Pinker 1978; Ciocca and Bregman 1987). Analogous to vision and touch, the auditory system groups certain sounds based on their tones, frequencies, or pitches, and perceives them to originate from one common source.

Taken together, the results of the current study successfully demonstrate that tactile shape perception is another perceptual completion phenomenon. Parallel to how the visual and auditory systems interpolate between the segmented contours and sounds, the somatosensory system interpolates between the object patches that the skin touches in order to perceive a completed shape.

This commonality among different sensory modalities provides further support for the hypothesis that there could be a common mechanism or a cortical area, which is devoted for general object recognition and can be activated by different sensory inputs. This, in fact, has been proposed by numerous previous studies. Many researchers showed that, when the same number of peripheral receptors is activated and low-pass filtering of the skin is equally employed, vision and touch exhibit a similar pattern of perceptual behavior in shape perception (Apkarian-Steilau and Loomis 1975; Loomis 1982; Phillips, Johnson et al. 1983); Cho et al. manuscript under review). Neurophysiology studies (Yau, Pasupathy et al. 2009) found parallel neural activities in the secondary somatosensory cortex (SII) and the visual area four (V4), implying an analogous shape mechanism in both modalities.

Imaging studies too support this idea. Several researchers (Peltier, Stilla et al. 2007; Lucan, Foxe et al. 2010; Lacey, Stilla et al. 2014) revealed that lateral occipital complex (LOC), traditionally believed to be a visual area, exhibits increased activity when performing tactile shape tasks. Combined with the present discovery that a comparable perceptual mechanism exists across different modalities, these imaging results could hint at where and how high level tactile shape perception might occur in the brain.

In order to expand the lessons from this study even further, the perceptual boundary of completion could be tested as the next step. In the current project, stimulus combinations that could be perceived as a single object only were presented. This restriction enabled us to investigate the underlying mechanism of tactile completion and the key parameters in the process. However, it prevented us from delving deeper into what constitutes as coherency in tactile object perception, and in what circumstances perceptual grouping stops in touch. Understanding the perceptual boundary of completion will allow us to develop a more comprehensive model of tactile shape perception, and ultimately, advance our understanding of how the brain works.

Applications

In addition to scientific implications, the results from this study have diverse engineering applications. For instance, the global completion model could shed light on how to design advanced prosthetic hands. One of the most challenging aspects of developing advanced prosthetic hands is providing haptic feedback. The biggest hurdle in doing so is how to overcome the limited bandwidth between the sensor inputs and the central computing unit. Given restricted power and resources, the control unit cannot possibly process every single piece of information from the countless sensors scattered all around the device. Among all the physical features the peripheral sensors pick up, what are the essential inputs that must be relayed to the control unit? The findings of this study could be a significant aid in figuring out the proper types and amount of sensory feedback those devices need, and ultimately, enrich the quality of life for amputee patients.

Another example could be various augmented and virtual reality environments with tactile feedback. As suggested by the studies on advanced tactile feedback devices

(Robles-De-La-Torre and Hayward 2001; Drewing and Ernst 2006; Provancher et al. 2005; Wijntjes et al. 2009), recent drastic improvements in computing power has led to more and more electronic devices equipped with tactile feedback capabilities. The results of the current study could contribute to designing the more naturalistic and efficient tactile feedback system that the users could enjoy.

Conclusion

This study attempts to understand how 3D shapes are perceived in the somatosensory system. Systematic examination of the relevant parameters reveals that local perception through a single finger differs from global perception across multiple fingers. While the brain mainly relies on the detailed surface profile of the contacting object when using a single finger, it utilizes the gross angle on the contacted fingers and the distance between them when touching with multiple fingers. Based on these findings, the present study makes, to our best knowledge, the first attempt to show perceptual grouping in tactile shape perception. Additional testing proves that both local and global shape perception in touch is fully modeled by perceptual completion. We conclude that global shape perception involves a completion process filling-in between the multiple contacting fingers, whereas local shape perception entails an interference process from the adjacent non-contacted finger based on the completion model.

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Appendix

The method of subjective magnitude estimate gives subjects the freedom to choose any numeric scale they wish to use. Due to this cross-subject variability in their response scales, it is necessary to compensate for different ranges used by subjects. Our method of normalization is to subtract each subject's grand mean from his or her raw responses and divide them by the range of that subject's response scale. Each subject's grand mean is computed by summing all the raw responses across all trials and dividing by the number of trials. The range of the response scale is the difference between the maximal and minimal raw response values. These steps are depicted in Equations 3 and 4 below.

$$\text{Normalized Responses} = \frac{\text{Raw Responses} - \text{Grand Mean}}{\text{max} - \text{min of Raw Responses}}, \qquad \text{(Equation 3)}$$

$$\text{where Grand Mean} = \frac{\sum All\ Responses}{Total\ Number\ of\ Responses} \qquad \text{(Equation 4)}$$

This method is similar to that of computing the standard Z-scores but with a slight difference. While the Z-score is calculated by dividing by the standard deviation of the data, our method is to divide by the range or width of each subject's response scale. The reason to employ our method is not to make any assumptions about the distribution of raw responses from different subjects.

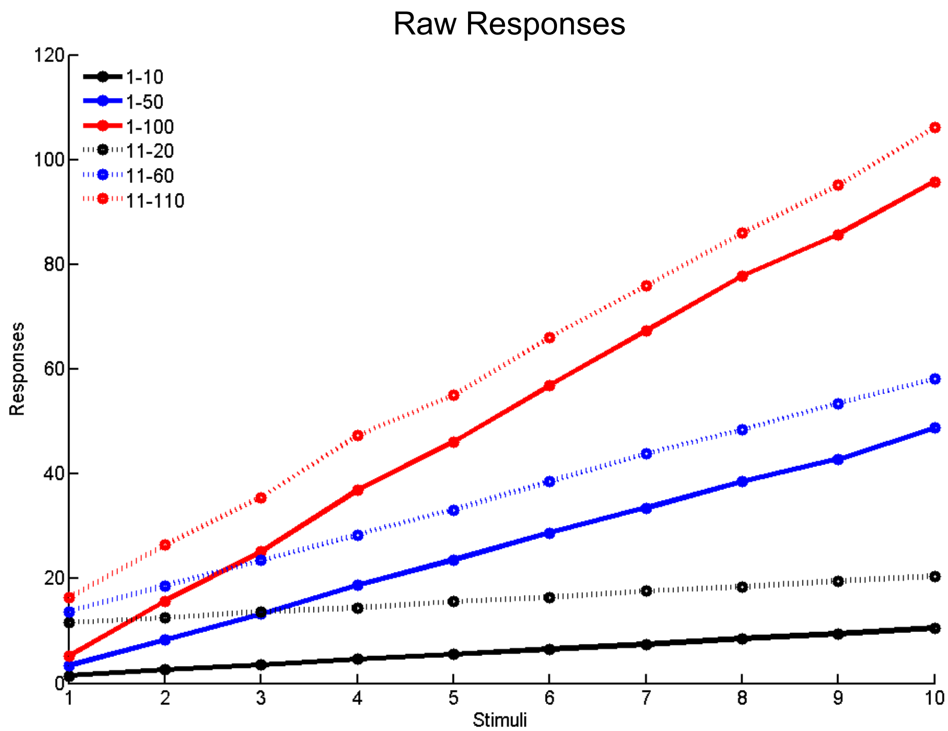

Figure 23. Raw responses of the simulation before any normalization. Responses of six simulated subjects are plotted, whose scales include 1-10, 1-50, 1-100, 11-2-, 11-60, and 11-110. In order to reveal the true perception signal in this raw data, proper normalization is essential.

In order to demonstrate strengths and weaknesses of different normalization techniques, we performed a simulation with different response scales. We created six simulated subjects whose responses mimicked those of real subjects. Their scales were 1-10, 1-50, 1-100, 11-20, 11-60, and 11-110 for the abstract stimuli of 1-10. These raw responses are plotted against the stimuli in Figure 23. The most ideal normalization method would bring all these different ranges onto a single plot, which would be the true signal of stimulus perception. When our method of normalization was applied to these simulated subjects, all the six ranges were brought onto one common plot as shown in Figure 24. This proves that our method of normalization indeed compensates for different means and ranges of responses in subjective magnitude estimate scaling.

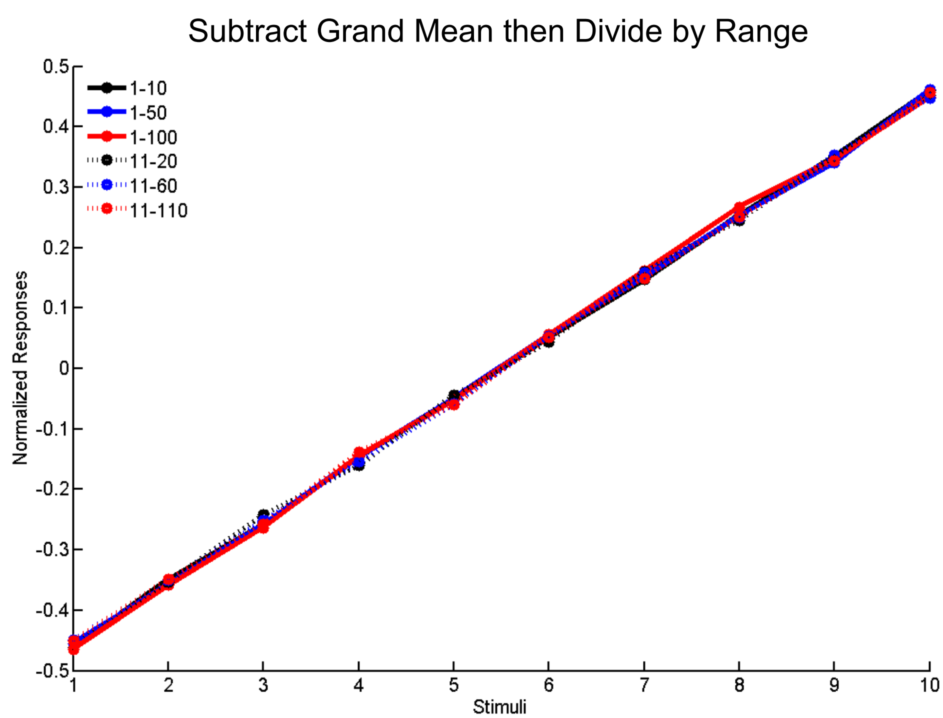

Figure 24. Normalized responses through our method of normalization. Grand mean of each subject is subtracted from his or her raw responses and the responses are divided by the range of his or her numeric scale.

In addition to our method, there were two other ways of normalization that were initially considered but eventually rejected. The first method was simple division by the grand mean for each subject. This is one of the most commonly used normalization methods in other psychophysics studies, including the curvature studies by Goodwin et al. (1991, 1992). The biggest problem with this technique is that it does not correct for various ranges of the scales used by subjects, as shown in Figures 25. Therefore, this method was not applicable to our data set.

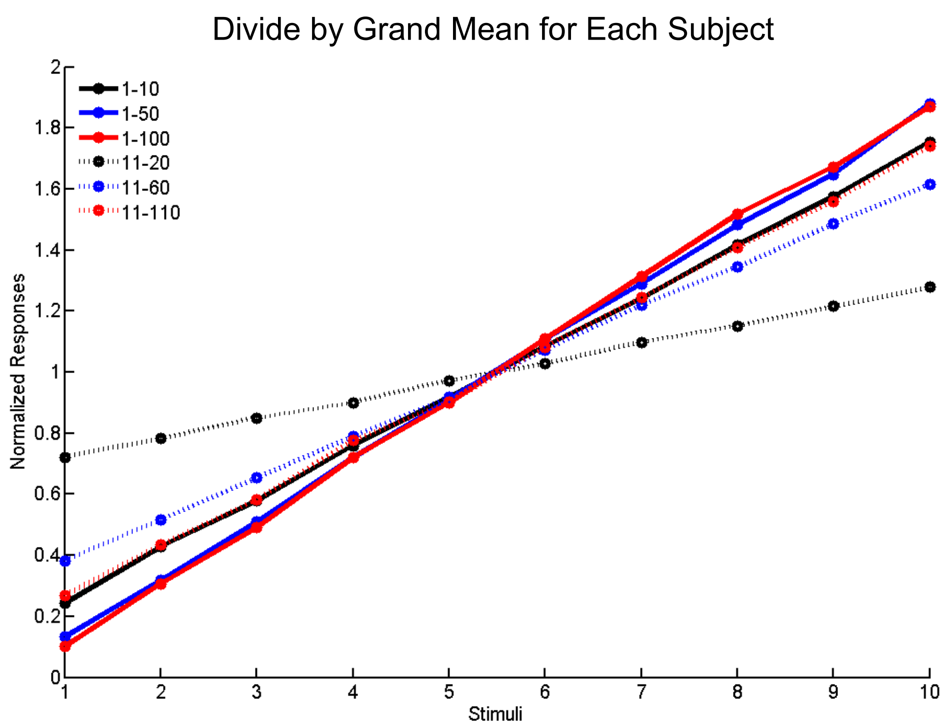

Figure 25. Normalized responses via division. Raw responses are divided by grand mean for each subject. Normalized responses of different scales fail to converge onto one true perception signal across subjects.

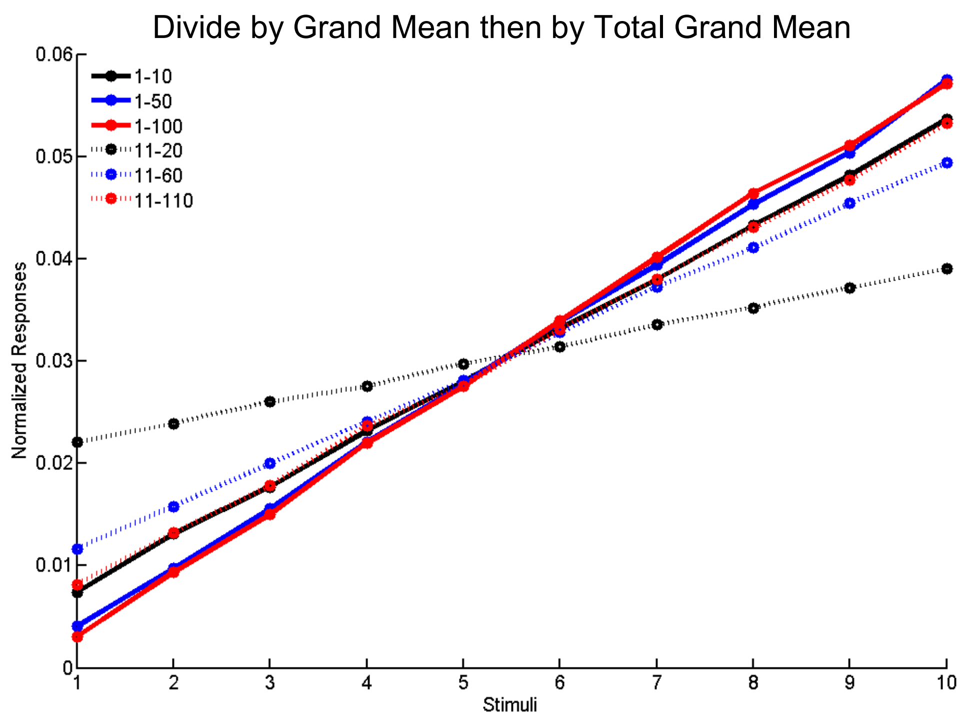

Figure 26. Normalized responses via division by total grand mean. Raw responses are divided by grand mean for each subject, then again by total grand mean across all subjects. This method too fails to remove cross-subject variabilitypresent among the normalized responses.

The last normalization technique considered was to use the total grand mean across all subjects. First, the total grand mean was computed by summing all the responses across all subjects and dividing by the total number of raw responses. The grand mean was also calculated for each subject. Each subject's responses were divided by that subject's grand mean, then, divided again by the total grand mean. This method has also been used by other tactile researchers (Klatzky and Lederman 1999). Similar to Goodwin's method of dividing by each subject's grand mean only, this technique also fails to correct for different ranges of response scales, as shown in Figure 26.

These simulation results confirm that our method of normalization could produce the most reliable normalized data regardless of diverse ranges and means of numeric scales used by different subjects.

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June 2011	Finalist in CIMIT Primary Healthcare Prize
Mar 2008	1st prize in MIT $100K Business Plan Competition
Apr 2007	2nd prize in MoshPit! Business Plan Competition
Mar 2007	1st prize in Hopkins Business Plan Competition
Sep 2006	Design Competition Finalist in EMBS Student Design Competition
May 2006	3rd Prize in JHU BME Instrumentation Competition
May 2005	*Summa Cum Laude* from Bucknell University
May 2005	*Distinguished Academic Achievement* from Bucknell University
2003 – 2005	member and president of Tau Beta Pi in Bucknell University
2001 – 2005	Dean's List in Bucknell University

Publications, peer reviewed:

Cho, Y., Craig, J.C., Hsiao, S.S., Bensmaia, S.J. (under review). "A fair comparison of shape perception in vision and touch." Journal of Neurophysiology

Publications, non-peer reviewed:

Aggarwal, V., Chatterjee, A., **Cho, Y.**, and Cheung, D. (2007) "Ultrasound Guided Measurement of Central Venous Pressure." Encyclopedia of Healthcare Information Systems

Posters and abstracts:

Cho, Y., Kim, S., and Hsiao, S.S. (2011) "Integration of cutaneous and proprioceptive inputs in tactile 3D curvature perception." *Proceedings of the 41st* *annual meeting of the Society for Neuroscience*, Washington D.C., 2011 [41: 385.09]

Cho, Y., Hsiao, S.S., Craig, J.C., Pei, Y.C., Solis, I.M., and Bensmaia, S.J. (2009) "Comparison of complex shape perception in vision and touch." *Proceeding of the 39th annual meeting of the Society for Neuroscience*, Chicago, IL, 2009 [39: 175.4]

Cho, Y., Liang, K., and Thakor, N.V. (2007) "Wireless Temperature Sensing Network Embedded in Cosmesis for Advanced Prostheses." *Proceedings of IEEE International Conference on Rehabilitation Robotics*, Noordwijk, The Netherlands, 2007

Ramos, A., Aggarwal, V., Chatterjee, A., **Cho, Y.**, Rasmussen, R., O'Rourke, B., Acharya, S., and Thakor, N.V. (2007) "Brain-Computer Interface for a Prosthetic Hand Using Local Machine Control and Haptic Feedback." *Proceedings of the IEEE International Conference on Rehabilitation Robotics*, Noordwijk, The Netherlands, 2007

Ramos, A., Aggarwal, V., Chatterjee, A., **Cho, Y.**, Rasmussen, R., O'Rourke, B., Acharya, S., and Thakor, N.V. (2006) "Noninvasive Cortical Control of a Prosthetic Hand with Local Machine Control and Haptic Feedback." *Proceedings of Annual Meeting of Biomedical Engineering Society (BMES)*, Chicago, IL, 2006

Aggarwal, V., Chatterjee, A., **Cho, Y.**, and Cheng, D. (2006) "Ultrasound-guided noninvasive measurement of a patient's central venous pressure." *Proceedings of the 28th IEEE Engineering in Medicine and Biology Society (EMBS)*, New York, NY, 2006

Aggarwal, V., Chatterjee, A., **Cho, Y.**, and Cheng, D. (2006) "Ultrasound-Guided Noninvasive Measurement of Central Venous Pressure." *Proceedings of Annual Meeting of Biomedical Engineering Society (BMES)*, Chicago, IL, 2006

Cho, Y. and Richerson, S. (2005). "Factors that influence detection of small-slip like perturbations." *Proceedings of Annual Meeting of Biomedical Engineering Society (BMES)*, Baltimore, MD, 2005

Service and leadership:

May 2013 – Present	Assistant and sub-instructor of yoga *Community yoga at Highfield*, Baltimore, MD
May 2013 – May 2015	Assistant and sub-instructor of yoga *Yoga for People With Parkinson's*, Timonium, MD
July 2013, June 2014	Teaching Assistant for *Organic Chemistry I and II* Johns Hopkins University
Jan 2012 – Apr 2012	Organizer of public science project *Touch and the Enjoyment of Sculpture* The Walters Art Museum, Baltimore, MD
Sept 2010 – May 2011	Head Teaching Assistant for *Design Team* Johns Hopkins University
Sept 2009 – Aug 2010	Student seminar organizer for PhD student counsel Johns Hopkins University