The Fishbone Tactile Illusion

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ABSTRACT

This paper describes a novel tactile illusion in which a convex and concave shape cannot be distinguished through stroking by the finger tip. The shape consists of a set of parallel flat ridges a few mm wide, separated by a few mm, a fraction of a mm high, and oriented perpendicular to the direction of finger tip motion. A similar central ridge underneath the finger tip is either at the same height as the space between the perpendicular ridges (concave), or raised at the same height as the tops of the perpendicular ridges (convex). We investigated the relationship between (1) the width of the central ridge and (2) the spatial frequency of the ridges. Our results showed that the smaller the size of the central ridge, the easier for subjects to feel an illusory concave shape. Also, the higher the spatial frequency, the more easily subjects could feel a concave shape. This illusion may provide a means for rendering geometric information without creating physical shapes, in both virtual environments and in the real world.

Keywords: tactile illusion, geometric perception, tactile rendering, brightness contrast

1 INTRODUCTION

When we touch an object, we can easily tell the difference between convex and concave surface geometry. This ability comes quite naturally, and tactile sensation usually provides reliable perception. We have found, however, a novel tactile illusion in which a concave shape is perceived even though it is actually a flat surface or a convex shape. The illusion occurs when stroking the finger tip along the smooth central strip between the set of raised ridges shown in Figure 1. It also occurs for flat textures (surface height variation $<< 1$ mm) with a smooth central strip.

Perceptual illusions have been the subject of considerable interest in a variety of sensory modalities, with visual illusions receiving the most attention. Perhaps the oldest report of a tactile illusion is from Aristotle [1]. Recently, several examples of haptic illusions have been presented in the research literature [7] [10] [12], including some that are analogous to visual illusions [9] or that involve the interaction between visual and tactile sensation [3] [4]. Illusion research can contribute to fundamental understanding of the mechanisms by which humans reconstructs the outside world from sensory stimulus. In addition, illusion mechanisms may prove useful in the design of displays or sensors, for example, in designing information compression approaches that minimize perceptual effects.

In this paper we present examples of our illusionary phenomenon, and show the results of sensory experiments for evaluating this illusion quantitatively. In particular, we examine the range of stimulus parameters that successfully evoke the illusion, including ridge height and central strip width. We also describe texture patterns that evoke similar illusory perceptions. We then discuss possible explanations for the illusion, in terms of associations between distributed skin stimulus and inferred surface geometry. Finally, we propose potential applications of this illusion in design of object surfaces and tactile displays.

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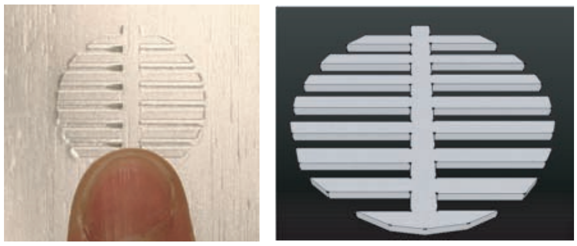

Figure 1: An example of the pattern for inducing an illusionary concave shape. The shape shown on the left is a milled aluminum plate, and the right is a CAD model of this pattern.

2 AN OVERVIEW OF THE ILLUSION

The designation "Fishbone Tactile Illusion" (FTI) derives from the shape of the prototypical stimulus which is most effective in evoking the illusory perception (Figure 1). If a finger tip is freely stroked back and forth along the centerline of the pattern (the fish's "spine"), the adjacent ridges generate strong stimulus to the sides of the finger pad skin. This generates a perception that the center of the pattern is concave, i.e. the central strip is lower than the ridge height, whether this central strip is in fact higher, lower, or the same height as the ridges. This illusion occurs regardless of the scanning direction of the finger; for example, the pattern may be rotated 90 degrees and the finger stroked laterally. In addition, this illusion can be perceived both in passive touch and active touch. For the raised ridge stimulus, the concave perception occurs with both a dry surface or with lubrication.

The illusion also occurs if a smooth central strip is placed between a variety of surfaces that provide cutaneous stimulus. In particular, the lateral surfaces can be rough pattern with small surface height variation, such as fine sandpaper. However, if the central smooth area is too wide, it becomes difficult to feel the illusory indented shape. This suggests that the difference between surface characteristics within the same finger tip contact area is essential for this illusion. In the following section, we present simple psychophysics experiments that examine the dependence of the concave perception on the stimulus parameters.

3 SENSORY EVALUATION EXPERIMETNS

3.1 Experiment 1: Central strip width vs. perceived depth

Methods. A set of aluminum stimulus plates was created using a 3D milling machine (MDX-20, Roland Inc.); one example is shown in Figure 2. The black areas are raised with respect to the white areas by 0.1 mm. Each plate contained two adjacent patterns, one with a central strip the same height as the ridges (shown as black in Figure 2a), and one with a central strip the same height as the inter-ridge spaces (white in Figure 2b). Ridge widths and inter-ridge spacing were 1.3 mm. There were six values for the width of the central smooth area (w=1.3, 2.0, 3.0, 5.0, 8.0, 10.0 mm) for each of the two shapes (a and b) shown in Figure 2.

To assess concave perception as a function of central ridge width, subjects held the test plate in both hands, then actively stroked the central ridges of each pattern with the adjacent thumb. Subjects were asked to select which pattern was concave in a two-alternative forced-choice procedure with unlimited time. Only a single trial was conducted for each pattern to minimize learning effects. Subjects could not see the test plate.

In a subsequent trial, subjects evaluated the depth of the illusory concave perception, using a "reference stimulus plate" shown in Figure 3. This plate had a series of 5 mm wide concave strips machined to a depth of 0.1 mm to 1.5 mm in 0.1mm intervals. Subjects compared the illusory depth of the central strip stimulus plate in Figure 2a to this reference plate by freely stroking both test and reference plates with their right index finger. In both trials, there were seven subjects (five male, two female, ages 22 to 30), all right handed.

Result. Results are shown in Figure 4. At the smallest central strip width (1.3 mm), all subjects chose the illusion as concave in preference to the actual concave pattern. The strength of the illusion decreased as the central strip width increased, with approximately equal responses at 3.0 mm width. Above 5.0 mm width, subjects almost universally chose the actual concave pattern over the illusion. In the depth evaluation trial, where subjects compared the test stimulus to the reference plate, the mean perceived depth was approximately 0.25 mm for widths of 5 mm and less, then decreased to less than 0.1 mm perceived depth for central strip widths of 10 mm. No subject reported a depth greater than 0.4 mm. Following the experiment, we used an ink transfer test to confirm that subjects were able to touch the bottom of each reference groove up to at least 0.5 mm.

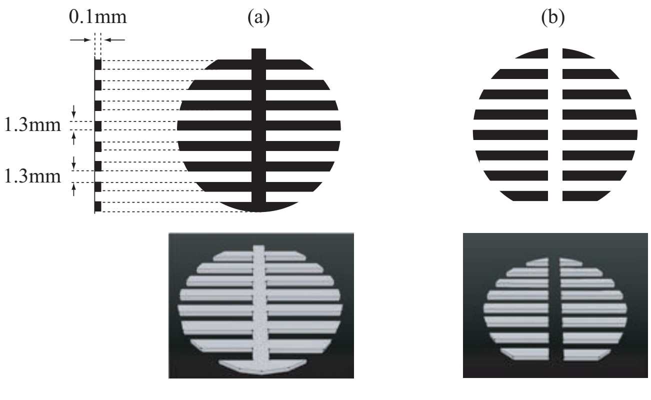

Figure 2: Machined aluminum stimulus plates containing two complementary stimuli and corresponding CAD models. (a) Illusionary concave shape (actual convex shape) (b) Concave shape, reversing the height distribution of (a). Black areas are raised 0.1 mm above white areas.

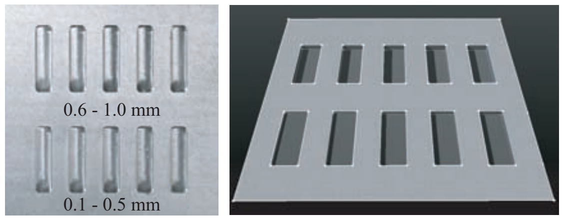

Figure 3: Reference stimulus metal plate and CAD model. The depth increased by 0.1mm in successive grooves. Width of the grooves is 5mm. Subjects compared this reference stimulus and test stimulus sets to evaluate the subjective depth perception.

3.2 Experiment 2: Ridge spatial frequency vs. perceived depth

Method. To investigate how the spatial frequency of the ridges affects the concave illusion, a stimulus consisting of thin cardboard paper, 0.25 mm thick, was incised with a series of cuts (Figure 5). The slits were made with a computer-controlled cutting machine (Design Cutter Stika SX-12, Roland Inc.) to ensure precise positioning. This stimulus was replaced every trial, to eliminate surface wear. Line intervals were 1, 2, 3, 4, 6, 8, 10 mm. The smooth central strip width was 3 mm and the lateral slits were 10 mm wide on each side.

Subjects evaluated the subjective depth of the central smooth strip through comparison with the reference stimulus plate used in the first experiment. To help standardize the velocity of subjects' finger movement, subjects were instructed to synchronize their finger movement with the audio signal from a metronome, so that the entire length of the stimulus pattern was covered between successive metronome beats (tempo 90 beats/min, stimulus length about 40 mm, finger velocity about 60 mm/s). Subjects were allowed to see the pattern to ensure that the fingers remained in the central strip. Five subjects participated (three male, two female, ages 22 to 30).

Results. The result showed that subjective depth amplitude decreased as the distance between stimulus slits increased (Figure 6) for the range of the tested values. The mean subjective depth was around 0.2-0.1mm for line intervals of 1 to 4 mm. For spacing above about 6 mm, stimulus depth was zero for 4 of the 5 subjects and 0.1 mm for the fifth subject. This suggests that at these low spatial frequencies, the stimulus in the lateral areas is not sufficient to create the illusion.

3.3 Other informal tests

In addition to the experiments reported above, we conducted a series of informal tests to further explore the dependence of the illusion on stimulus conditions.

3.3.1 Effect of the height of the smooth surface

We created fishbone pattern test plates with a smooth central strip raised above the ridge heights. The height difference between background and the top of the smooth area was up to 0.3 mm. Subjects still perceived concave geometry with these highly convex surfaces.

3.3.2 Material Difference including temperature difference

To verify that it is possible to create this illusion by simply using materials of different surface properties, we created the examples shown in Figure 7. A 3 mm wide acrylic plate was sandwiched

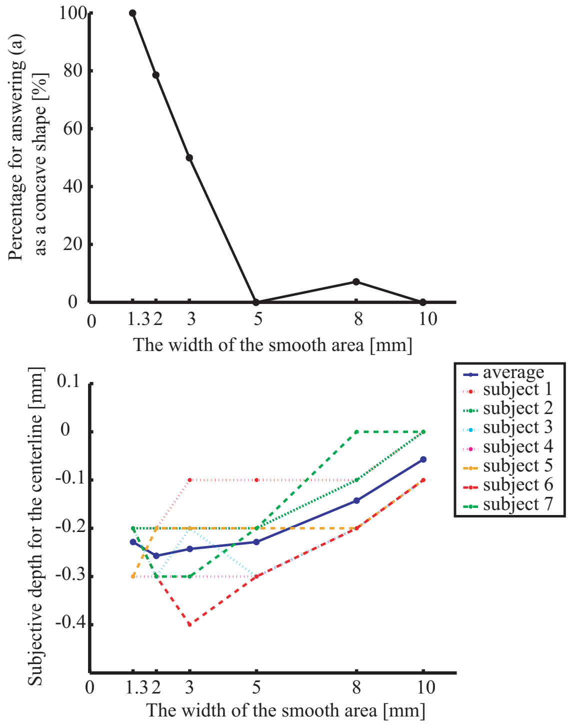

Figure 4: Results of experiment 1. Top: Fraction of subjects choosing the illusionary concave shape in preference to the actual concave shape. Bottom: Subjective depth of the test plate selected by comparison with the reference stimulus plate in Figure 3.

with different kinds of materials (a) synthetic wood (main component is polyurethane); (b) foamed aluminum; and (c) natural wood. The surface of each face was cut flat by using a milling machine. These three materials exhibit three very different ranges in friction when cut, from very low (a) to very high (b). In informal experiments, most subjects felt an indentation in the acrylic plate area when stroking (b) and (c), but no subject reported that (a) felt concave. This correlates with the higher surface roughness of the surrounding material in (b) and (c) compared with (a). In addition, in object (c), the roughness of the surface was slightly different in regions (1) and (2) (see Figure 7), and some subjects reported a perception of an inclined concave shape at the boundary between (1) and (2).

On the other hand, thermal conductivity difference does not appear to generate the illusion. We created the same type of composite object by gluing an acrylic plate between a pair of aluminum bars, which were then machined smooth. No illusion of depth resulted. These materials had very low and approximately equal surface roughness, and it was very difficult to judge by touch whether it was made of one material or two.

3.3.3 Vertical stimulus isolation using a pin matrix

To help to separate the relative contributions of vertical and horizontal skin stimuli in the illusion, we used a passive high density pin matrix [11]. This passive device is composed of steel pins 0.8 mm in diameter with 1.0 mm center-to-center spacing. The pins' movement is constrained by close-tolerance holes in fiberglass boards to allow free movement in the vertical direction and essentially prohibit motion in the vertical direction. Users place the index finger over the top of the pin array and grasp the boards between thumb and middle finger, then stroke the array over the test surface (Figure 8). Each pin samples the height information from the surface pattern and relays it to the finger tip. Under these conditions the concave shape illusion is also produced. As the pin array removes most, if not all, of the lateral stretch from stroking the test pattern directly with the finger tip skin, this suggests that the illusion can be produced through vertical displacement alone. This is further reinforced by the observation that lubrication of the test surface does not eliminate the illusion.

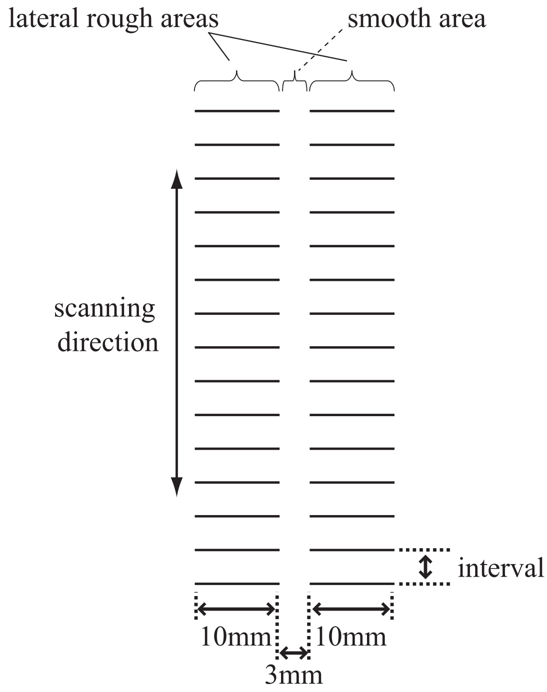

Figure 5: Stimulus pattern in experiment 2. Black lines represent slits in the cardboard substrate (Readers can readily create a concave illusion stimulus from this figure. Please see Appendix).

4 GENERAL DISCUSSION

The results above show that the fishbone tactile illusion is a robust sensory phenomena across a specific range of stimulus parameters. The key requirements appears to be a smooth central region up to a few mm wide with a significant tactile stimulus on either side. The spatial frequency, materials and pin matrix tests suggest that a range of tactile stimuli in the lateral regions are effective in inducing the illusion, as long as the spatial period of stimulation is less than a few mm. Thermal conductivity differences, however, do not appear to produce the illusion.

4.1 Causes of the Fishbone Tactile Illusion

Figure 9 represents the information flow of the sensory signal from the patterned surface to mechanical skin stimulus to neural signal processing to conscious perception. We advance two plausible mechanisms to explain the concave illusion. First, the mechanical deformation of the finger tip may be same for both the concave and convex patterns. This might occur, for example, if the dominant stimulus for the ridged patterns in Figure 2 is from the edges that are perpendicular to the direction of finger tip motion; in this case, both the concave and convex patterns produce the same stimulus. The second mechanism is an association between roughness perception and shape perception, so that the absence of surface rough-

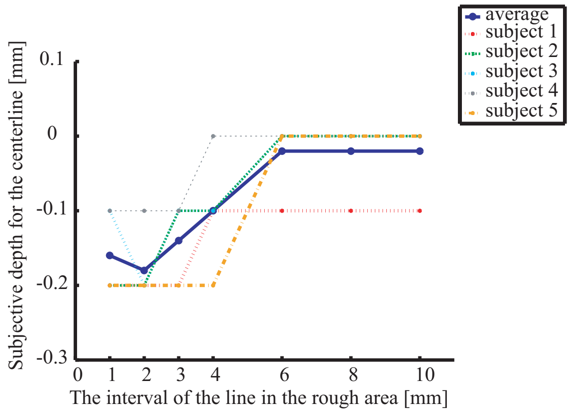

Figure 6: Results of Experiment 2. The smaller the interval between slits (i.e., the higher the spatial frequency), the deeper the illusory perception.

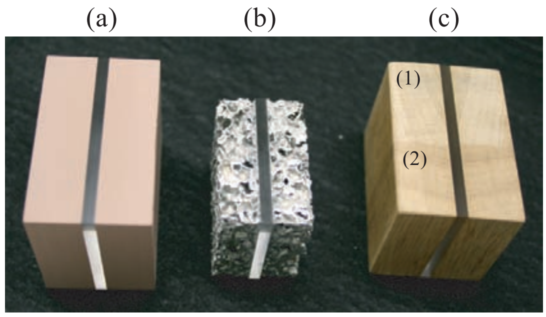

Figure 7: Examples for evaluation of depth illusion surface differences. An acrylic plate (width 3 mm) is sandwiched between (a) synthetic wood; (b) foamed aluminum; and (c) natural wood.

ness is interpreted as the absence of a surface. While the initial experiments presented here cannot definitively establish the basis of the illusion, in the following sections we discuss the evidence for the causal mechanism.

4.1.1 Mechanical deformation

If the mechanical stress patterns within the finger tip skin are identical between the concave and convex fishbone patterns, then they will be perceptually indistinguishable. For the raised fishbone pattern in Figure 2, this is plausible because the leading and trailing edges of the ridges encountered by the finger tip are likely to induce the largest integrated stresses in the skin. The stresses induced by the ends of the ridges adjacent to the smooth central strip are presumably much smaller in magnitude, and are approximately equal for the concave and convex patterns [8]. To help understand the difference between patterns, we conducted preliminary experimental measurements of the finger skin deformation behavior. A microscope and high speed camera (120 frames/s) imaged then finger print deformation as the finger was stroked over concave and convex fishbone patterns machined on a transparent acrylic plate. Analysis of the finger print deformation revealed little difference between the patterns.

There are, however, two problems with mechanical deformation alone as an explanation for the illusion. First, if the perpendicular edges on the surface pattern are the only information used for geometric perception, the result should be the same for various widths of the smooth area in experiment 1 above. In contrast, the experimental results showed a strong variation of perceived depth with central strip width. Second, even if the patterns produce indistinguishable mechanical stimulus, there is no apparent reason why the concave interpretation would dominate the convex perception and not vice versa. This difficulty is further illustrated by the spatial frequency (slit cardboard) and materials experiments above, which showed that distributed surface roughness a fraction of a mm in height was quite effective in producing the illusion. In this case, there was no "true concave" surface as a comparative stimulus, so the universal perception of a concave surface requires another explanation.

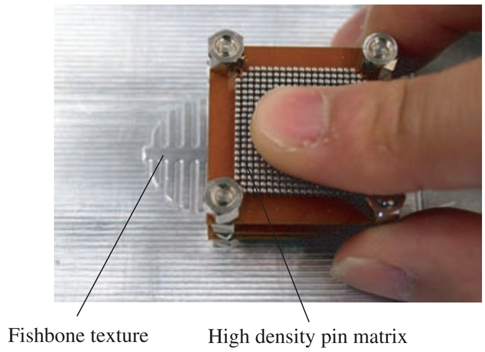

Figure 8: Rubbing fishbone tactile pattern with a high density pin matrix. Stroking the test pattern with a pin matrix, which delivers only vertical height information to fingertip.

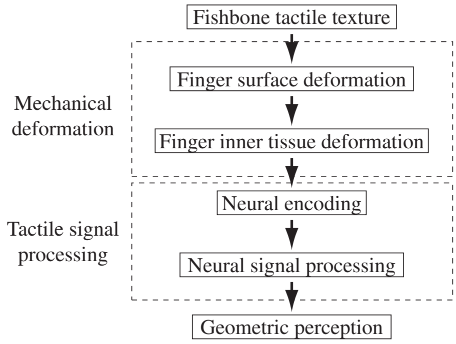

Figure 9: Diagram of information flow for tactile signal. The surface information is transformed into a tactile signal through mechanical interaction with the skin, then the signal is processed in the central nervous system.

4.1.2 Tactile signal processing

The second potential mechanism is based on the processing of the tactile signal in the central nervous system. In particular, tactile stimulus may be interpreted as both confirming the presence of a surface texture and the presence of the surface itself. In other words, the absence of tactile sensations in the smooth central strip and the presence of tactile sensations in the adjacent regions may be interpreted as the absence of a surface in the center, i.e., a concave shape. This association between surface texture and surface shape is presumably based on the observation that flat surfaces typically have the same texture across the entire surface. Therefore the absence of sensation in the central region implies the absence of a surface. This is an interesting argument because it implies that the surface

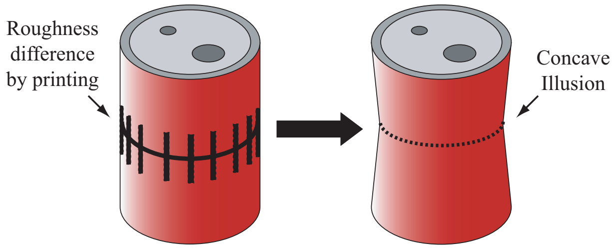

Figure 10: An example of a potential application of the illusion.

geometry may be reconstructed by not only from the stimulus of the local contact area itself but by information from other regions of the contact area as well.

This mechanism is supported by the spatial frequency experiment, where decreasing the slit interval and thus the tactile stimulus decreased the illusion. It also consistent with the dominance of the concave illusion over a potential convex illusion, because both concave and convex fishbone test patterns have smooth central regions that provides little tactile stimulus, and the absence of stimulus can only denote lack of a surface and thus a concave shape. This mechanism requires that the central stimulus is below some threshold. This threshold value may be effected by the relative stimulus magnitudes of the central and lateral regions, so that, for example, the concave illusion persists even for significant central roughness if the lateral region roughness is also high. This scaling of perceived magnitude is observed in other sensory systems, e.g. "brightness (lightness) contrast" in vision [1] [2].

An additional constraint on the illusion is that the difference in the mechanical skin stimulus between the concave and convex patterns cannot be too large, or the central nervous system would presumably detect the difference based on prior experience, and the illusion would fail.

This suggestion that the fishbone tactile illusion is based on a learned association between surface texture and surface shape has analogies in other sensory modalities. One example is the size-weight illusion, where people assume that the size of an object co-varies with its weight. Studies have shown that such visual size-weight cues are not only consciously perceived but are directly used in programming motor commands in manipulation [6]. Another example is proximity-luminance covariance in vision, based on the fact that in many settings, objects appear dimmer and lower contrast as their distance from the viewer increases [5].

4.2 Potential applications

The illusion reported in this paper can produce a virtual concave perception by simply creating a roughness distribution, without creating actual shapes. Therefore, it may be possible to extend the illusion to create useful surface patterns. For example, such a surface might assist in achieving a desired grasp of an object, as illustrated in Figure 10. The users might be induced to configure the finger tips or operate a control in specific ways without verbal or visual instructions. This method may also prove useful for tracking a specific trail on a map, or it may be applied to a surface which must be dragged in a wheel interface. Because of the simplicity of producing the illusion through surface printing with rough inks, it may be possible to add new tactile features to a variety of commercial products.

APPENDIX

The illusionary concave shape can be readily perceived by making a cut paper stimulus as shown in Figure 5. In fact, the figure itself may be printed (preferably on relatively thick paper) and used as a template for cutting the slits with a razor blade or graphics knife. We have also found that some laser printers deposit sufficient toner to allow the illusion by simply stroking the finger along the central strip of the printed pattern.

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