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Passive human touch cannot recognize the shape of a pattern imprinted on the fingertip

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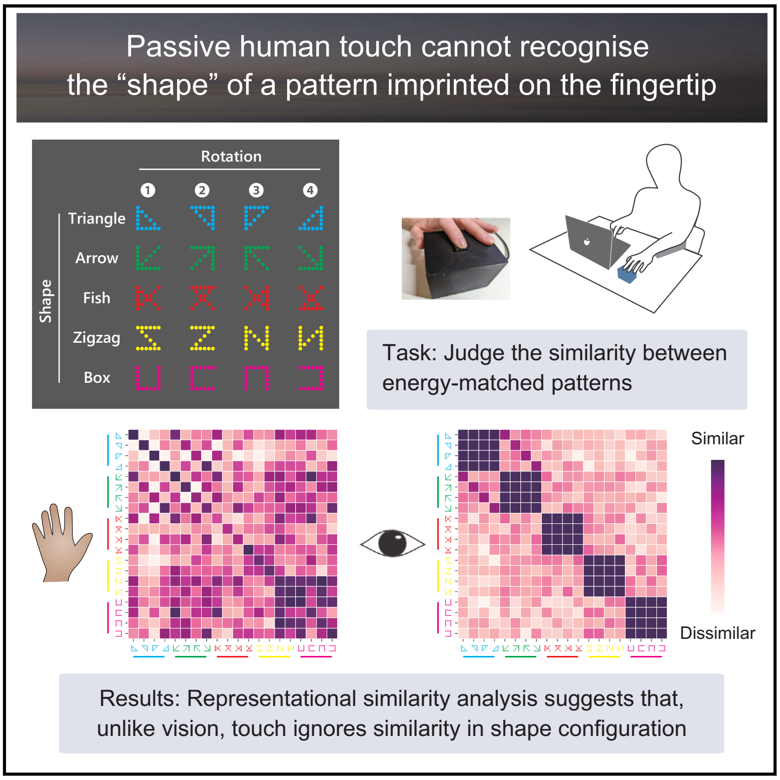
In brief

Social sciences

Graphical abstract



Passive human touch cannot recognise the "shape" of a pattern imprinted on the fingertip

Task: Judge the similarity between energy-matched patterns

Results: Representational similarity analysis suggests that, unlike vision, touch ignores similarity in shape configuration

Highlights

- Passive human touch is poorer at recognizing simple 2D shapes than vision
- The modality difference cannot be ascribed to the spatial resolution of sensing
- Passive touch is insensitive to configuration but sensitive to deformed skin location
- This is a clear limitation to using passive touch as a sensory substitute for vision

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Article

Passive human touch cannot recognize the shape of a pattern imprinted on the fingertip

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SUMMARY

While tactile spatial pattern recognition has been suggested to be qualitatively similar to visual recognition, our study challenges this notion, particularly under passive touch. Previous electrophysiological and behavioral research suggested that the tactile system can process complex spatial patterns in the same way as the visual system and can be modeled as a low-pass version of visual spatial perception. However, we found that when using energy-matched simple patterns, participants were highly dependent on local skin deformation and largely ineffective at distinguishing basic shape features, such as a closed triangle vs. an open arrow, or to discern the similarity of rotated versions of the same shape, regardless of whether they were presented as vibrotactile patterns or braille patterns. This study provides compelling evidence that tactile representation of spatial patterns differs not only in resolution but also in how the brain processes shape features compared to visual representation in standard passive viewing.

INTRODUCTION

Humans can recognize various spatial patterns through touch, ranging from natural objects like strawberry tops to artificial designs like keyboard bumps. Touch holds promise for conveying spatial patterns that aid in navigating and adapting to diverse environments. Additionally, artificial tactile patterns are widely used in sensory substitution systems as a complement or alternative to vision.[1,2] Despite its widespread use in daily life, relatively little is known about the mechanism underlying tactile pattern perception.

How spatial patterns are processed through the skin has often been compared with visual processing through the eyes, another modality that processes spatial patterns. It is widely recognized that the accuracy of spatial pattern processing through touch is inferior to that through vision, but are the two modalities similar otherwise? There have been ongoing debates about the mechanisms underlying spatial pattern processing, with some arguing for similarities and others emphasizing decisive differences.[3–5] Physiological studies have highlighted parallels between visual and tactile systems, such as both having 2D sensor arrays and a gradual establishment of orientation and curvature sensitivity from the periphery to the central nervous system.[3,6–10] Psychophysical studies have also supported these similarities, showing that human observers can read letters of the alphabet presented to the fingertip with similar recognition and confusion rates to visual character reading.[11–13] Indeed, Loomis[13] suggested that tactile shape processing could be modeled as a low-pass version of visual shape processing. However, studies in different contexts have shown discrepancies between the two modalities.[4,14–17] Identifying abstract 2D shapes using active finger movements has been shown to become markedly more challenging when the stimulus is rotated,[4,15] a tendency that has not been associated with visual shape perception. Additionally, sensitivity to spatial texture shows differences between touch and vision with regard to the degree of sensitivity to higher-order statistical features.[18]

One important factor that should be considered in the study of tactile pattern perception mechanisms is how participants gather tactile information. A participant touching an object while making voluntary hand movements is called active touch, while a participant touching an object without making any voluntary movements is called passive touch. Although some reports suggest that these two types of touch are equivalent in terms of the resulting perceptual abilities e.g.,[19] there remain significant differences in the source of the associated sensory system that is involved in each type of touch and how the information received is processed. Active touch, where participants move their hands to scan patterns, is the most natural and well-studied method,[4,15,20] but it incorporates not only spatial information from skin deformation patterns but also information from finger position tracking via efference copy and proprioceptive feedback, which moves the task beyond the purely spatial realm. Consequently, it is potentially problematic to compare behavioral performance obtained

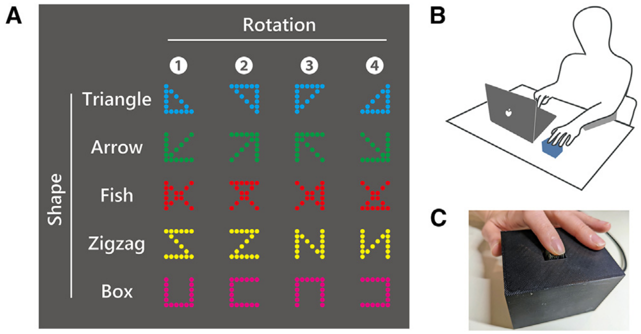

Figure 1. Experimental stimuli and setup

(A) A set of 20 spatial patterns. Stimuli were presented in 1 cm squares as tactile stimuli and visual stimuli.

(B) View of the setup used in the experiments. The blue box represents the stimulator.

(C) The stimulator used to present tactile stimuli.

via active touch with that obtained via standard passive viewing[21–25] or with neurophysiological tactile responses measured under passive touch. Thus, this study focuses on identifying the characteristics of one-shot tactile spatial pattern recognition primarily under static (passive) touch conditions.

Another complicating factor is the inherent complexity of defining shape. Tactile 2D patterns can be characterized by multiple cues and features such as spatial frequency, energy, number of lines, curvatures, and textures. To evaluate the fundamental level of ability in 2D pattern perception, here we examined the discrimination of fingertip-sized patterns consisting of three-line segments (Figure 1A). This stimulus set serves to elucidate purely spatial haptic shape perception with minimal influence from prior knowledge or familiarity (cf. alphabet letters). We systematically varied the spatial arrangement of lines to create differences in edges, corners, and overall configuration while keeping the number of lines and energy constant. For instance, configuration differences, such as those between a closed triangle and an open arrow, are known to be easily distinguishable by the human visual system.[24]

In our experiments, we directly compared perceptual representations in tactile 2D pattern perception—where stimuli were imprinted as skin deformations (without finger movement)—with visual 2D pattern perception based on retinal image (without eye movement). Our main interest was in the qualitative representational differences between the modalities, not the absolute performance differences. Our working hypothesis was that tactile shape perception lacks sensitivity to some pivotal features that visual shape perception captures well, in a way that is comparable to the disparity observed between tactile and visual perception in texture perception.[18] To induce a clear experience of tactile patterns within a brief stimulation period, the patterns were presented as vibrotactile stimuli delivered through an arrayed-type tactile stimulator (Figures 1B and 1C), which also functions as a braille display.[26,27] The visual patterns were presented as static images on a computer screen. Despite the ease with which vision discerns configuration differences, tactile perception struggled to distinguish these differences or recognize the similarity of rotated versions of the same shape. The observed representational similarity matrices (RSMs) indicate that tactile spatial pattern perception is sensitive to the locations of skin deformations but not to orientation or configuration. To explore the limitations of human ability more thoroughly, we assessed pattern identification ability between four closed triangles and four open arrows using printed dot (braille) patterns alongside vibrotactile patterns. We found that participants were more likely to confuse differing patterns presented at the same location than patterns with the same configuration presented in different orientations. This divergence between modalities underscores the unique characteristics of tactile perception and challenges conventional sensory substitution systems that simply translate visual patterns into tactile formats by changing the resolution.

RESULTS

Visual and tactile perceived shape

In the first experiment, two randomly selected spatial patterns were briefly and sequentially presented, and participants were asked to rate the similarity of the two patterns in terms of their shape. Twenty patterns were tested, each consisting of a combination of vertical, horizontal, and diagonal line segments (Figure 1A). A group of ten participants completed 400 trials for each of three conditions: V-V (comparing two visual shapes), T-T (comparing two tactile shapes), T-V (comparing a tactile shape presented first with a visual shape presented second). Both visual and tactile stimuli were presented within a 1 cm square area.

Figure 2A shows histograms of the reported similarity scores. When the same patterns were paired (black bars), the reported similarity rating score was high in visual (V-V) and tactile (T-T) conditions while slightly lower in the tactile-visual (T-V) condition. However, when different shapes were paired (white bars), the distribution of reported scores was different for V-V and T-T. We calculated the mean difference of that distribution between pairs of the same pattern (black in Figure 2A) and pairs of different shapes (white) as an index of task difficulty. Although this index varied depending on the conditions (6.2 for V-V, 1.5 for T-T, and 1.1 for T-V), there were statistical differences between the black and white distributions (i.e., the difficulty index was larger than 0) under all conditions ($p < 0.01$). This suggests that participants were reasonably committed to the task. Note that we are not interested in the absolute performance differences, but in the qualitative representation differences between modalities. In order to look at this, we computed RSMs. Intersubject consistency correlations were significantly above zero, supporting the conclusion that participants' responses were neither completely independent nor random: Pearson's $r = 0.85$, 95% CI [0.65, 0.95] for V-V; $r = 0.39$, CI [0.066, 0.54] for T-T; and $r = 0.23$, CI [0.052, 0.38] for T-V (see detail in STAR Methods section).

As clearly shown in Figure 2B, the RSMs showed different patterns for different conditions: the correlations obtained between V-V and T-T were not significant for the off-diagonal values (Figure 2C: $r = 0.012$; $p > 0.1$, n.s.; CI includes zero). This is in apparent contradiction to previous findings showing a high

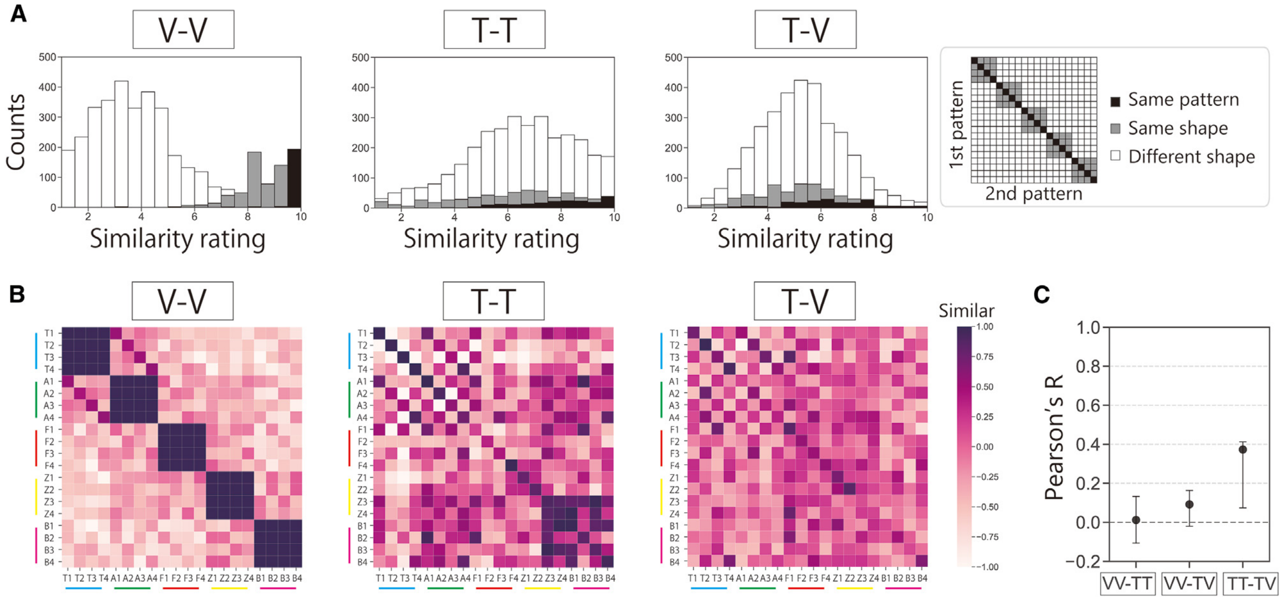

Figure 2. Similarity judgments between energy-matched patterns

(A) Histograms of raw similarity ratings for all participants, color-coded for cases where the compared patterns were the same, in the same shape group, or in different shape groups. A rating of 10 means exactly the same shape, and 1 means completely different.

(B) Characterizing behavioral data by representational similarity structure. Representational similarity matrices (RSMs) are very different between touch and vision. Panels show Z-scores of all pairs of similarity ratings averaged across participants for each of the V-V (comparing two visual shapes), T-T (comparing two tactile shapes), T-V (comparing tactile and visual shapes) conditions. For V-V and T-T conditions, results for the same stimulus pairs were averaged, irrespective of the order of stimulus presentation. For the T-V condition, the vertical axis represents the tactile stimulus presented first and the horizontal axis represents the visual stimulus presented second.

(C) Correlation between off-diagonal values of RSMs. Dots represent the mean and error bars represent 95% CI.

correlation in stimulus reading between vision and touch (approximately 0.4–0.8) when raised letters or braille patterns were actively explored[13] or statically touched.[28] In the V-V condition, the reported similarity was markedly higher when comparing the same patterns with the same or similar configuration, which seems to reflect the configuration sensitivity of the visual system (see detailed discussion in the next section). Meanwhile, such response patterns were not found in the T-T condition. When averaged over the same configuration, it was found that some shapes, such as the box, were rated as similar while some, such as the triangle, were not. Additionally, when participants were asked to compare the perceived tactile shape image with the visual one (T-V), the observed RSM was not similar to that for the visual condition (Figure 2C: r = 0.092, p = 0.07, n.s. for T-V and V-V for the off-diagonal values). Notably, however, the observed RSM was correlated with that of the tactile condition (Figure 2C: r = 0.37, p < 0.001 for T-V and T-T for the off-diagonal values; 95% CI is above zero), supporting the conclusion that participants' responses were not completely random.

Comparing representational similarity with simple models

To gain further insight into the mechanism underlying tactile shape perception, we compared the measured RSMs with the theoretical RSMs for three models. In each model the pattern similarity was computed based on the pixel distribution similarity, orientation histogram similarity, and configuration similarity of the two presented patterns, respectively (Figure 3A). Figure 3B shows the correlation value between the behavioral RSMs and the model RSMs. The results for the V-V condition showed positive correlations (CI does not overlap with 0) with all three models, with the highest correlation occurring with the configuration model (CI does not overlap with other conditions). On the other hand, the T-T and T-V conditions showed positive correlations only with the pixel model. An aligned rank transform (ART) ANOVA demonstrated that the effects of modalities (i.e., V-V, T-T, and T-V), model, and their interaction were significant (modality: F(2, 72) = 75.9, p < 0.0001; model: F(2, 72) = 10.8, p < 0.0001; interaction: F(2, 72) = 25.7, p < 0.0001). Post-hoc pairwise comparisons with Bonferroni correction showed a significant difference between V-V and the other two conditions (p < 0.0001). These results suggest that tactile shape perception is different from visual shape perception in the sense that it does not feature a sensitivity to the orientation and configuration of the compared spatial patterns.

As a control condition to check the effect of the higher spatial resolution of vision, a visual experiment was also conducted using stimuli with 1 mm square dimensions, which had almost the same perceptual scale between modalities. The results obtained were consistent with those obtained with 1-cm squares, and are provided in the supplemental information (Figure S1).

Thus far, we had found notable dissimilarities in shape representations between touch and vision. Still, some issues needed

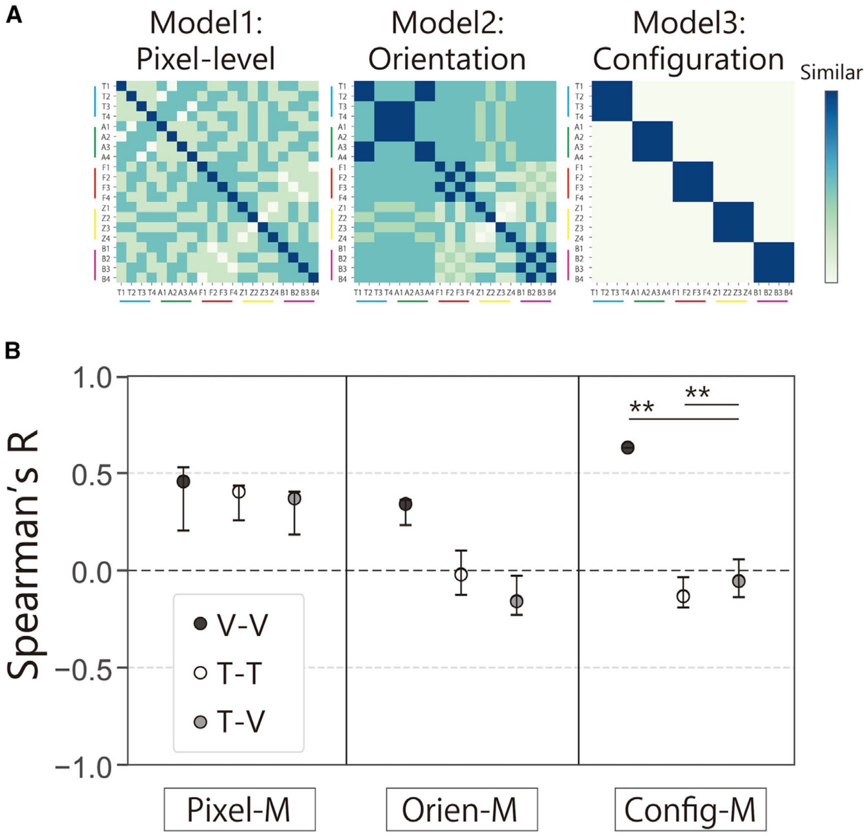

Figure 3. Representational similarity analysis between models and behavioral data

Comparing RSMs using representative models revealed a clear dissociation between visual shape perception and the other two tactile shape perceptions.

(A) RSMs calculated from the theoretical value of the three models. Each model represents pixel-level, orientation-level, and configuration-level matching of compared shapes.

(B) Spearman's rank correlation values between off-diagonal RSM of each stimulus presentation condition and that of each model. Error bars represent 95% CI. Asterisks represent significant differences at $p < 0.0001$ (Bonferroni-corrected).

to be further investigated, leading to changes in the methods adopted in the next experiment. Given that human observers can read tactually presented alphabet characters through touch,[12,29] and the performance of such tactile character recognition closely resembles visual character recognition,[13,14,30,31] one may speculate that the observed difference between touch and vision in experiment 1 could be specific to the stimulator we used (i.e., the vibrotactile pattern). If so, the results would be different when the shape was presented by a static object, such as a printed braille pattern, rather than by vibration. To address this issue, in experiment 2, we used physically printed spatial patterns made of braille-like dots, in addition to using the same stimulator employed in experiment 1 (referred to below as the vibration condition). Braille can be read in two ways: transcribing the pattern to create skin deformation without moving the finger laterally (spatial pattern recognition with passive touch, which we refer to below as the braille static condition) and scanning the pattern with the finger (spatiotemporal pattern recognition with active touch, which we refer to below as the braille active condition). We conducted experiment 2 not only in passive mode, but also in scanning mode, since the latter mode is also commonly used in real-life braille reading. This procedure allowed us to see the possible difference between passive touch and active touch. Finally, to address the issue of task generality and to directly measure the limitations of the tactile system in pattern identification, experiment 2 involved an identification task rather than similarity judgments as an objective quantification.

Tactile shape identification

In experiment 2, one of eight patterns with particularly similar configurations (Triangle and Arrow configurations in Figure 1A) was presented, and participants were asked to identify the perceived pattern from among eight candidates that were visually presented to them. In the vibration condition, tactile patterns were presented using the same stimulator employed in experiment 1. In the braille static and braille active conditions, tactile patterns were presented using physically printed shapes made of braille-like dots.

Overall, we found that the effect of the method difference on shape recognition was minor. The response pattern of the presented and reported pattern is shown as a confusion matrix in Figure 4A. Here, data exhibited moderate variability across participants. The correlations of results within the same condition were similar when participants were passively exposed to the pattern stimuli (r = 0.62, CI [0.25, 0.87] for the vibration condition; r = 0.63, CI [0.02, 0.85] for the braille static condition), and were lower compared to when participants moved their finger over the stimuli (r = 0.85, [0.44, 0.97] for the braille active condition).

First, we calculated the correct rate of the task (Figure 4C). The presented pattern was correctly identified above the level of chance, but this was only true for less than half of the trials (0.5) with static touch regardless of the stimulus presentation methods (Figure 4C, left two bars). The accuracy increased with active touch but was far from perfect (Figure 4C, right bar). A Friedman test indicated a significant difference among presentation conditions ($\chi(2) = 15.6$, $p < 0.001$). Pairwise Wilcoxon signed-rank tests showed that the active touch condition is significantly better than the other two conditions ($p < 0.01$). Next, by treating these confusion matrices as RSMs, we examined the representational similarity between the conditions. When the correlation values of the off-diagonal RSMs between stimulus conditions were calculated as a measure of the similarity of results across conditions, the correlation value of the RSMs was around 0.5 with a CI greater than 0 (Figure 4D), indicating that participants' responses were similar between all these conditions. Then, representational

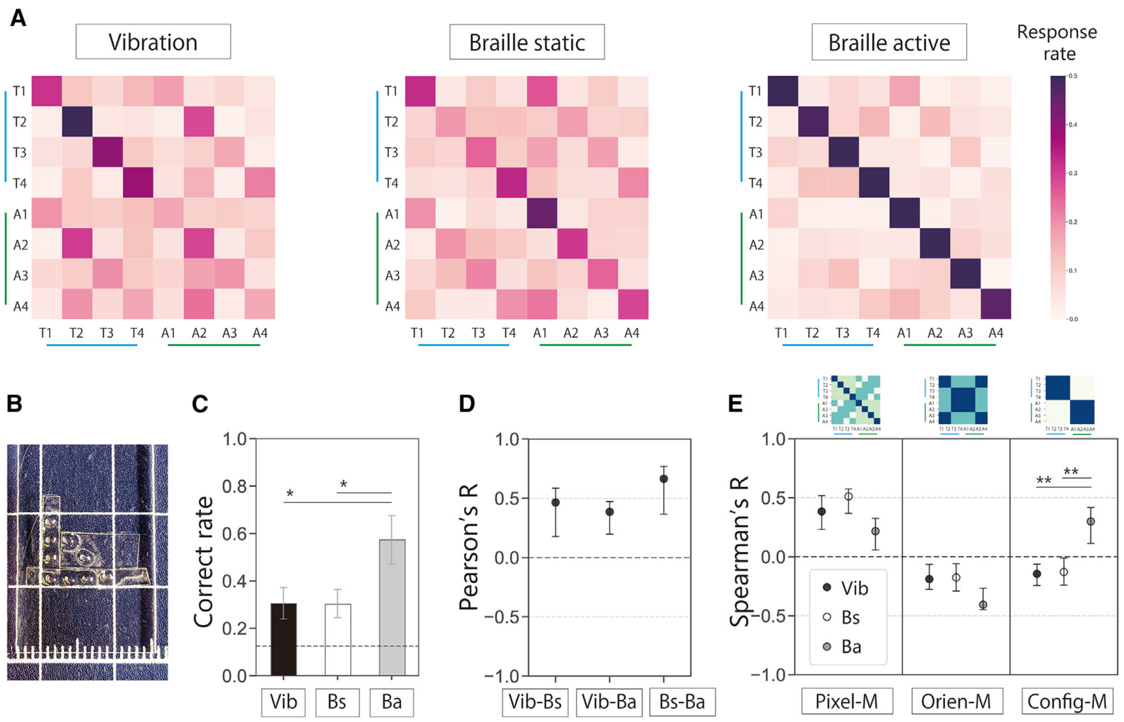

Figure 4. Tactile pattern identification with three presentation modes

(A) Confusion matrices when the stimuli were presented by the vibrotactile stimulator (Vib), static braille patterns (Bs), or braille patterns that were scanned with finger movements (Ba).

(B) An example of a physically printed dot pattern used in braille conditions. Transparent plastic seals, printed by a braille printer, attached to an acrylic plate.

(C) Pattern identification accuracies. The dotted line represents chance level. Asterisks represent significant differences at $p < 0.001$. Error bars represent 95% CI.

(D) Correlation between off-diagonal values of confusion matrices.

(E) Representational similarity analysis with representative models (equivalent to the upper 8x8 matrix in the RSMs for models in Figure 3A) supports similarity in tactile shape perception under static touch conditions (Vib and Bs), with some correlation with pixel-matching and the orientation-histogram model and no correlation with the configuration sensitivity model. Spearman's rank correlation values between off-diagonal confusion matrices of each stimulus presentation condition and RSM of each model. Asterisks represent significant differences at $p < 0.0001$.

similarity analysis was conducted between the behavioral data and representative models (Figure 4E). For the passive conditions (the vibration and braille static conditions), similarity was observed with the pixel model (CI greater than 0), but not with the orientation or configuration model. In other words, participants used local skin deformation sites, rather than shape configuration for the shape identification task, regardless of whether the shape was presented via vibration from a stimulator or surface patterns of braille. This is consistent with the representational similarity analysis in T-T and T-V conditions in experiment 1. For the braille active condition, the observed trend was different from that of the other conditions: similarity was observed with the configuration model, in addition to the pixel model. An ART ANOVA showed that, in addition to the model (F(2, 104) = 69.3, $p < 0.0001$), the interaction between the presentation condition and model had a significant effect on the correlation values (F(4, 104) = 10.0, $p < 0.0001$). Post-hoc tests revealed significant differences in the levels of the presentation conditions, with the active touch condition being significantly different from the other two conditions in the configuration model ($p < 0.001$). In other words, there were no significant differences between the vibration and static touch conditions at either model level.

DISCUSSION

There has been considerable debate as to whether the mechanisms underlying tactile shape perception are similar to those underlying visual shape perception[7,9–13,28] or not.[4,14–17] To clarify the nature of tactile shape perception under conditions comparable to visual shape perception, we examined human ability to recognize simple patterns consisting of three-line segments by passive touch with a fingertip. The first experiment allowed us to estimate a RSM by comparing pairwise similarity judgments among 20 patterns in five shape groups, within vision or touch, or between the two modalities. Tactile patterns were presented as vibrotactile stimuli delivered through an arrayed tactile stimulator, while visual patterns were presented on a monitor; both presentations lasted less than 1 s. In conditions including tactile presentation, we found low perceptual similarity among patterns in the same shape group: it was hard for participants to discern, by touch, fundamental shape differences, such as a closed triangle vs. an open arrow, or to find, by touch, the similarity of rotated versions of the same shape. Using RSMs, we compared behavioral data with model predictions and revealed that the tactile system prioritizes localized skin deformation cues over shape configurations and other statistical attributes (e.g., the distribution of oriented line segments, terminators, corners, intersections, etc.) to which the visual system is highly sensitive.[21–25] To investigate the influence of stimulus presentation methods on tactile pattern processing, we conducted a second experiment using physically printed patterns resembling braille dots, in addition to the stimulator used in experiment 1. We found that methodological differences had little impact: whether patterns were presented by pin vibrations or surface bumps, participants could not identify patterns with high accuracy, relying mainly on local skin deformation rather than spatial configuration. Pattern identification was poor in the passive touch condition, regardless of the presentation method, compared to the active touch condition, highlighting the limitations of spatial processing with passive touch. In summary, the study provides convincing evidence that the tactile representation of spatial patterns passively sensed by the fingertip differs not only in resolution but also in the participant's ability to recognize the same shape features from the visual representation obtained through standard passive viewing.

To the best of our knowledge, the present study provides the most convincing evidence yet for the surprisingly poor shape recognition ability of passive tactile perception. In agreement with our findings, Miller[4] and Ballesteros[15] reported that haptical judgment of shape identity between rotated patterns was difficult. The methods they used, however, differed from ours in two important ways. First, their stimuli were more complex and mutually similar in shape than ours. This made their task significantly harder than ours. Second, their stimuli were larger in size than a fingertip, and the participants were allowed to actively explore the stimulus to judge the shape.

One may point out that humans can recognize spatial patterns by touch in some cases, in apparent contradiction with our findings. For example, past studies have shown that humans can recognize alphabet letters or braille characters with similar recognition and confusion rates to visual reading, when the stimulus size relative to the resolution is matched between the modalities.[11–14,28] Moreover, it is well known that experienced individuals can read braille characters remarkably well. However, we don't consider these facts to be contradictory to our findings. Characters are intentionally designed to be distinct in terms of low-level features (e.g., the number of dots), making them easy to distinguish. (In the case of the braille version of the English alphabet, the number of dots for each letter varied between one and five, only four/five out of 325 pairs of the 26 letters are horizontal/vertical reversed pairs. In fact, reversed pairs are more likely confused with each other than other pairs.[13]) The tactile system can utilize the difference in lower-order surface statistics[18] to discriminate most of the characters. In contrast, the stimuli used in our study were matched in low-level features (all consisting of three segments, resulting in a roughly similar number of actuator pins or printed dots), forcing the tactile system to rely on higher-order shape features for differentiation. Furthermore, the previous studies with untrained observers used stimuli slightly larger than the fingertip, which required participants to make circular finger movements over the patterns,[17] but see also in the study by Phillips et al.[28] This allowed participants to capture shape information as spatiotemporal patterns through dynamic finger tracking. Therefore, we believe that the ability of experienced individuals to read tactile characters does not contradict our conjecture about the computational limitations of one-shot, purely spatial shape processing by touch.

In favor of our findings, previous studies have reported various disabilities in tactile spatial processing. For example, Kuroki et al.,[18] demonstrated limitations in texture discrimination: participants had difficulty discriminating between two textures with similar amplitude spectra, which indicates that the tactile system had difficulty computing the correlation of nearby spatial frequencies/orientations. Limitations in spatial segmentation of multiple stimuli have also been reported: participants had difficulty reporting which part of the body (e.g., which finger) the target stimulus was presented to when multiple stimuli were presented simultaneously, where the target is defined by a difference in frequency,[32–34] texture,[35] spatial pattern,[17,33,36,37] motion,[18,33,38,39] timing,[40] or temperature.[41,42] The tactile system cannot spatially segment multiple signals, while the visual system can easily do so.

To be more precise, the spatial processing of the tactile system is poorer than that of the visual processing system when central foveal visual processing is considered. The spatial processing of the visual system deteriorates with retinal eccentricity. In peripheral vision, not only is the spatial resolution lowered, but the crowding effect significantly impairs complex spatial pattern segregation and recognition.[43] The characteristics of tactile spatial processing are qualitatively similar to those of visual processing under the crowding effect. It is possible that tactile spatial processing at the fingertip, where spatial resolution is the highest or nearly so, is functionally similar to spatial processing in peripheral vision.

While there are well-established parallels in neural representation and processing between the visual and tactile systems at the peripheral nerve and early cortical levels,[3,8] our results highlight the limitations of similarities in shape processing between touch and vision. For example, neurons in the primary somatosensory area have receptive fields with spatial structures similar to those observed in V1, and neurons in a higher somatosensory area (SII) show tuning for curvature magnitude and direction, similar to properties found in V4 for vision.[10] Still, how these neural activities are utilized in the brain remains unclear, and they do not ensure performance in solving our task. The main implication of our study is that despite analogous neural structures between vision and touch, the behavioral outcomes are significantly different. Although previous behavioral studies have shown that humans can discriminate differences in orientation and curvature,[44–47] this may be explained by sensitivity to somatotopic locations—where the deformation occurs on the skin—rather than by sensitivity to the overall configuration of shapes, and is not inconsistent with our findings that passive touch struggles with shape discrimination when spatial configuration is the only distinguishing factor. For example, the triangle and arrow shapes in experiment 2 had the same number of 45- and 90-degree angles, but differed only in their spatial arrangement. In addition, our stimuli with multiple lines in a small area likely induced a strong crowding effect. Taken together with previous studies, our results highlight the difficulty human observers have in recognizing tactile spatial patterns, even when some bottom-up spatial neural information is available.

In the second experiment, in addition to the passive touch condition, we also tested an active touch condition in which participants moved their hands to scan the surface patterns and found a hint of configuration sensitivity. Note that this is not contradictory to the past tactile letter recognition studies that found a great deal of similarity between passive and active touch for discerning alphabet letters.[29] Unlike in our study, passive touch in these studies was not purely spatial, since the stimuli were passively scanned under a finger of each participant's hand (but see also in the study by Phillips et al.[28]). The difference between active touch and passive touch could be attributed to various differences, such as those in the input signal, existence of motor signal, exploratory mode, and resulting perception.[20,48–52] It can be assumed that, at least in the case of active touch, shape is processed using a different strategy from standard visual processing. Note that even with active exploration, the improvement in pattern identification is limited, and rotation-invariant coding of tactile shape is not always supported,[4,15] as noted previously. It remains an interesting direction for future studies to determine the limits of tactile shape perception during active exploration and how different methods affect sensitivity to shape features. Notably, haptic 3D object recognition involving detailed hand manipulation achieves accuracy comparable to vision, despite significant differences in the way information is acquired and processed.[53–55]

Our findings, which reveal qualitative differences—beyond those merely related to resolution—between visual and tactile spatial pattern processing, have important implications for the design of future sensory substitution and tactile communication systems. It is worth noting that much previous research has reported on the excellent spatial abilities of the sense of touch in a situation where there is no crowding. For example, touch can detect tiny, invisible irregularities on very smooth surfaces[56] and discriminate orientation differences on the scale of individual fingerprint ridges.[45] Thanks to these abilities, we are good at selecting appropriate materials and dexterously manipulating objects while skillfully sensing and adapting to situations. Meanwhile, our research has shown the limitations of tactile spatial pattern perception under the crowding effect: it was hard for touch, while very easy for vision, to discern fundamental shape differences, such as a closed triangle vs. an open arrow. Touch is sensitive to the locations of skin deformations but not to what one would call *shape* information. In any case, tactile spatial perception is not a low-pass version of visual spatial perception. Active touch appears to be crucial for acquiring configuration information, highlighting the dominance of temporal processing over spatial processing in touch. Furthermore, achieving vision-like pattern recognition remains challenging even with active spatiotemporal processing in touch. These findings underscore the limitations of conventional tactile substitution systems that merely convert visual 2D patterns into tactile ones, while also shedding light on the intricate nature of human spatial pattern perception.

Limitations of the study

We concluded that the tactile system is insensitive to configuration information. However, the participants in our experiments were all sighted and had no special training in tactile pattern recognition. The present results, therefore, cannot rule out the possibility that extensive training may significantly change the pattern of results. In the future, we would like to conduct similar tests with blind participants who are experts in reading braille.

While we have found a clear difference in behavioral performance between touch and vision, the underlying neural mechanisms remain elusive. While certain physiological parallels between the visual and tactile systems are well documented,[3,6–10] it remains unclear where and how the difference between them arises. Neuroimaging or electrophysiological approaches could provide valuable insights into this question.

Compared to the advanced computational and neural modeling of visual processing, the modeling of tactile processing has lagged behind, with the exception of the modeling of the peripheral neural response.[57] There is currently no widely accepted framework capable of predicting tactile metamers, discrimination thresholds, and perceptual similarity. The development of such a model will be crucial in linking neural activity to behavior, ultimately providing a more comprehensive understanding of tactile perception and its relationship to vision.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Scinob Kuroki (scinob@gmail.com).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- The data have been deposited on Open Science Framework. The DOI is listed in the key resources table.
- This study did not generate unique codes.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

Conceptualization: S.K. and S.N.; methodology: S.K., T.H., H.K., and S.N.; data curation: S.K.; formal analysis: S.K.; visualization: S.K. and T.H.; writing—original draft preparation: S.K. and S.N.; writing—review and editing: S.K., T.H., H.K., and S.N.; funding acquisition: S.N.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Raw data	This study	https://osf.io/us5rm/

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

A total of 34 naïve participants (14 females; aged 20-37 years, mean age 23.7±4.28; all right-handed; all Asians) were recruited from a staffing agency to perform a psychophysical experiment lasting approximately four hours (including breaks) and were paid. All participants had normal tactile sensitivity (based on their self-report) and normal or corrected-to-normal vision. Three groups of ten participants took part in each of the three conditions of Experiment 1. Different groups of 14 participants took part in all conditions in Experiment 2. Some participants took part in more than one condition or experiment. We determined this sample size based on previous studies of tactile perception that used fingertip stimulation with similar stimuli.[4,18,32,33,58,59] All participants gave their written informed consent to participate. The NTT Ethics Committee approved the recruitment of the participants and the experimental procedures, which were conducted under ethical standards that have their origin in the Declaration of Helsinki (2008). (Approval number: R02-001).

METHOD DETAILS

Experiment 1: Task

In experiment 1, participants performed a similarity judgment task where they were asked to determine how similar two spatial patterns were in terms of their shape by pressing a number key using the Likert scale from 1 (completely dissimilar shape) to 10 (identical shape). We did not give the participants specific instructions as to what shape similarity means. Two stimuli were sequentially presented for 600 ms each with a 1-s interval following the participant's key press, in a block of 10 trials. The two stimuli were the same or different patterns selected from the 20 patterns shown in Figure 1A. The 20 patterns were all composed of the same three-line segments divisible into five shape groups {Triangle, Arrow, Fish, Zigzag, Box}. The patterns within the same shape groups were rotated versions of the same shape, with a few exceptions. We will also refer to the spatial patterns as having the same shape if they are not strictly rotationally symmetric but have very similar configurations, such as the letters "b" and "d" of the alphabet. In all conditions, participants sat facing forward, with the computer in front of their body and the tactile stimulator slightly to the left. For tactile conditions, participants were instructed to place the index or middle finger of the left hand on the stimulator with their left arm resting on an armrest and to swap fingers after each block to prevent finger fatigue and adaptation. These fingers have been well used in previous studies (e.g.,[12]). The stimulator always remained in contact with the finger throughout the experiment. Participants performed the experiments with their eyes open to maintain their arousal level, although they could not see the actuators. They wore earplugs to mask any noise made by the vibration of the stimulator. All trials began with an approximately one-second temporal gap after the participant pressed a key and either a visual image stimulus was presented on the center of the computer screen or a vibrotactile stimulus was presented on the stimulator.

There were three conditions: V-V (comparing two visual patterns), T-T (comparing two tactile patterns), T-V (comparing a tactile pattern presented first with a visual pattern presented second). There were a total of 400 combinations of the 20 patterns. All combinations were tested each with cm- and mm-dimension images in the V-V condition and with the index and middle fingers in T-T and T-V conditions. Participants were given ∼10 practice trials before the start of data collection. Each participant completed one condition in 80 blocks of 800 trials, and the duration of the experiment was approximately 4 hours, including practice and breaks.

Experiment 1: Tactile stimuli

As vibrotactile stimuli, spatial patterns were generated by the 'Latero'[27] (Tactile Lab, Montreal, Canada, Figure 1C). An array of 8 x 8 = 64 pins constructs 10 x 10 mm contact surfaces with ∼1.2 mm pin-to-pin spacing. Each pin can independently move across the contacted surface of the skin laterally. The outer pins were used as fixed ends to prevent vibrations from spreading to the skin surface and to concentrate the strain energy. The shape was therefore presented by the pins on the inner block of the array: Each line segment, 8∼11 mm in length, was produced by six pins. During the stimulus presentation, the pins sinusoidally vibrated at 40 Hz, but in opposite phases between odd and even rows of pins. Driving neighboring pins in opposite phases is expected to increase the skin strain and thus the perceived intensity.[58,60] The amplitude of the vibration was less than 1mm. The frequency and amplitude were selected following the practice of previous studies using the same stimulator,[33,57] which was taken to confirm their suitability for shape presentation under the conditions of the current experiments.

The duration of the stimulus was always 600 ms. To prevent the participants from judging shape from abrupt skin deformation during onset and offset of stimuli, each vibrotactile stimulus had 100-ms cosine ramps at both its onset and offset.

Experiment 1: Visual stimuli

As visual stimuli, an abstract shape drawn with white dotted lines was presented on a uniform grey background. Each line segment consists of six dots and each shape stimulus had the appearance of a monochrome version of Figure 1A. Stimuli were presented on a MacBook Air laptop. The duration of the stimulus was always 600 ms. The participants were seated about 50 cm away from the computer and instructed to minimise their motion during the task to maintain a constant distance from the computer.

We tried to roughly match the perceived scale between the two modalities, and tested two matching conditions. The methods used were the same as in our previous study.[18] In the first matching "cm" condition, visual images were scaled based on the minimum discriminable spatial resolution of static touch. Without active tracing, the minimum discriminable spatial resolution is 0.2 mm,[61–64] while that of central vision is one minute of arc (30 cycles per degrees) for 20/20 observers. To match the adopted vibrotactile shape dimensions of a square of 8 mm per side, the visual image was presented with dimensions of a square of 1 cm per side at a distance of 50 cm (i.e., visual angle of 1/30 of degrees × 8 mm / 0.2 mm = 1.3 degrees). In the second matching "mm" condition, visual images were scaled based on the two-point discrimination ability of touch. Two-point discrimination refers to the ability to perceive two distinct points of contact on the skin as separate stimuli rather than a single touch, and is widely used as an indicator to assess the spatial resolution of tactile sensation.[65] According to the two-point discrimination ability, the fingertip has a resolution of approximately 2 mm. Tactile roughness sensitivity also reaches a peak around the grating stimuli of 2 mm (0.2 mm × 10) pitch.[66,67] To match this ability, the visual image was presented with dimensions of a square of 1 mm per side at a distance of 50cm (i.e., visual angle of 1/30 of degrees × 8 mm / 2 mm = 0.13 degrees).

Testing of the V-V condition was conducted in both matching conditions with the same participants. The results for the "cm" condition are shown in the main text and those for the "mm" condition are shown in the supplemental information. Testing of the T-V condition was conducted in the "cm" condition only.

Experiment 2: Task

In experiment 2, participants performed a pattern identification task where they were asked to touch one pattern and then choose one out of eight candidates. In this experiment, the candidates were focused on eight patterns in two configurations {Triangle and Arrow}.

There were three conditions as to how participants observed the stimuli: Vibrotactile (a similar condition to experiment 1), Braille static (statically touching a printed pattern), and Braille active (actively scanning a printed pattern). In the vibrotactile condition, the stimuli and procedure were similar to experiment 1. In each trial, one vibrotactile stimulus was presented for 600 ms, and eight visual images of candidate patterns each 1cm square were presented on the screen after a 1-second interval. In the braille conditions, a physical stimulus (see below section for details) was presented to the participant's left index or middle finger (the same finger that was used in the vibrotactile condition). Before each trial, participants were asked to lift their fingers and the experimenter placed the target stimulus in a comfortable position where the participants' fingers would naturally positioned. In the braille static condition, participants were instructed to slowly lower their fingers onto the stimulus, remain still, and then slowly lift their fingers within one second. In the braille active condition, participants were free to move their fingers to scan the stimulus for one second. Participants indicated their response by verbally reporting the number corresponding to each shape (one to eight). One block lasted 10-20 trials, with fingers swapped after each block to prevent finger fatigue and adaptation. Participants were given ∼10 practice trials before the beginning of each touch condition. Touch conditions were fixed throughout one block and changed between blocks in a random order. Identification of each of the eight shapes was repeated 10 times for each finger, resulting in 20 repetitions for each shape and a total of 160 trials in each touch condition. Each participant completed all three touch conditions, and the duration of the experiment was approximately four hours, including practice and breaks.

Experiment 2: Tactile stimuli

Vibrotactile shape stimuli were generated as in experiment 1. Braille shape stimuli were custom-made by piecing together printed braille labels made of plastic seal printed by a Braille printer (BL-1000LINK, KGS, Japan) and attached to acrylic plates (Figure 4B). As the dot spacing is approximately 2.4 mm under Braille standards, our Braille shape stimuli were created with four dots per side to present a shape of the same size as the vibrotactile stimulus, keeping it within 1 cm per side. To minimize the influence of the accuracy of our stimulus creation process on the experimental results, multiple sets of stimuli were created and changed for each block. Also, stimulus sets were replaced as necessary to avoid deterioration of the stimuli due to repeated use.

QUANTIFICATION AND STATISTICAL ANALYSIS

The following analysis was mainly carried out in Python, with only some parts in R, but in principle any language that is suitable for analysis can be used.

Representational similarity matrix

In experiment 1, the distribution of similarity scores was first plotted as histograms (Figure 2A), and an index of task difficulty was calculated by taking the mean difference of this distribution between pairs of the same pattern and pairs of different shapes. Statistical differences between the means of these two distributions were tested using a paired t-test ($n = 10$), and the results are presented in the text of the results section.

Representational similarity matrices (RSMs) were then calculated after converting the original similarity scores to Z scores so that they could be compared across participants. Note that the RSMs were symmetrised to remove the effect of the order of stimulus presentation for conditions V-V and T-T (Figure 2B).

For a sanity check, we calculated the inter-subject consistency for the RSMs for each condition (Figure 2B). Specifically, we performed 10,000 iterations of a bootstrap procedure that computed Pearson's correlation between one participant's RSM and the mean value of those of the other participants. The results are presented in the text of the results section in terms of correlation coefficient r and CI.

We have evaluated the similarity of the two RSMs by calculating the correlation coefficient of the confusion error (off-diagonal) values.[13,68] The bootstrapping method (resampling method[69]) was used to compute the CIs of the correlations. We calculated the correlation values for each pair of data or model, and the data of participants were then resampled and averaged to calculate the distribution of correlation values. Note that we used Pearson's correlation coefficient to compare behavioral data in different conditions while using the Spearman rank correlation coefficient to compare behavioral data and models since we do not want to assume a linear match between the behavioral data and models. The results of the analysis are presented in the text of the results section and in Figures 2C and 3B. Dots represent the mean and error bars represent 95% CI, with n=10.

In experiment 2, pattern identification accuracies were first calculated as correct rate (Figure 4C). The differences between stimulus conditions were tested using a Friedman test with n=14, and the results are presented in the text of the results section and Figure 4C.

The confusion matrix was then calculated for the original response probabilities (Figure 4A). Then, a symmetrisation transformation of the confusion matrix was performed: if Pij is the probability of occurrence of response j to stimulus i, then the symmetrized P'ij is the average of Pij and Pji. This transformation was employed for noise reduction in a previous study.[13] Although the confusion matrices in experiment 2 were computed according to a different definition than the RSMs in experiment 1, the results for experiment 2 were analyzed similarly to those for experiment 1. The results of the analysis are presented in the text of the results section and in Figures 4D and 4E. Dots represent the mean and error bars represent 95% CI, with n=14.

Model

The representational similarity matrix (RSM) of behavioral data was evaluated in comparison to the predictions made by three models: pixel distribution similarity, orientation histogram similarity, and configural similarity models. Each model evaluated the pattern similarity from the degree of (dis)agreement in a certain feature between the two patterns. The pixel distribution similarity model evaluated how many line segments are mismatched. For example, the output for the T1 and A1 pair is 2/3, since the vertical and horizontal segments coincide and only the diagonal segment is mismatched; the index for the T1 and T2 pair is 1/3.

The orientation histogram similarity model evaluated the degree of (dis)agreement in the histogram of the angle of segments {0, 45, 90, 135 degrees}, ignoring the position of each segment. For example, the index of the T1 and T2 pair is 3/3 because the number of vertical, horizontal, and diagonal segments is exactly equal; the index for the T1 and Z1 pair is 1/3 because only the number of left-diagonal segments is equal while that of the vertical and horizontal segments is off by 1. The configuration model judged whether the two patterns were in the same configuration group or not. For example, the index of the T1 and A1 pair is 0 while that of the T1 and T2 pair is 1. The similarity of all pairs was calculated and an RSM was created for each model. Note that the absolute value of each element of the RSM has no meaning, only the relative pattern of the RSM has significance.

Metric evaluation

To test the differences between the correlation values of behavioral data and the model prediction, we used a non-parametric aligned rank transform (ART) analysis.[70] The number of participants were 10 for experiment 1 (Figure 3B) and 14 for experiment 2 (Figure 4E). Participants were treated as a random factor, and each correlation score was aligned and rank transformed prior to factorial ANOVA (ART-ANOVA). Where a main effect or interaction was significant, multiple comparisons were performed with a corrected alpha level using the Bonferroni method. The results of the analysis are shown by F ratios and p-values in the text of the results section and figure legends. These analyses were performed in R using the ARTool package.