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Tatsuhisa Takahashi[1) Yinlai Jiang[2) Shuoyu Wang[3)
Masanaga Ikegami[4) Akihito Yoshimura[1) Ryosuke Miyazawa[1)
Shin-ich Watanabe[5) Takashi Matsuo[5) Hirotaka Yanagida[6)

ABSTRACT

Humans can identify partly occluded objects such as fragmented letters and the process involved could be considered as a common ability to discriminate, for example, between animal camouflage and jungle surroundings. The present study found that the same mechanism is responsible for visual identifying fragmented letters. Psychological experiments showed that individuals with normal vision most frequently imagined the shortest-linear links when observing three points corresponding to the vertices of virtual scalene triangles. Computer simulation also showed that multiple lines between pixels in close proximity remaining within the fragments with randomly removed pixels reproduced the shapes of original letters. Therefore, these results suggest that fragmented letters can be identified via linkages of spontaneously-induced illusory lines that interpolate elements remaining in close proximity within the visual system of the brain.

INTRODUCTION

Ancient arboreal primates must have been able to promptly distinguish between favorable prey and unfavorable predators. However, the ability to identify such animals would have been complicated by partial or total occlusion by various types of vegetation. Various animals can conceal themselves by blending into environments by virtue of natural colors and patterns on the skin[1)]. A camouflaged animal is difficult to imagine as a three-dimensional object constructed from fragmented pieces of two-dimensional retinal information in the brain or mind. Primitive humans adapted to survive via natural selection, and probably developed the type of vision neces-

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[1)]Department of Mathematical Information Science, Asahikawa Medical University [2)]Brain Science Inspired Life Support Research Center, The University of Electro-Communications [3)]School of Mechanical Engineering, Kochi University of Technology [4)]Department of Psychology, Asahikawa Medical University [5)]Department of Clinical Engineering, Kanagawa Institute of Technology [6)]Department of Informatics, Faculty of Engineering, Yamagata University

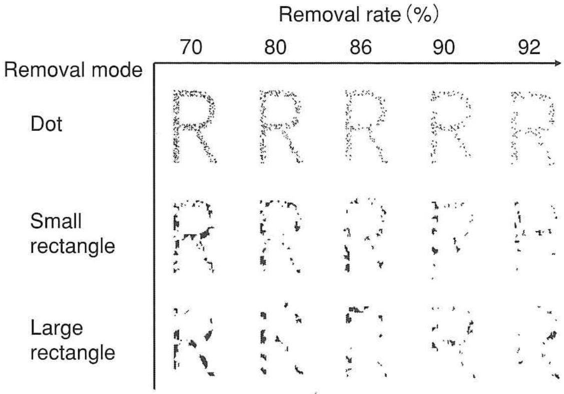

Fig. 1 Letter "R" coarsened into five grades of fragmentation

Pixels that constituted complete letters were randomly removed in the form of dots (one pixel each), or small (3× 6 pixels) and large (6×12 pixels) rectangles that were randomly rotated. Fragmented letters are shown with 70%, 80%, 86%, 90%, and 92% of pixels removed. Difficulty of identifying fragmented letters increased as more pixels were removed from original letters.
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sary to promptly become aware of an approaching predator or a hidden prey in the environment.

Now, we can use "visual interpolation" to identify fragmented images signaled from the retinae to the brain. The fact that humans can identify fragmented letters is evidence of this. A fragmented letter is produced by deletion of parts of the original whole letter, which if known can be identified from the incomplete letter. **Fig. 1** shows examples of fragmented letters. The fragmented letters, R's, in the left column are equivalent to 30% of the complete letter and those in the right column are 8% of the complete letter under different fragmentary conditions. The correct identification of fragmented letters becomes progressively more difficult as more of the constituent elements are deleted from the complete letters. According to Jiang et al.[2], the difficulty of identifying fragmented letters is proportional to the rate of fragmentation or to the removal of visual information.

Fig. 1 also shows that the degree of the difficulty in identifying fragmented letters also depends on how constituent elements are removed, such eliminating a dot or a rectangle. Fragmented letters are described with the same rate, but with different modes of pixel elimination. Fragmented letters with eliminated rectangles seem more difficult to identify than those with eliminated dots. These facts have led to the conclusion that a shorter distance between two mutual pixels enables correct reading of the fragmented letter. The present study aimed to determine the underlying mechanism involved in fragmented-letter identification. We therefore tested the hypothesis that the identification of fragmented letters is associated with the recognition of structures in which imaginary lines or illusory contours are evoked between pixels in close proximity by mental interpolation[2)].

METHODS

1 Participants

Forty-five healthy individuals (men, $n=35$; women, $n=10$; age 24.6±5.1 [average±SD] years) with normal or corrected-to-normal vision volunteered to participate in the present study. All were fully informed about the procedures, risk, and benefits of the study. We had obtained each written informed consent from them before the study, which proceeded in accordance with the principles outlined in the Declaration of Helsinki (6th revision 2006). The Human Investigation Committee of Kochi University of Technology approved the experimental protocol.

2 Visual stimuli

We examined mental interpolation during which the linkage of imaginary lines between the closest points would take priority over other points that were farther way. The points P_1, P_2, and P_3 were located on the vertices of a scalene triangle (**Fig. 2a**): the interior angle at the vertex P_1, α; the opposite side of α, s_1; the adjacent sides of α, s_2 and s_3 (always $s_3 = 1/2\, s_2$, hence $s_3 < s_2 < s_1$ in length). If s_3 equals $s_2/2$, the dimensional relationships of the three sides are given as $s_3 + s_2 < s_3 + s_1 < s_2 + s_1$. At first, only three points were displayed for 200 milliseconds on the monitor of a personal computer (**Fig. 2b**). The participants imagined the linkage of imaginary lines among the three points. Three types of linkage were then shown on the monitor and the participants selected one as being the same combination of lines that they had imagined (**Fig. 2c**). This process was repeated but the locations of points P_1, P_2, and P_3 displayed in a square differed among frames as the interior angles of α were 90°, 120°, and 150° and the points P_1 and P_2 rotated around the point P_3 by 0°, 60°, 120°, 180°, 240°, and 300°. As a result, 18 (=3 triangles×6 rotations) possible variations of the three points were created in different scalene triangles and thus each volunteer participated in 18 trials.

In this psychological experiment, 18 three-point locations were displayed individually on the screen of a notebook computer (Dell Studio 1536; Computer Inc., Red Rock, TX, USA) with an LCD resolution of 1280×800 pixels and 32-bit color codes. All points were presented in black MSP Gothic 14-point font. Three points in each figure were shown in the middle of a square with 5-cm sides against a white background. Each of the 18 figures was randomly displayed once per test and the duration of each presentation was 200 milliseconds. The participants mentally select one of three figures from a sample board on the display after each presentation of three-point figures and then used a mouse to select the linkage on the screen that matched their mental image.

RESULTS

1 Psychological experiments

Fig. 2 shows a schematic representation of the results. Forty-five volunteers mentally linked the shortest side s_3 to the second shorter side s_2 ($n=220$, 81.5%; top left, **Fig. 2c**) or to the longer side s_1 ($n=42$, 15.6%; top middle, **Fig. 2c**) between the vertices of the triangles with an angle of 90° in terms of six rotations around an acute angle (total of 270 triangles): $s_3 < s_2 < s_1$ and hence $s_3 + s_2 < s_3 + s_1 < s_2 + s_1$ in length relationships (**Figs. 2a, b**). The two types of selected imaginary links always included the shortest side s_3. These results indicated that 44 (97.8%) of the volunteers imaged linkages including the shortest line among the three points by mental interpolation. Similarly, the shortest links of two sides ($s_3 + s_2$) as imaginary lines among three points corresponded to the vertices of triangles

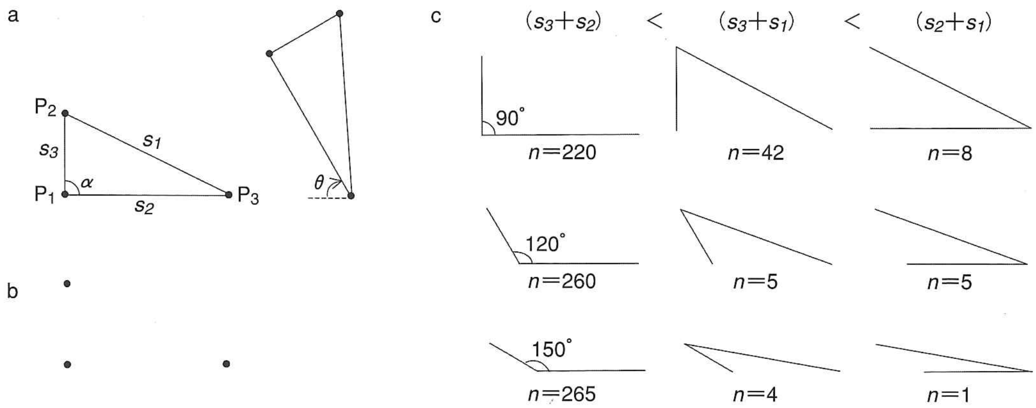

Fig. 2 Psychological experiments and results

a and b : Three dots are spaced as the vertices of scalene triangle $P_1P_2P_3$; sides are defined as s_1, s_2, and s_3 and the interior angle is α. Geometric relationships among three sides are given as $s_3+s_2<s_3+s_1<s_2+s_1$, because s_3 was $s_2/2$. Location of point P3 remained unchanged, but points P_1 and P_2 were rotated clockwise at angle θ (0°, 60°, 120°, 180°, 240°, and 300°). Rotation did not affect any distance among three points. c : During psychological experiments with visual stimuli, three points shown in (b) were displayed for 200 milliseconds on computer screen, while participants imaged linkages of two imaginary lines among points. Three linkages are possible between three points (c, top low). Values represent numbers of individuals who selected linkages that corresponded to those that they had imagined. Three linkages in each low (c) were induced by three points with internal angles of 90°, 120°, and 150° at a rotation of 0° ; for simplicity, linkages in rotations of 60°, 120°, 180°, 240°, and 300° have been omitted. Each of 45 volunteers selected a total of 18 linkages from the product of three triangles and six rotations.

with an angle of 120° in six rotations in 260 (96.3%) of 270 triangles selected by all 45 volunteers who were each shown six triangles (middle left, **Fig. 2c**). With respect to triangles with an angle of 150° in six rotations (bottom low, **Fig. 2c**), the shortest links of two sides (s_3+s_2) as imaginary lines among three points corresponding to the vertices were selected in 265 (98.1%) of 270 triangles.

The ratios of the longest (s_2+s_1) to the shortest (s_3+s_2) link were 1.41, 1.55, and 1.64 for the virtual 90°, 120°, and 150° triangles, respectively. The difference in length between the shortest link and the next shortest link in right-angled triangles was considered subtle, because the ratio of (s_3+s_1) to (s_3+s_2) was 1.08. As a result, rather than the shortest link, the second shortest links (s_3+s_1) were selected by 15.6% (42 of 270 right-angled triangles), which was significantly more than the 1.9% and 1.5% of such selections in obtuse triangles with angles of 120° and 150°, respectively (15.6% vs. 1.9% and 15.6% vs. 1.5% ; both $p<0.004$, ANOVA with Dunnett's post-hoc test).

2 Simulation

We examined the mechanism of mental interpolation as follows. A computer was used to simulate whether or not connections between elements close to each other in fragments can reconstruct the letter as it was before elements were removed. The process of connecting lines with each minimum distance modeled the mental interpolation involved in identifying fragmented letters. This model was designed on an algorithm that drew lines between remaining adjacent pixels on a computer display (**Fig. 3**). In the computer simulation, a large number of lines between adjacent pixels in remaining fragmen-

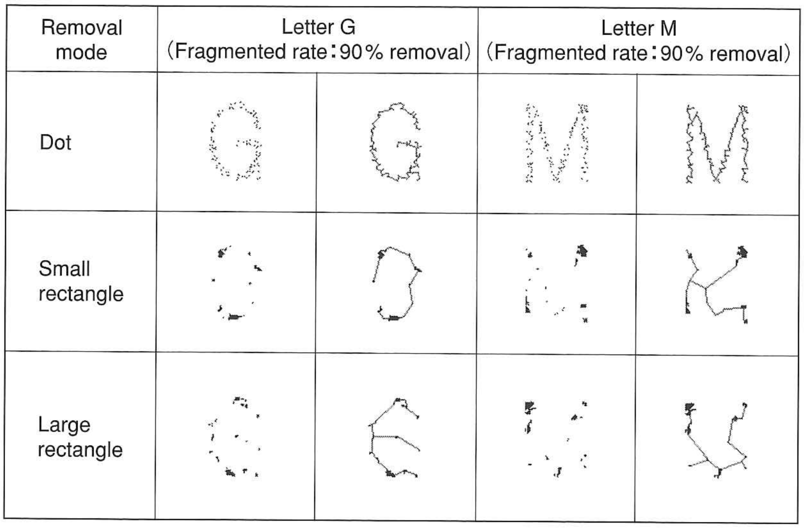

Fig. 3 Typical results of computer simulation
Simulation shows letters partially occluded by surrounding white background interpolated during perception. When relatively closer elements in fragmentations with 90% pixel removal were connected by straight lines, line drawings in fragmentations that had been produced by dot-removal mode reconstructed the letters “G” and “M,” which were comparable to the original letters. Results were identical for other English letters. In contrast, line drawings in letters that had been fragmented by small-and large-rectangle-removal modes could not be reconstructed to configure original letters.

tary elements after the random removal of dots ensured good reproduction of the letter. However, lines linking pixels in close proximity could no longer form the original letter after fragmentation with the random removal of rectangles. These results simply confirmed our previous findings that different degrees of difficulty are involved in identifying letters that have been fragmented by eliminating dots and rectangles (**Fig. 1**).

DISCUSSION

Our psychological experiments showed that when individuals observed elements (points) corresponding to the vertices of virtual triangles, they preferentially imaged that the most frequent lines that linked two points were shorter rather than longer. The results of the computer simulation showed that the shortest lines that linked the individual elements remaining after the random removal of elements constituting a letter accurately reconstructed the original letter. The psychological and simulation results were in agreement. Therefore, the notion that the mechanism in the visual system of the brain responsible for identifying fragmented letters is the preferential interpolation of closely situated elements to create a linkage that is spontaneously induced by imaginary lines.

Fig. 4a shows a word,“ASAHIKAWA.” When the word in a black type is covered with a number of black rings (shown separately in **Fig. 4d**), the occluded word cannot be determined (**Fig. 4b**). On the other hand, when the word is covered with the same size and number of white rings, the occluded word can be easily read and

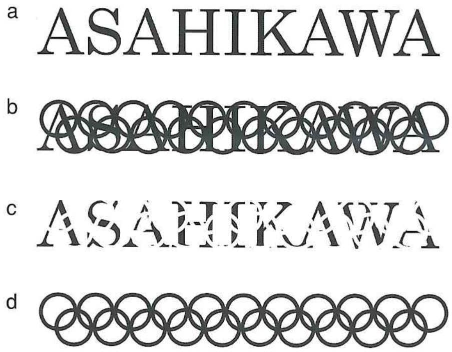

Fig. 4 Perception of fragmented letters through minimum-distance link interpolation between the remaining pieces of information in visual field

a : Plain black letters "ASAHIKAWA" on white background. b : The letters "ASAHIKAWA" are partly occluded by black rings similar to Olympic symbol. c : The letters "ASAHIKAWA" are partly occluded by white rings in the same shape as that of black rings. d : Representative series of these occlusive rings used in (b) and (c).

reproduced (**Fig. 4c**). The present findings of the computer simulation showed that accurate reproduction of the original letters was ensured when the remaining elements of fragmented letters were connected with the shortest lines. Likewise, the letters in the word "ASAHIKAWA" were easily recognizable when occluded by white rings, but illegible when occluded by black rings, since connections of virtual lines between mutually close elements in black are quite distinct from the letters. In this situation, fragmented elements were restored to the original letters by virtual lines connecting mutually close elements that remained by subtracting the white rings from the original letters. Simple links with the minimum number of straight lines between elements should be adopted to ensure accurate reproduction.

Primitive humans must encountered ferocious animals that were essentially invisible thanks to camouflage, and this might have been powerful influence on human destiny in terms of developing an innate ability to perceive and process visual fragmentary information. Drawing a distinction between camouflaged animals and their surroundings is a problem that is related to the recognition of fragmented letters. The mechanism of minimum-distance link interpolation to identify fragmented elements is common between the perception of the shapes of spotted animals and of fragmented letters in our hypothetical model. Still, spotted animals seem prime candidates for camouflaged animals in jungle, as shown in **Fig. 4b** by analogy.

The present results reflect a perceptual rule of interpolating a virtual minimum-distance link into the space created by lack of elements in fragmented letters or parts of occluded figures. In a random distribution of short-line elements, more than two collinear line segments will be conspicuous from a background without the need for a focus search by an observer[3,4]. In general, the intensity of the conspicuous elements is dependent on both the shortness of spacing and the smoothness of a series of line elements. These properties of the perception of contour elements are consistent with the mechanism of the interpolation of individual minimum distances between elements of fragmented object in our model.

A large number of cells in the primary visual cortex selectively respond to the orientation of lines and edges of objects[5]. All retinal images activate neurons in the superficial and deeper layers of V1 and V2, respectively, during object recognition. V1 cells in the primary visual cortex function as local detectors that are responsive to oriented line segments[6,7]. V2 cells in the secondary visual area analyze the local orientation of contours (lines and edges) of geometric figures. The neurons in V1 and V2 also respond to whether or not the contours would actually exist in the visual field[7~9]. Accordingly, imaginary figures such as an illusory line or luminance contrast can be visualized even though they do not physically exist (**Figs. 5a, b**). Illusory lines join the tips of the inducer gratings at right angles to the axes of existing lines. The distance between the ends of physical parallel lines is critical for the brightness of the illusory line. Circumstantial evidence is provided by the illusory line in **Fig. 5a** which appears to be more luminous than that in **Fig. 5b**. That is, the shorter the distance between the tips of inducers, the brighter the illusory line ; this phenomenon and the minimum-distance interpolation in this study might be closely associated in a fundamental process of the visual nervous system. The appearance of illusory contours seems to be dependent on the spatial relationship between the tips of inducers. The tips of the right and left inducers were closely located along the identical illusory straight line. When the tips of the inducers were not located along the straight line, the illusory line did not emerge from the mutually intercalative tips of the physical lines (**Fig. 5c**). Thus, the illusory line appeared as a simple straight line connecting the closest tips of physical figures. These phenomena of illusory lines might conform to the calculation rules of the proximity and collinearity of visual elements involved in the perceptual processing that integrates them into a recognizable contour or separates them as a specific entity from others or the background[3,4,10].

The population of cells clustered in a number of columns in the primary visual cortex selectively responds to the orientation of both line segments and object contours[5]. The columns of cells with similar orientation specificity are mosaically distributed and are horizontally connected by axons extending from pyramidal cells. The properties of a network of cells with a similar orientation preference are important for integrating the elements of a visual image into a unified perception through sharing information[5,11]. This cooperative activity might be essential for the propagation restraint of some accidental errors or noise encoded through the network as well as for the promotion of more important signals[12]. Nevertheless, illusory lines of minimum-distance link interpolation into the remaining elements of fragmented letters do not physically exist. Furthermore, the illusory interpolation can adopt all orientations, but none that are specific, a feature that is most probably requirements for accurate reconstruction of a shape. However, little is actually known about the neurological processes involved in illusory-line interpolation that originates in the primary visual cortex network.

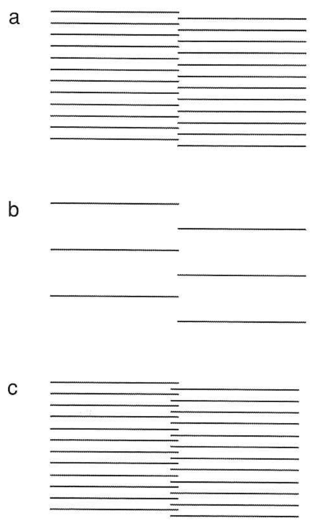

Fig. 5 Illusory lines evoked as luminance contrast by abutting line gratings
Denser line grating induced brighter illusory line in (a) than (b). c : Illusory line disappears when opposite gratings encroach.

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