

Short communication

## Integration process of contours defined by different attributes

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### Abstract

We examined how contours defined by different attributes are integrated into a shape using the visual search paradigm and found that the search for the bar orientation is particularly difficult when each bar is composed of motion-defined and luminance- or color-defined contours. This does not support the view that the shape integration process is based on the unified contour representation entirely common to all attributes, but suggests that motion-defined contours are integrated through a different process.

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We can recognize the same shape whether it is depicted by a difference in luminance, color, or by motion, even though the visual system processes these attributes separately using their respective modules [4,5]. This leads to the question of how such attribute-independence is secured in the shape processing. A simple and plausible hypothesis is that contours of an input image are represented attribute-independently, as suggested by evidence such as the inter-attribute tilt effect [9], and then integrated into shape. According to this hypothesis, basic shape features should be extracted irrespective of the attribute defining the contours. This appears to be supported by Cavanagh et al. [1], who found that the efficiency of visual search for bar orientation was not varied even if the attribute defining the bars was changed. Their result, however, does not mean that the shape integration process is independent of the contour attributes because in their experiment, each bar was defined by a single attribute. Here we report that when each bar is composed of two kinds of contours, the search efficiency depend strongly on the combination of contour attributes, which does not fully support the above view.

Subjects were instructed to search for a bar oriented 45° to the right among bars oriented 45° to the left, or vice versa, and to respond to the presence or absence of the target by pressing one of two keys. (The orientations of a target and distractors were counterbalanced between subjects.) A target was present in one-half of the trials. Four, 8, 12, or 16 bars were presented on a square background (15×15°) filled with a black-and-white random-dot pattern; each dot (0.054×0.054°) was randomly assigned black (0.56 cd/m<sup>2</sup>) or white (30 cd/m<sup>2</sup>). Each bar comprised a pair of squares (0.76×0.76°) adjacent to each other (Fig. 1).

A luminance-color display contained equal numbers of luminance-defined and color-defined squares. One-half of the luminance-defined squares were filled with a random-dot pattern of black and gray (15 cd/m<sup>2</sup>), and the other half with a random-dot pattern of gray and white. Similarly, the color-defined squares were filled with a random-dot pattern of red and black or green and black, where the red and green stimuli were set to be equiluminant with white stimuli using the minimum flicker technique for each subject. The luminance-motion display was the same as the luminance-color display but the color-defined squares were replaced by motion-defined ones. One-half of the motion-

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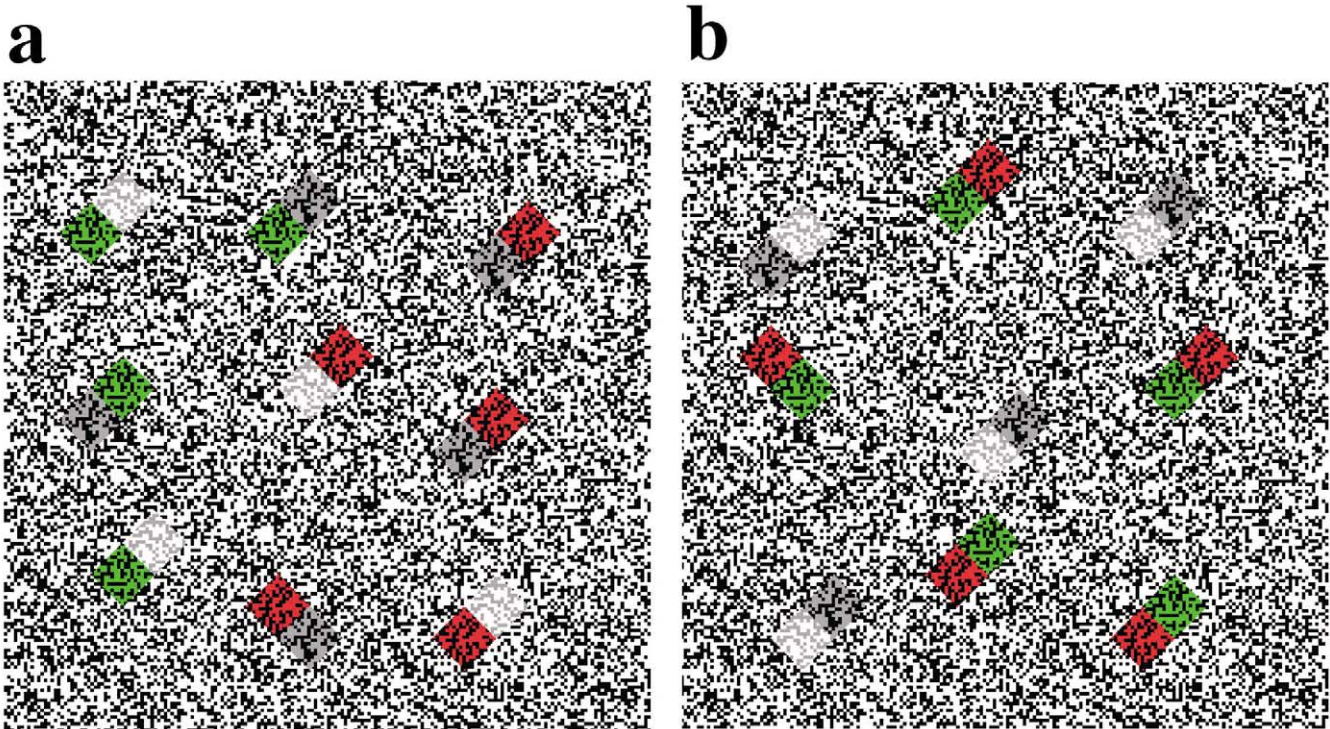


Fig. 1. Schematic representation of luminance-color displays under (a) inter-attribute and (b) intra-attribute conditions.

defined squares were filled with random dots of black and white moving coherently to the left at a speed of  $2.2^\circ/s$ ; the other half were filled with the same dots moving to the right at the same speed. The color-motion display was composed of the color-defined and the motion-defined squares.

For each of these three types of displays, two conditions, inter- and intra-attribute conditions, were used. Under the intra-attribute condition, for a pair of squares forming a bar, each had the same attribute but different values (e.g., red-and-black and green-and-black random dots), whereas they were defined by different attributes under the inter-attribute condition. Note that the components are the same but the configurations are different for these two conditions.

After a 1-s presentation of a white fixation circle subtending  $0.16^\circ$  ( $120 \text{ cd/m}^2$ ) at the center of the display, bars were presented in square areas selected randomly within a  $4 \times 4$  matrix. The display remained until the subjects responded. Each type of display was observed by 12 paid volunteers who did not know the purpose of the study. They participated in one practice and two experimental blocks of 160 trials for each condition. The experiments were carried out with the understanding and written consent of each subject.

The response time (the time measured from the presentation of the display to the subjects' response) as a function of the number of bars (search function) was compared between the inter- and intra-attribute conditions. We analyzed the data focusing on the slope of the search

function (search rate), which corresponds to the difficulty in the search, for the target-present trials (Fig. 2); we omitted the data in the target-absent trials where subjects often searched the display more than once and the response time varied considerably widely. The search rate is considered to reflect the time required to integrate two squares and to extract the orientation of the bars. There was no significant difference in search rate between the inter- and intra-attribute conditions for the luminance-color displays ( $F(1,10)=2.484$ ,  $P>0.05$ ). The search rates were 31 and 21 ms/item for the inter- and intra-attribute conditions, respectively. In contrast, for the luminance-motion displays, the search rate for the inter-attribute condition was significantly higher than that for the intra-attribute condition (75 and 35 ms/item, respectively) ( $F(1,10)=16.984$ ,  $P<0.005$ ). The difference was even greater for the color-motion displays, that is, the search rates for the inter- and intra-attribute conditions were 83 and 18 ms/item, respectively ( $F(1,11)=77.343$ ,  $P<0.0001$ ).

This difference might be caused by the boundary line between two squares which can be a key for determining the orientation of the bars because its saliency is possibly different for the inter- and intra-attribute conditions. To test this possibility, we eliminated the boundary line by inserting a small gap of  $0.19^\circ$  between each pair of squares. The result was, however, almost the same as the previous one (Fig. 2), indicating that the boundary line does not affect the search rate; the difference in search rate between inter- and intra-attribute conditions was not significant for the luminance-color display (32 and 25

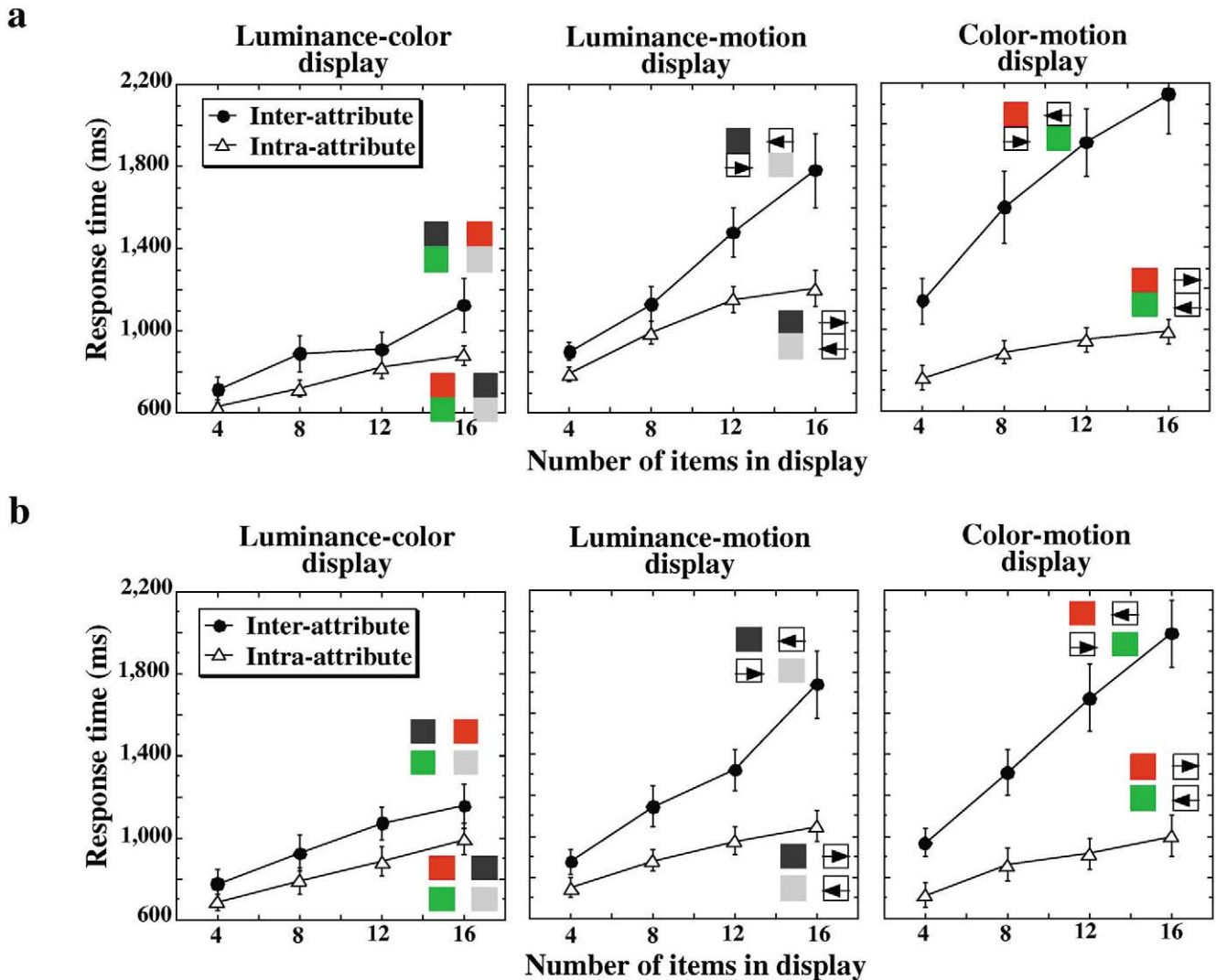


Fig. 2. Response time as a function of the number of items in a display under the inter-attribute (black circles) and intra-attribute (white triangles) conditions for the luminance-color, luminance-motion and color-motion displays: the results of the experiments (a) using bars composed of adjacent squares and (b) using bars with a small gap inserted between the adjacent squares. Each point represents the mean for 8 to 12 subjects. Error bars indicate  $\pm 1$  S.E.

ms/item, respectively;  $F(1,8)=2.007$ ,  $P>0.05$ ), but was highly significant for the luminance-motion display (75 and 24 ms/item, respectively;  $F(1,11)=45.490$ ,  $P<0.0001$ ), and for the color-motion display (85 and 23 ms/item, respectively;  $F(1,7)=101.684$ ,  $P<0.0001$ ). It is therefore concluded that integrating motion-defined contours with luminance- or color-defined contours into a complete shape requires a much longer time than integrating those defined by the same attribute.

These results are not in accordance with the view that the shape integration process is based on a completely unified representation of contours which is entirely common to all attributes, since although this view predicts that the search rate will be constant for all displays and conditions, the contour attributes affected the process of orientation extraction of shape or integrated contours. The results also suggest that luminance- and color-defined

contours may possibly have unified representation on which the shape integration process is based, but motion-defined contours may be processed separately from it.

With regard to this, it is widely known that the ventral pathway of the visual cortex processes shape and color perception and the dorsal pathway deals with spatial and motion processing [3,8,12]. Physiological evidence, however, indicates that motion-defined shape is processed in the ventral pathway. For example, neurons in the inferior temporal (IT) cortex respond to their preferred shape irrespective of whether it is defined by luminance or motion contrast [10], whereas neurons in area MT do not exhibit an orientation-selective response to motion-defined contours [6]. Also, orientation discrimination of motion-defined shape is impaired by lesions of area V4 [2,11]. In addition, neurons with selectivity in orientation of motion-defined contours are found in area V2 [7], and most of

them respond to luminance-defined contours of the same orientation. This evidence appears to support a model in which information on motion and luminance boundaries converges on single cells in V2 to form unified contour representation, and the integration processes in V4 and IT are based on such representation. Nevertheless, as discussed above, this model does not agree with the results of our experiment.

A clue to solve this problem might be the finding that the V2 neurons responded about 40 ms slower to motion-defined boundaries than to luminance-defined ones [7], although the latencies in IT do not differ [10]. This indicates that contour representation in V2 is attribute-independent but not common to all attributes in the temporal aspect. Together with our experimental results, this suggests that the attribute-independence is not secured by the simple bottom-up stream of processing but is involved with some top-down process, as assumed in the model presented by Marcar et al. [7] in which motion information is injected into the ventral pathway, possibly at V4 from V3, and sent backward to V2. It is interesting that the difference in the search rate between inter- and intra-conditions for luminance-motion display (40 or 51 ms) is close to the above difference in response onset of V2 neurons; this may not be a mere coincidence but may reflect a process of merging two representations by adjusting the time difference.

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