ACTA
NEUROBIOLOGIAE
EXPERIMENTALIS

Acta Neurobiol Exp 2003, 63: 361-368

The role of lines and corners of geometric figures in recognition performance

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Abstract. A relative role of lines and corners of images of outline geometric figures in recognition performance was studied psychophysically. Probability of correct response to the shape of the whole figure (control) and figures with lines or corners masked to a different extent was compared. Increase in the extent of masking resulted in a drop of recognition performance that was significantly lower for figures without corners, than for figures without part of their lines. The whole 3D figures were recognized better than 2D ones, whereas the opposite relations were observed under conditions of masking. Significant gender difference in a recognition performance was found: men recognize entire and partly masked figures better than women. Possible mechanisms of relatively better recognition of figures with corners than with lines are discussed in connection with finding of high sensitivity of many neurons in the primary visual cortex to line crossing and branching.

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Key words: visual, recognition, perception, figures, lines, corners, masking

INTRODUCTION

Biederman (1987) showed the leading role of apexes in comparison to the sides of 2D images of the natural figures (a plane, a cup and so forth) in their recognition. In a number of studies this finding was specified and supplemented (Brown and Koch 1993, Elder and Zucker 1993, Field et al. 1993, Kovacs 1996, Kovacs and Julesz 1993, Ringach and Shapley 1996, Saarinen and Levi 1999, Uttal et al. 1995). It was shown that stimuli that contain discontinuity of curvature are easily found among stimuli containing only smooth changes in curvature (Kristjansson and Tse 2001). These results suggest that the visual system effectively detects abrupt changes in curvature in the image to extract most significant signals from the visual space. In the studies of human distinction of line orientation (Fahle 1994, Orban et al. 1984, Scobey 1982) there is some evidence of early cortical processing of corners (Fahle 1994). It seems natural to suppose the existence of "primitives" or the features of second and higher orders, describing different combinations of the first order features in the visual cortex (Marr 1970, 1976, 1982, Marr and Hildreth 1980, Marr and Nishihara 1978).

The problem of splitting of an entire image in its significant features carried out by the neuron-detectors during perception was posed at the neurophysiological level in the pioneer works of Lettvin et al. (1959), Hubel and Wiesel (1962, 1965). Detectors of orientations of lines and contrast borders were found in the primary visual cortex of cat and monkey (Hubel and Wiesel 1962, 1965). Detectors of complex figure elements and entire images, including faces, were studied in the inferior temporal cortex (Fujita et al. 1992, Janssen et al. 2000, Kobatake and Tanaka 1994, Rolls 1984, 1991, 1992, Rolls et al. 1997, Tanaka et al. 1991, Wallis and Rolls 1997, Wachsmuth et al. 1994, Wang et al. 1998).

Recently, neurons with sensitivity to line crossing and branching – crosses, corners and Y-like figures (Lazareva et al. 1995, 1998, Shevelev 1998, 2000, Shevelev et al. 1993, 1994, 1995, 1996, 1998a,b, 1999a,b) or local orientation discontinuities (Sillito et al. 1995) were found in the cat and monkey primary visual cortex. The content of such neurons reached 40-60% of the studied cells, their responses were, on average, 3-fold more intense, and response latency was markedly shorter to a figure than that to an optimal bar. It seems natural to suppose that both classical orientation detectors (Hammond and Andrews 1978, Hubel and Wiesel 1962, 1965, see Review: Orban 1984) and detectors of line-crossing (Lazareva et al. 1995, 1998, Shevelev 1998, Shevelev et al. 1993, 1994, 1995, 1996, 1998a,b, 1999a,b) are used by the primary visual cortex for feature extraction during processing of a shape information.

It must be taken into account that the sides of the natural figures used by Biederman (1987), as against geometric figures formed by the straight lines, are typically curvatures. This complicates the neurophysiological analysis of preference for apexes, because the sides of such figures can also be detected by neurons sensitive to local orientation discontinuities, instead of units sensitive to orientation of line fragments. It seemed interesting to compare a relative role in recognition of geometric figures of direct lines (first-order image features) vs. corners (second-order features). We suggested the leading role in this recognition of the second-order features and tested the idea comparing probability of correct response in three testing conditions – presentation of the entire figures (control), and figures with masking of different portion of their lines or corners.

METHODS

Subjects. Eight observers: four females, four males, aged between 20 and 30 years (physiology and psychology students) with normal vision took part in the experiments. Ethical permission of all observers for the experiments was received.

Stimuli. The observers sat at a distance of 208 cm from the PC monitor screen in the room with the background luminance of 0.08 cd/m^2. The mask constructed from the elements of the applied figures occupied the whole screen and as well as a centered on the screen fixation point was presented all ISI time except a figure presentation. A fixation point disappeared with the mask during figure presentation (17 ms), but immediately after that the fixation point and the mask appeared again. The set of centered on the screen geometric figures (Fig. 1A) consisted of five 2D and five 3D images with the size of 1.2°, formed by white lines of 25" width against the dark screen (background of 0.09 cd/m^2).

Figures of different shape and pattern (with or without different type and degree of masking and with 2D or 3D shape) were presented in pseudo-randomized order with equal probability: figures with complete contour (Fig. 1B, 1), with masked portion of lines (2), or masked portion of corners (3). In the case of 3D figures we

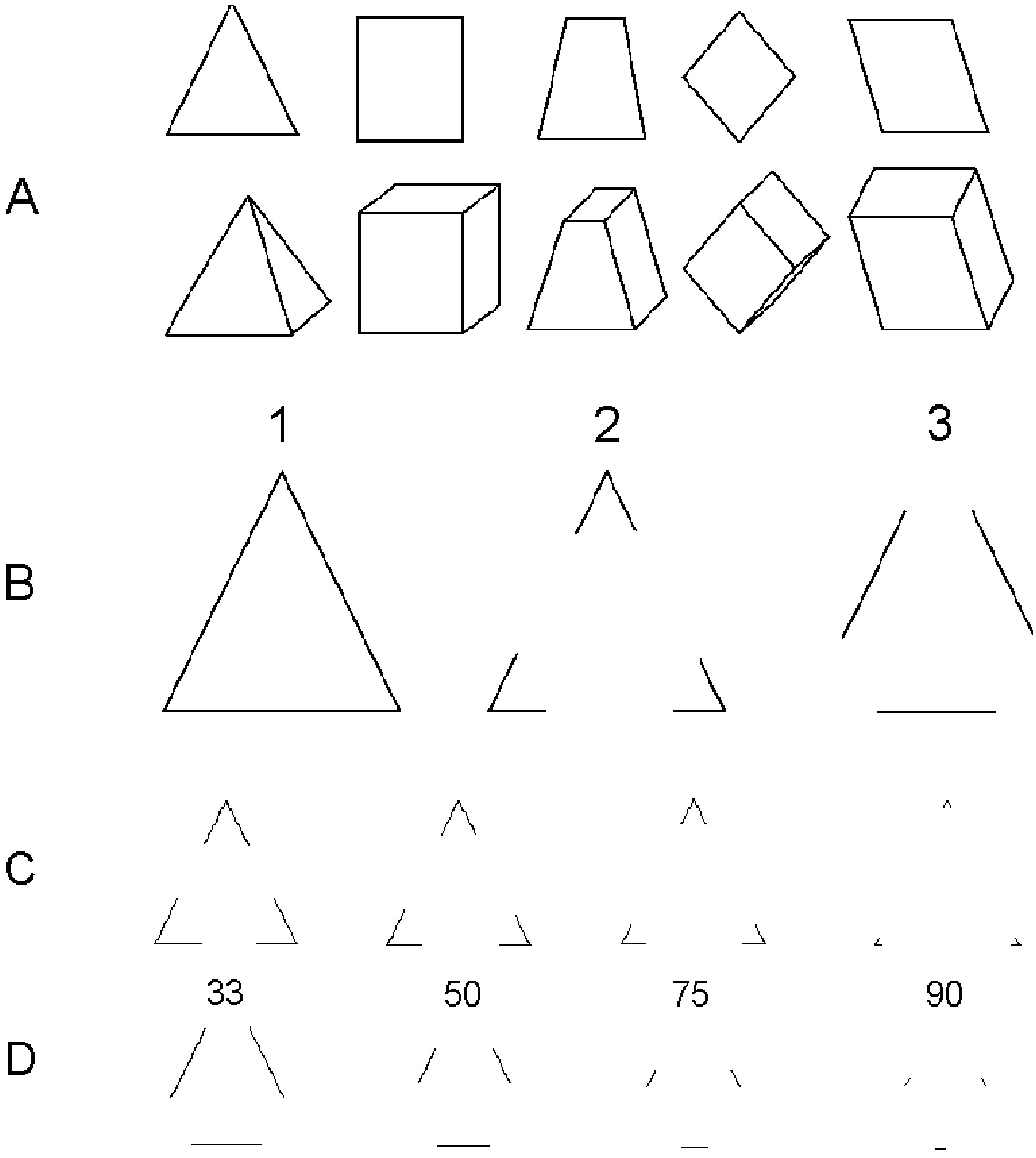

Fig. 1. Stimuli: (A) 2D and 3D geometrical figures, (B) an entire triangle (1), triangle with partly masked lines (2), and partly masked corners (3). Examples of a triangle with a different degree of masking (%) of lines (C) and corners (D).

masked all their lines or corners (both the side facing to observer and the other sides). The extent of masking varied in 6 steps from 33.3% to 90%. Masking of 50% of a figure line means, for example, that the middle half of each line was not seen (Fig. 1B, 2). In case of masking of corners an appropriate part of each line forming corner was excluded (3). Four examples of masking degree of 33.3, 50, 75 and 90% of a triangle lines (C) and corners (D) are also shown in Fig. 1.

Procedure. At the beginning of the first experiment, the training session was performed to introduce the stimuli set to observer and to standardize their nomenclature. We used a forced-choice procedure: observer had to name a figure shape ("triangle", "square" and so on). The next stimulus was presented after ISI of 10-15 s. During one experiment (about 1.5 hours), 360 stimuli were presented. Significance of data was estimated with standard parametric statistics: paired t-test and MANOVA (General Linear Model, repeated measures).

RESULTS

Recognition of two-dimensional figures

We have found a successive decrease in recognition performance with an increase in figure masking as compared to the control recognition performance. Figures without corners were recognized worse than figures without lines (Fig. 2). Overall estimation of recognition performance of the entire figures shows that it was rather stable during repeated testing (Fig. 2, zero level of masking).

For all degrees of masking, the figures without a portion of each side (Fig. 2, open circles) were better recognized than the figures without a portion of each corner (black dots). In the range of 50-90% of masking this difference was significant. Thus, under masking of 33.3% of each line or corner, the recognition dropped markedly ($0.00005<P<0.0005$) as compared to the control condition, but the difference between mean level of recognition performance for figures without part of lines or corners was insignificant ($P>0.05$). Masking of 50% of a figure elements led to a further decrease in correct recognition compare to the control level ($P<0.0005$), and the line-corner difference became highly significant ($P<0.005$). Masking of 66.6-80% of figure element decreased recognition even more and the line-corner difference stay significant ($0.0005<P<0.005$) as before. Under the 90%-masking, the probabilities of correct recognition became even lower and the line-corner difference was significant ($P<0.05$).

The analysis by MANOVA revealed significant effect of two factors: 3 × "types of stimulus" (entire figure vs. figure with masked corners vs. figure with masked sides) and 7 × "degree of masking" (0 vs. 33 vs. 50 vs. 66 vs. 75 vs. 80 vs. 90%). A significant effect on the level of correct recognition of a stimulus type ($F_{2,6}=46.21$, $P<0.0005$), a significant effect of a degree of masking ($F_{3,5}=46.6$, $P<0.005$), and insignificant effect of their interactions ($P>0.05$) was found.

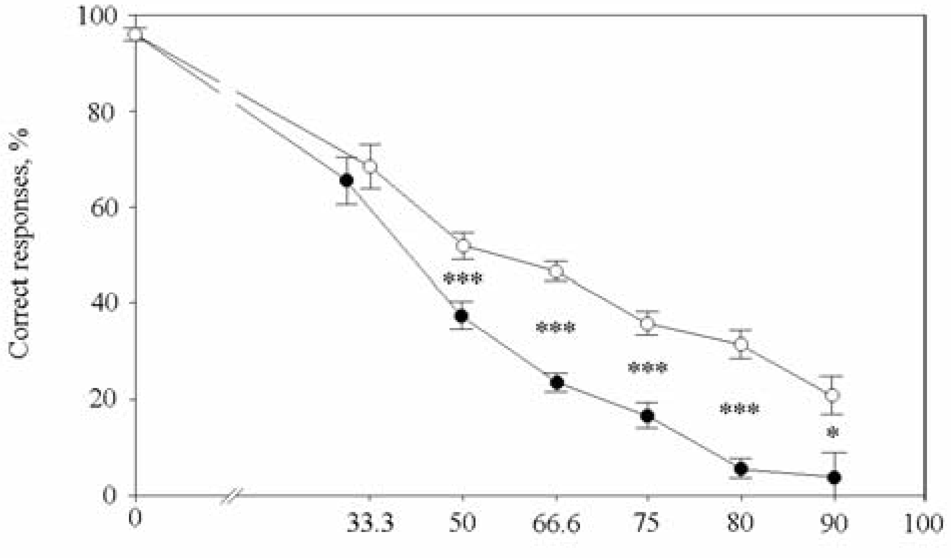

Fig. 2. Recognition performance (ordinate, percentage of correct responses on a figure shape) under different degree of masking of its elements (abscissa, %). Zero masking corresponds to the entire figure (control), open circles – to figures with partly masked lines (consisting from corners), and black dots – to figures with partly masked corners (consisting from central parts of their lines). Averaged data of 32 experiments with eight observers (mean ± S.E.M.) are shown. Probability of differences between mean data in two curves (paired t-test) is indicated: (*) $P<0.05$, (***) $0.0005<P<0.005$.

A comparison was made also of recognition performance for figures without corners or without lines (not including the control data for the entire figures). That means that effects of two factors were calculated: 2 × "type of stimulus" (masked corners vs. masked sides) and 6 × "degree of masking" (33 vs. 50 vs. 66 vs. 75 vs. 80 vs. 90%). In this case MANOVA also showed a significant effect of stimulus type ($F_{1,7}$=33.947, P<0.001), and significant effect of degree of masking ($F_{5,3}$=65.57, P<0.005). Interaction of these factors was insignificant ($F_{5,3}$=4.51, P=0.1). These results confirmed the significance of a stimulus type (figure with masked corners vs. figure with masked sides) and the degree of masking for the accuracy of recognition.

Recognition of three-dimensional figures

Comparison of recognition of 2D and 3D figures shows that the mean number of correct responses to the entire figures was significantly higher for 3D than for 2D ones (P=0.005). This relation changed for opposite under relatively strong masking (75-90%) of 3D figures: the performance level became higher for 2D than for 3D figures. The difference is better expressed for figures with corners than for figures with lines only.

The MANOVA analysis of data for 2D- and 3D-figures revealed significant effect on the level of correct recognition of two factors: 3 × "types of stimulus" (entire figure vs. figure with masked corners vs. figure with masked sides) and 7 × "degree of masking" (0 vs. 33 vs. 50 vs. 66 vs. 75 vs. 80 vs. 90%). Effect of a stimulus type was equal to $F_{2,7}$=126.86 (P<0.0005) and of a degree of masking to $F_{3,6}$=79.24 (P<0.005). At the same time, the third factor, dimensions of figures (2D vs. 3D) appears to be insignificant ($F_{1,7}$=1.89, P>0.05). The interaction of the stimulus type and dimension was significant ($F_{2,6}$=5.08, P<0.05).

For a strict comparison of recognition performance for 2D and 3D figures we excluded the data for the whole figures. Thus, effects of three factors were calculated with only two types of stimuli: 2 × "type of stimulus" (masked corners vs. masked sides), 6 × "degree of masking" (33 vs. 50 vs. 66 vs. 75 vs. 80 vs. 90%) and 2 × "dimensions of the figures" (2D vs. 3D). In this case, MANOVA showed significant effects of a stimulus type ($F_{1,7}$=4.25, P<0.05), degree of masking ($F_{3,5}$=64.67, P<0.005), and, additionally, of stimulus dimension ($F_{1,7}$=42.9, P<0.0005). The interaction of all these factors (stimulus type, dimension and degree of masking) was significant ($F_{3,5}$=19.37, P<0.05). These results confirmed significance of the stimulus type and dimension, as well as the degree of masking for the accuracy of recognition of 2D and 3D figures.

Gender differences in figure recognition

Significant gender difference in a recognition performance was found in our experiments in spite of a small sample (four men and four women). In total, men recognize entire and partly masked figures at all degrees of masking significantly better than women (2.1<t<9.7, df =30, 0.0005<P<0.05). MANOVA analysis has revealed significant effect of the sex ($F_{1,7}$=7.80, P<0.05) and significant interaction of the sex and a figure type (entire figure vs. figure with masked corners vs. figure with masked lines): $F_{2,6}$=111.46 (P<0.0005), and significant interaction of the sex and the degree of masking ($F_{3,5}$=48.5, P<0.005).

DISCUSSION

Recognition performance of geometric figures in our study

Using a shape discrimination task we compared the relative role of two mechanisms in humans recognition performance: extraction of the first-order features (orientation of line fragments) and the second-order ones (line-crossing and branching). We supposed that recognition of geometric figures formed of straight lines under near-threshold conditions would reveal the leading role of the second-order features (corners) as compared to orientation of lines. This hypothesis was confirmed in this study: figures without part of their lines were recognized better than figures without corners. This finding supports and makes more precise a previous finding on a relatively greater importance of apexes vs. lines for recognition of partly masked natural figures (Biederman 1987). The use of the natural figures in this study complicates the neurophysiological analysis of preference to apexes, because the sides of such figures, as against geometric figures composed from the direct lines, are curvatures rather than direct lines and can be detected by neurons sensitive to local orientation discontinuities rather than by neurons sensitive to orientation of line fragments only. That is why we studied a relative role of lines in comparison to corners in the accuracy of shape perception of outline geometrical figures.

Gender differences in recognition performance

In spite of the limited size of our sample we found significant gender differences in recognition of geometric figures: men recognize entire and partly masked figures better, than women. There were evidences on more successful recognition and mental rotation of images in men than in women (Delgado and Prieto 1996, Hammer et al.1995, Jobson and Watson 1984, Masters 1998, Masters and Sanders 1993, Richardson 1994), while their hemisphere dominance was different (Geheb et al. 1994, Hausmann and Gunturkun 1999). Evoked potentials to faces have also gender differences in amplitude and latency of components (Orozco and Ehlers 1998), although MRI did not show gender differences under visual spatial tasks (Unterrainer et al. 2000). Besides physiological, some psychological gender differences in performance were described: man usually are more active in difficult recognition tasks (Vecchi and Girelli 1998) that was typical for our experimental conditions (near-threshold tachistoscopic presentation of the images).

Possible mechanisms of detection of corners and lines

Recently, neurons with selective or invariant sensitivity to line crossing (crosses, corners and Y-like figures) were found in the cat primary visual cortex (Lazareva et al. 1995, 1998, Shevelev 1998, 2000, Shevelev et al. 1993, 1994, 1995, 1996, 1998a,b, 1999a,b, 2001) while Sillito et al. (1995) found sensitivity of neurons in cat and monkey visual cortex to a local orientation discontinuity. This property of striate neurons seems natural, because lines crossing and branching are the key features of practically all images and the most frequently used elements of the feature library. For instance, Y-like elements are present in an image of a tree (branching of a crown) and in any rectangular 3D object (converge facets). There are some indications of the existence of neural mechanisms that ensure angle coding in the human visual system (Carpenter and Blakemore 1973, Chen and Levi 1996, Eriksson 1970).

It may be supposed that the mechanisms of the revealed effects are based on the activity of two subgroups of neurons in the striate cortex: classical orientation detectors (Hammond and Andrews 1978, Hubel and Wiesel 1962, 1965, Orban 1984), on the one hand, and neurons selective to line crossing and branching, on the other (Lazareva et al. 1995, 1998, Shevelev 1998, 2000, Shevelev et al. 1993, 1994, 1995, 1996, 1998a,b, 1999a,b, Sillito et al. 1995).

It was revealed also that recognition of partly masked 3D figures used in our study was worse compared to 2D figures, however, entire 3D figures were recognized better. These findings can be connected with different complexity of the 2D and 3D stimuli. It must be mentioned that information about 3D shape may be selected also by neurons in monkey inferior temporal cortex sensitive to 3D shape (Janssen et al. 2000).

Possible mechanisms of recognition of incomplete figures

The role of a contour closure in recognition connected with figural completion or "buildup effect" was investigated mainly psychophysically (Kellman and Shipley 1991, Williams and Jacobs 1997). Contour closure was shown to enhance the accuracy of shape perception: it was more precise and fast for closed contours than for non-closed ones (Biederman 1987, Elder and Zucker 1993, Pettet et al. 1998, Ringach and Shapley 1996, Saarinen and Levi 1999). Ffytche and Zeki (1996) demonstrated an increase in the local cerebral blood flow in V1 and V2 only under a figure completion.

The mechanisms of a figure completion, or "buildup effect" are still unknown. Previously we characterized the degree of invariance of striate neurons tuning to a shape, orientation (Lazareva et al. 1995, Shevelev 1998, Shevelev et al. 1998a,b, 1999b), and an existence of a central rupture in a cross-like figure (Lazareva et al. 1998, Shevelev 1998). It was shown that sensitivity to crosses is more or less invariant to these features in about 30% of the studied neurons. It can be suggested that the ability of the visual system to fill in the ruptures in incomplete objects may be based on these neuronal properties.

ACKNOWLEDGEMENT

The study was partly supported by the Russian Foundation for Basic Studies (Project No. 99-04-48207).

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Received 7 April 2003, accepted 10 September 2003