Neuroscience and Behavioral Physiology, Vol. 38, No. 6, 2008

Optical-Geometrical Characteristics of Fragmented Figures and Integral Perception Thresholds in Repeated Tests

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Translated from Rossiiskii Fiziologicheskii Zhurnal imeni I. M. Sechenova, Vol. 93, No. 8, pp. 886–897, August, 2007. Original article submitted December 6, 2006, revised version received March 12, 2007.

The causes of reductions in the integral perception threshold for fragmented figures in repeat trials using the Gollin test were investigated. The first study involved four trials with 5-day intervals using one set of figures. The amplitude-frequency characteristics of the test stimuli were interpreted using correlation analysis, as were the thresholds in each trial. The second study involved two trials with a three-day interval. On repeat testing, half of the figures were known (from the first test) to the subjects. In addition, half of the figures (both familiar and unfamiliar) were fragmented such that their amplitude-frequency characteristics had values similar to those in the first test. The results showed that the decrease in thresholds were mainly due to optimization of the functioning of the mechanisms operating with the statistical rather than the subject characteristics of the images.

KEY WORDS: fragmented figures, Gollin test, amplitude-frequency spectrum.

The ability to recognize objects in which only isolated fragments are visible is an important property of visual perception. One of the most effective methods of studying this phenomenon is the Gollin test, which gives quantitative evaluations of the thresholds for perception of fragmented figures as whole figures [10]. However, despite the long history of such studies, the nature of tasks solved by the visual system in performing the Gollin test have remained uninvestigated [11]. The reason for this is quite simple: a "black box," which is what the visual system is, can only be studied by comparing information at its input and output. However, information at the input, i.e., the characteristics of the test stimuli themselves, are generally ignored.

Our previous studies reported data on a number of characteristics of test stimuli affecting integral perception thresholds [5, 6]. Recognition of figures was found to occur at a defined degree of outline completeness, which was not random. Each figure had its own individual threshold; thresholds varied in accord with the normal distribution around a particular value, though the order of presentation of the fragments changed randomly from subject to subject. Differences in the amplitude-frequency spectra of all test figure images were significantly lower at threshold fragmentation than at subthreshold fragmentation and on presentation of the entire outline [5]. Comparison of data obtained in [6, 7] showed that thresholds were surprisingly constant at identical rates of fragment presentation, even over different age groups (Fig. 1, *E*), i.e., early school students [6] and subjects aged 18–22 years [7].

A fragmented figure can formally be regarded as a combination of two images – the whole figure and an overlapping "invisible" mask with apertures through which the isolated fragments are visible. In the Gollin test, fragmentation is obtained by a different method (see Methods), though the same result is obtained (Fig. 1, *B*). The "invisible" mask was found to behave as a real visual interference. The greater the correlational similarity of the amplitude-frequency spectra of the images of the whole figure and the "invisible" mask, the greater the integral perception threshold of these figures. The dynamics of the signal:noise ratio during formation of the figures were studied. The signal was the similarity of the amplitude spectra of the fragmented and whole figures; the noise was the similarity of the spectra of the fragmented figure and the "invisible" mask. When the pro-

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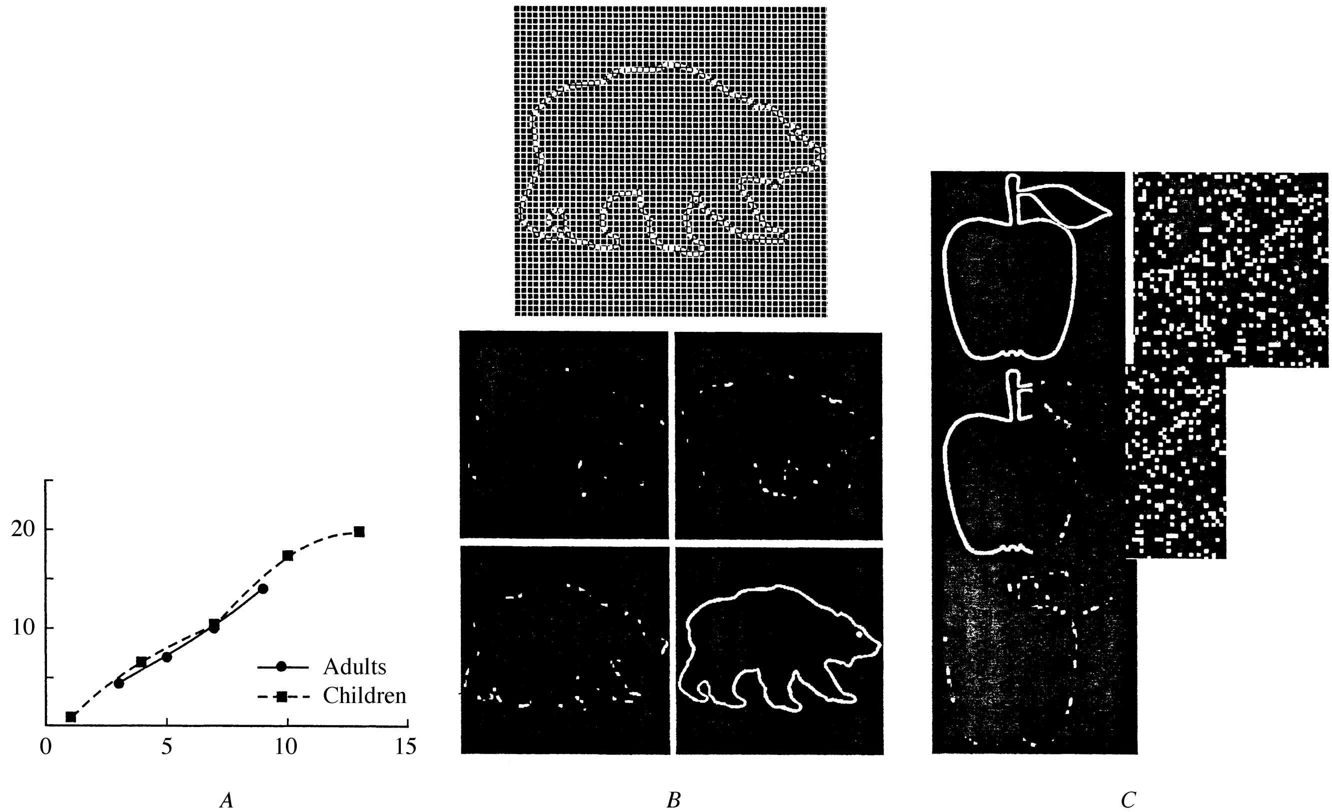

Fig. 1. Reducibility of mask fragmentation. *A*) Relationship between threshold size and the size of the program window forming the figure for different age groups: the abscissa shows window size, pixels; the ordinate shows the threshold value of the outline, %; *B*) image of a figure arbitrarily divided into program windows (above) and selected frames of formation of the figure in the Gollin test (below); *C*) perforated mask superimposed on a figure.

gram window displaying the fragments on the screen had different sizes, recognition of figures only occurred after the signal:noise ratio was greater than unity [6].

All these data showed that threshold fragmentation was a transitional point between chaotic and structured sets of fragments. The point or area of this transition was seen in the structure of the test images themselves, i.e., it was physical in nature. However, this result generated questions regarding the decrease in the threshold on repeat tests. The physical area of the transition cannot move; consequently, the signal:noise ratio at threshold fragmentation in repeat tests can be less than unity. Does this mean that the main role here is played by the mechanism of perception, for which the subject characteristics of stimuli are more important than the statistical characteristics of stimuli? The aim of the present work was to address this question.

METHODS

The Gollin test. Thresholds were measured using a modified computerized Gollin test [1]. Subjects were presented with outline figures. Outlines were white and had a mean thickness of 8.5 pixels. The program arbitrarily divided the images stored in the computer memory into squares (the program window whose size was specified prior to the experiment) and then one program window containing outline pieces was displayed after another (Fig. 1, *A*). The subject had to provide a correct name for the figure, after which the experimenter terminated presentation of the fragments; the threshold value for the outline was displayed, this being determined as V(fr)/V(i) × 100%, where V(fr) is the absolute value of the outline of the figure (in pixels) for the fragmentation recognition threshold and V(i) is the absolute value of the outline of the initial unfragmented figure (in pixels).

Spectral analysis of images. Spatial-frequency spectra of images were obtained using a rapid Fourier transformation program [12]. Two-dimensional amplitude spectra of one of the test figures ("apple") and the "invisible" mask, presented in polar coordinates, are shown in Fig. 2, *A*. Each point in the spectrum corresponds to an individual Fourier coefficient whose amplitude was expressed in degrees of gray, representing the distance from the center; the orientation was shown by the angle from the horizontal. One-dimensional slices in the major orientations, 0°, 45°, 90°,

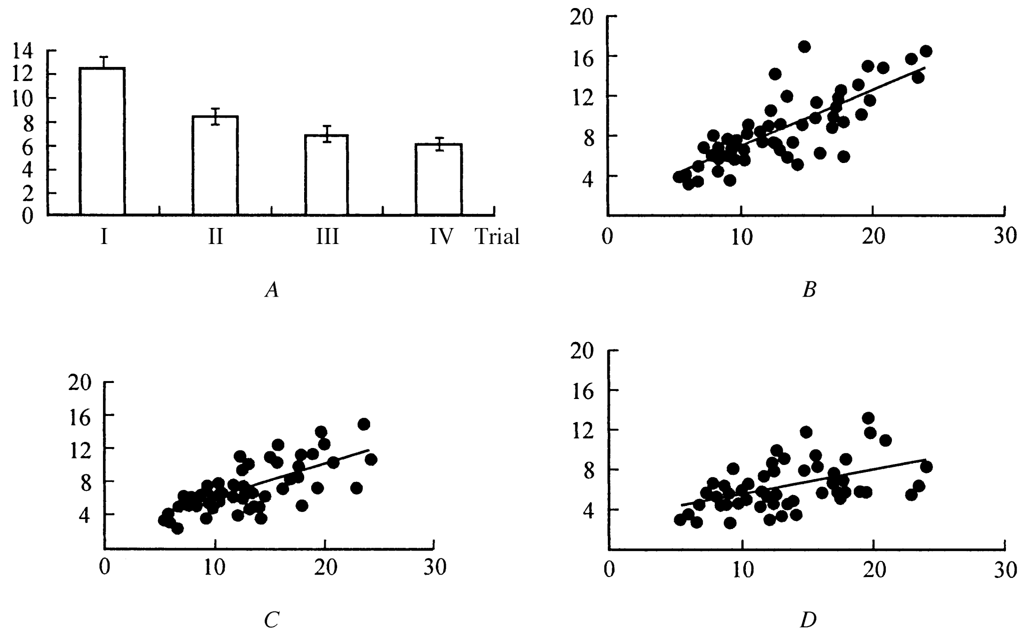

Fig. 2. Results of four trials. *A*) Threshold values of the outline in four trials ($x \pm 2S_x$, %); *B*, *C*, *D*) relationships between threshold values in trials 2, 3, and 4 (ordinate) and threshold values in the trial 1 (abscissa) for each figure.

and 135°, were isolated from each spectrum, and these slices were averaged.

One-dimensional profiles of the amplitude spectra of the "apple" and the "invisible" mask spectra are shown in Fig. 2, *B*. The periodic form of the spectrum arises because images are dominated by elements of identical size. The outline thickness of test figures was about 8–9 pixels, which is half the period (a complete period corresponded to a black-white pair). The period was 1/30 of the image of size 512 × 512 pixels, i.e., the spatial frequency of the outline was 30 cycles/image. The peaks in the spectrum of the figures at spatial frequencies of about 90, 150, and 210 cycles/image, corresponded to the odd (3rd, 5th, and 7th) harmonics of the outline. The peaks on the spectrum of the "invisible" mask also corresponded to the 3rd, 5th, 7th, and 9th harmonics of their spatial apertures.

RESULTS

First study. The first study involved four sequential trials using the Gollin test, with intervals averaging five days. The 11 subjects were those who were investigated in [5], which described the results of the first testing. The size of the program window showing fragments on the screen at a rate of one fragment/sec was 10 × 10 pixels. The effects of the amplitudes of coefficients of the spectra of the initial figures and the similarity between the spectra of the initial figures and the "invisible" masks on thresholds were evaluated in each test.

Repeat testing was found to result in a significant decrease in the threshold value of the outline. By the fourth trial, thresholds decreased almost two-fold (Fig. 2, *A*). Correlation analysis of these data revealed the following features (Table 1).

1) the integral threshold perception of fragmented figures on repeat trials showed a significant correlation with the corresponding values obtained in the first test, with an identical level of significance ($\alpha = 99.9\%$);

2) nonetheless, the correlation with threshold values obtained in the first test consistently decreased from the second trial to the fourth (Fig. 2, *B–D*).

Thus, the factors determining the difference in thresholds for different figures in the first trial continued to act in subsequent trials, though their influences gradually decreased. Comparison of the thresholds with the amplitude spectra supported this suggestion. The results of the first test showed that the threshold magnitude of the outline was correlationally linked with the amplitudes of virtually all Fourier coefficients of the images of the initial figures. Some of the coefficients showed positive and some showed negative correlations with thresholds (Fig. 3, *A*). On repeat testing, negative correlations remained virtually unchanged, while positive correlations decreased sharply (Fig. 3, *B–D*).

The maximal and minimal correlational functions coincided with the maxima and minima of profiles obtained by averaging the profiles of all 73 initial test images of figures with whole outlines (Fig. 3, *E*). The harmonics of the whole contour had negative influences on thresholds. However, coefficients located between the harmonics of the

TABLE 1. Correlational Links between Integral Perception Thresholds in Four Trials

Trial No.	Trial I	Trial II	Trial III	Trial IV
Trial I	1.00	–	–	–
Trial II	0.78	1.00	–	–
Trial III	0.70	0.78	1.00	–
Trial IV	0.51	0.69	0.79	1.00

Note. $p < 0.001$ for all data.

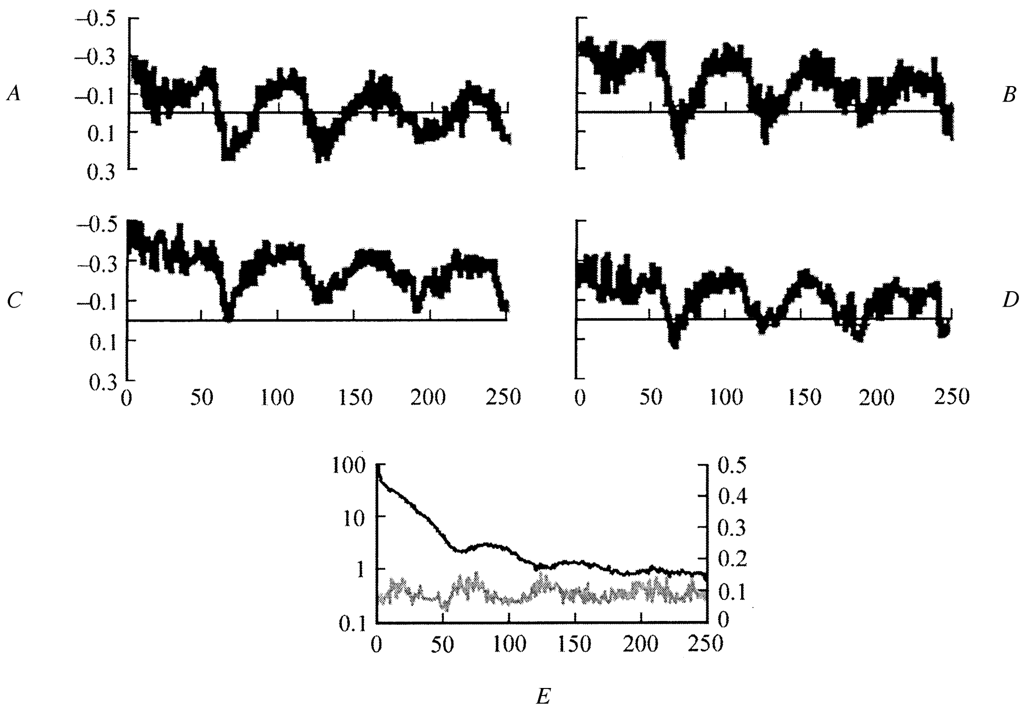

Fig. 3. Amplitude spectra of images of whole figures and threshold values. *A*, *B*, *C*, *D*) Relationships between amplitude spectra of images with threshold values in trials 1, 2, 3, and 4, respectively; *E*) variability of correlation functions compared with mean profiles of the spectra of images of whole figures. The abscissas (all plots) show spatial frequency, cycles/image; *A*, *B*, *C*, *D*) ordinates show correlation coefficients (r); *E*) the right-hand ordinate (gray plot) shows standard deviation (S_x); the left-hand axis (black plot) shows amplitude, relative units.

outline demonstrated a positive correlation with thresholds, i.e., they hindered integral perception of figures, thus functioning as interference. Repeat testing was associated with decreases in the effects of this interference on integral perception thresholds for fragmented figures. Thus, the status of this interference for the visual system changed.

As established in the previous study, a further characteristic with significant influences on threshold was the similarity between the amplitudes of the spectra of the "invisible" mask and the initial images of figures with whole outlines [6]. In this study, this similarity in the amplitudes of the spectra of the images of the figure and the "invisible" mask was expressed quantitatively using two methods.

In the first method, point-by point comparisons of the two-dimensional spectra of the figure and mask were made. The similarity of the spectra was characterized by the components coinciding in terms of spatial frequency and orientation, without consideration of amplitude differences between them. Two-dimensional images of spectra were digitized, i.e., the amplitudes of all components were taken to a single value (Fig. 3, *A*). The number of spatial-frequency components coinciding with components of the spectrum of the "invisible" mask was then calculated for each

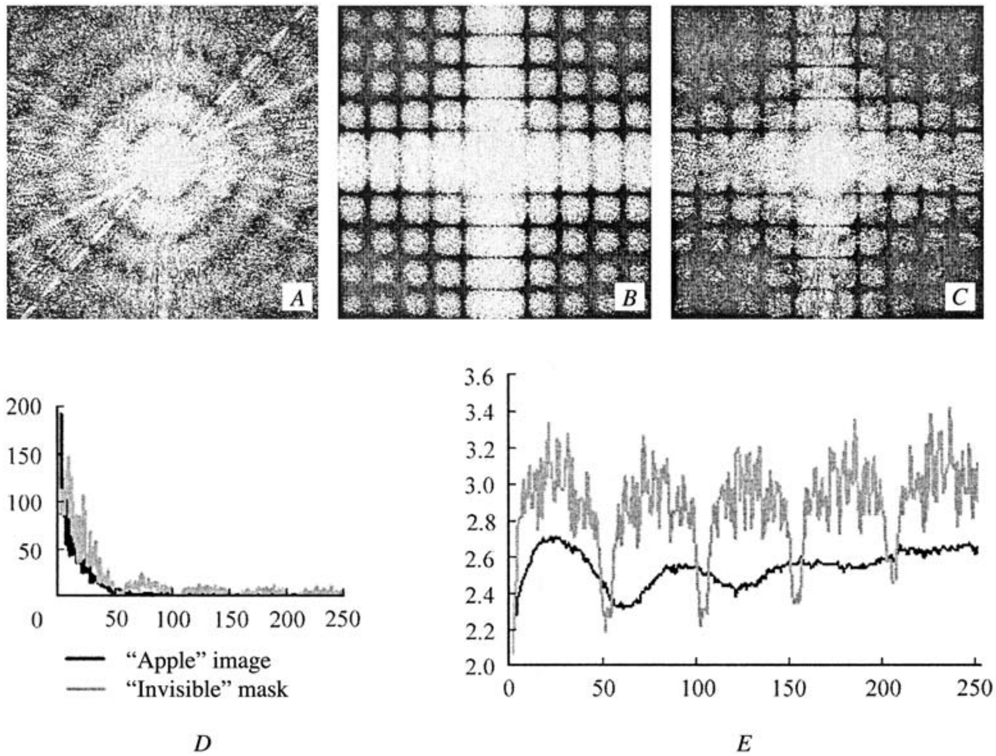

Fig. 4. Assessment of the similarity of the amplitude spectra of figures and the "invisible" mask. Two-dimensional amplitude spectrum of one of the test images (*A*) and the "invisible" mask (*B*); *C*) components common to the spectra of the figure and the mask; *D*) profiles of the spectra of the figure and mask; *E*) the same profiles after logarithmic equilibration. *D*, *E*) The abscissas show spatial frequency, cycles/image; the ordinates show amplitude, relative units.

figure (Fig. 3, *C*) as a percentage relative to the total number of components in the spectrum.

In the second method, the similarity between the spectra of the figure and the "invisible" mask was expressed in terms of the coefficient of the correlation between their one-dimensional profiles. However, comparison of the profiles of the spectra of figures and masks by correlation analysis was hindered by the fact that the amplitude of the low-frequency coefficients was 2–3 orders of magnitude greater than the amplitude of the high-frequency coefficients (Fig. 3, *B*). Thus, the results of correlation analysis are mainly affected not so much by the shape of the spectra as by the nature of the decreases in amplitude from low to high spatial frequencies. This can be ignored on comparison of the spectra of figures with the spectra of masks with apertures of different sizes (Fig. 1, *C*). However, comparison of the spectra of figures with the spectrum of one "invisible" mask showed that all correlation coefficients had very similar values.

In the previous study, this problem was addressed by comparing the profiles of spectra over short areas of width 30 coefficients. The analysis window was moved from low to high frequencies with a step of 50%. This allowed the range in which the similarity between the spectra of the figure and mask had a major influence on the threshold value of the outline to be identified [6]. However, general assessment of the influence of the similarity between the profiles of the spectra on thresholds by this method was not possible. In this study, the profiles of the spectra of figures and the "invisible" mask were subjected to logarithmic equilibration before correlation analysis, using the equation $Ae_i = \log_{10}(Ai_i + 1) + \log_{10}(i)$, where Ai_i is the initial amplitude of the component of spatial frequency i and Ae_i is the amplitude of this component after equilibration. This equilibration converted the profiles of the spectra of the figure and the "invisible" mask to a form suitable for comparison by correlation analysis (Fig. 4).

The correlation coefficient obtained for each test figure, characterizing its similarity with the "invisible" mask, were replaced by ranking values (to allow assessment of the simultaneous influences of these two characteristics). These data were then compared with the rank values of the outline obtained in the four trials. The following findings were obtained (Table 2):

1) The threshold for the outline depended on the similarity of the amplitude-frequency spectra of the figure and the mask, as expressed by both methods. The similarity expressed in terms of the number of coincident coefficients

TABLE 2. Correlation of Thresholds with Amplitude-Frequency Characteristics of Initial Figures in Four Trials

Trial No.	Similarity with the "invisible" mask		
	In terms of profile shape	In terms of disposition of components	In terms of profile shape and disposition of components
Trial I	0.52***	0.39**	0.58***
Trial II	0.58***	0.43**	0.63***
Trial III	0.42**	0.43**	0.53***
Trial IV	0.44**	0.38**	0.52***

Note. $^{**}p < 0.01$; $^{***}p < 0.001$.

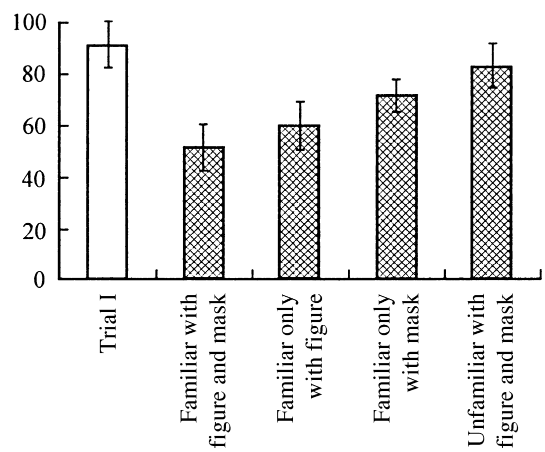

Fig. 5. Threshold values of outline in repeat trials in different presentation conditions. The abscissa shows the threshold value of the outline ($x \pm 2S_x$, % of normal).

for two-dimensional spectra generally demonstrated a lower correlation with thresholds ($\alpha = 99\%$) than the correlational similarity of the shapes of the one-dimensional profiles ($\alpha = 99.9\%$). If the two similarity characterizations were averaged, the correlation with the thresholds became significantly greater. This means that both characteristics of the similarity of the spectra of the figures and the "invisible" mask were complementary. In one case, the degree of overlap in the spatial frequency spectra is considered; in the other, their shapes are considered (Fig. 5).

2) The influence of the similarity of the spectra of the images of the figure and the "invisible" mask on the threshold generally decreased on repeat testing. This was particularly notable on comparison of the data from the first and second trials with those from the third and fourth. However, these changes occurred at the same level of significance ($\alpha = 99.9\%$). That is, the correlation with the threshold, although decreasing, remained quite high (Table 3).

Second study. In the second study, with seven subjects, two trials were performed with a three-day interval. The first trial involved 20 figures formed by a program window of size 7×7 pixels at a rate of one fragment per second. The second trial included 40 figures: 10 figures already familiar to the subjects, the size of the program window and the rate of formation being the same as in the first trial (set 1); 10 familiar figures formed by a program window of size 4×4 pixels at a rate of five fragments per sec (set 2); 10 not previously presented figures formed by a program window of the same and size and rate as in the first trial (set 3); 10 not previously presented figures formed by a program window of size 10×10 pixels at a rate of five fragments per sec (set 4). Test figures from different sets were presented in random order.

Separate assessments of the contribution to the reduction in thresholds on repeat trials were made for two factors in the present study: the subjects' familiarity with the characteristics of the "invisible" mask and their familiarity with the characteristics of the initial figures. Therefore, repeat testing used four sets of images differing in terms of these characteristics (Table 3). Set 1 consisted of figures already familiar to the subjects formed on the screen by program windows of the same size as in the first trial. Program window size formally corresponds to the size of the apertures in the "invisible" mask, so in the case of set 1, subjects were also familiar with both the characteristics of the figures and the amplitude-frequency (but not phase-frequency) characteristics of the "invisible" mask.

Set 2, correspondingly, contained familiar figures which were presented in conditions of an unfamiliar "invisible" mask. The figures in set 3 were not familiar to the subjects, but they were familiar with the amplitude-frequency characteristics of the mask. Finally, in the case of set 4, subjects were presented with unfamiliar figures in conditions of an unfamiliar "invisible" mask. As the sizes of the program window displaying the figure fragments on the screen and the rate of fragment presentation were different for the different groups, the resulting threshold values for the outline were expressed as percentages relative to the thresholds measured in other studies with the same parameters (Table 3).

Presentation of familiar figures with the same program window size (set 1) and familiar figures with a different

TABLE 3. Parameters and Results of Second Trial

Trial No.	Test figure set No.	Experience of perception		Threshold size in normal conditions	Threshold size in experiment	Threshold, % of normal
		figures	mask			
Trial I		–	–	9.7	8.8	91.2
Trial II	1	+	+	9.7	4.9	50.9
	2	+	–	6.4	3.8	59.6
	3	–	+	9.7	6.9	71.4
	4	–	–	17.3	14.3	82.7

program window size (4×4 pixels, set 2) was found to lead to a significant reduction in thresholds. The reduction also occurred on presentation of unfamiliar figures with the same program window size (set 3) as in the first trial. Presentation of unfamiliar figures with a different program window size (10×10 pixels, set 4) produced no significant reduction in thresholds (Fig. 3). Thus, repeat testing resulted in a decrease in thresholds even for figures unfamiliar to the subjects if they were presented in conditions of a familiar "invisible" mask.

DISCUSSION

The Gollin test is traditionally used for studies of perceptive learning [1, 10]. What is this learning? Two types of learning are known: procedural and declarative. Procedural learning occurs unconsciously and consists of a gradual improvement in the performance of defined procedures (for example, drawing) [4]. Declarative learning is a conscious process based on remembering concrete events, appearances, and facts.

Some investigators believe that the decrease in threshold on repeated performance of the Gollin test depends on memory of the image parameters, which narrows the range of choices, and on the formation of traces of the complete images, which can occur on stimulation by incomplete figures [8]. That is, the decrease in thresholds is explained by the influence of declarative learning. However, patients with amnesia due to bilateral temporal lesions also show better performance on repetition of test, though they do not remember the figures themselves [13]. This suggests that the improvement in the results on repeat trials is due to procedural learning [4]. However, the decrease in the thresholds on repeat trials in amnesia is generally explained by the phenomenon of "hidden" memory, or "memory for a hidden image." It is presumed that a previously presented figure is remembered, though the patients are not aware of this [3, 8].

The present study established that on repeat trials, the nature of the correlation of thresholds with the amplitude spectrum of the initial images changed. While in the first trial some components of the spectrum showed a positive correlation with the threshold size, others showing a negative correlation, the positive correlations virtually disappeared on repeat trials. Before interpreting this result, it is important to establish what this correlation means.

In the first trial, the subjects were not familiar with the initial figures. Furthermore, in the spectrum of the image of the fragmented figure, even at threshold fragmentation, peaks corresponded to harmonics of the "invisible" mask rather than with the whole outline (Fig. 3, *E*). Nonetheless, the negative correlation with thresholds was shown by the harmonics of the whole outline. However, that which is neither in the image nor in the subject's memory cannot influence the size of the threshold. However, it follows automatically from the reality of the "invisible" mask for the visual system established in our previous study [6] that the presence in the image of the fragmented figure of the whole outline is also real (in masked form). The correlation of the amplitude spectra of the initial images with the thresholds is superfluous to this support.

The change in the nature of the correlation of the amplitude spectra with the thresholds in repeat trials may be explained either by optimization of the functioning of the mechanisms extracting the signal from noise (figures from the "invisible" mask) or by recruitment of other mechanisms. However, in the latter case, the similarity of the spectra of the test images with the spectrum of the "invisible" mask would cease to influence the threshold of the outline. As shown by our data, the influence of this factor actually decreased on repeat testing, albeit insignificantly. The correlation with thresholds during the four trials remained at the same level of significance, though the magnitude of the threshold decreased two-fold. And the threshold size, even by the fourth trial, correlated at a high level of significance with threshold size measured in the first trial.

There is no doubt that part of the reason for the decrease in the threshold in repeat trials is an increase in the probability of random guessing without recognition. In the first trial, this probability was minimal and was identical for each figure. In subsequent trials, there was a significant increase. Firstly, the set of test figures was limited. Secondly, with a priori knowledge of the set, the probability of random guessing increased as the set neared completion – theoretically, the last image could be named correctly even before it was presented.

Assessment of the separate and combined influences of these statistical characteristics was aided by the second study. Repeat testing in the situation in which the subject was familiar with the amplitude-frequency characteristics of the images and the "invisible" mask led to the greatest reduction in threshold sizes. In cases in which the subject was familiar with the amplitude-frequency characteristics of the images or the mask, the decrease in threshold was minimal but still significant. And when subjects were familiar with the amplitude-frequency characteristics of neither the images nor the "invisible" mask, the reduction in thresholds was not significant.

The fact that thresholds decreased even for unfamiliar figures presented in conditions of a familiar "invisible" mask also explained the reduction in thresholds on repeat trials in amnesia. The Gollin test is fundamentally unsuited to studies of declarative memory. The processes of exhaustively searching for information in memory occur in a fraction of a second. The duration of the search also decreases by a fraction of a second in the case of a familiar alphabetic figure [2]. We assume that in the first trial, the memory search for each figure takes an average of 300 msec, decreasing to 100 msec in the second trial. However, in the Gollin test, the outline does not change even by 1% of times of 300 or 100 msec. Thus, the differences in thresholds cannot be associated with differences in the speeds of actual recognition processes.

Blinnikova proposed the hypothesis that two images are formed during the process of perception. One, the primary image, has a rough spatial configuration allowing the analysis to start. The second, is a refined, well drawn shape [1]. Nikitin, studying the recognition of tachistoscopically presented images [9], made a similar suggestion long before this. The Gollin test method is suitable mainly for studies of extraction of the first image. Of course, without recognition, measurement of thresholds in the Gollin test would be impossible. However, recognition here is only a signal of the end of preliminary processing bringing the fragmented image to a form suitable for recognition.

The present study leads to the following conclusions:

1) Changes in the functioning of the visual system leading to decreases in threshold on repeat trials are quantitative rather than qualitative;

2) Decreases in thresholds should be regarded as a consequence of learning, in which the greater role is played by the statistical rather than the subject characteristics of the images.

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