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Review

Physiology and Technology of Clinical Gollin Test

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Abstract: This review provides a detailed description of the Gollin test technique based on the recognition of fragmented images. Important stages in the development of this method are considered, too. The attention is paid to a review of our research conducted using the Gollin test to solve various problems in studying the mechanisms of signal extraction from noise, invariant perception, the insight phenomenon, and modeling the functioning of the nervous system. The neurophysiological mechanisms of incomplete image recognition are discussed. Suggestions are made for possible ways of the further development of the technique and its application in fundamental psychophysiology, systems of artificial intelligence, and medicine.

Keywords: Gollin test, Incomplete images, Visual perception, Signal extraction from noise

1. Visual Tests with Incomplete Images

The imposing diversity of psychophysical tests was designed to study visual perception. Each of these tests is specialized in operating with a particular aspect of vision. Among them, Mooney's [1] visual test is traditionally used in the gestalt psychology paradigm. Stimuli in this case represent degenerated images that contain the parts of the silhouettes of a face, and the whole image must be recognized from the partial information. The Poppelreuter test provides an effective tool for investigating signal extraction from noise since stimuli used in this method consist of a few contour images of different objects, superimposed on each other [2]. The task is to recognize all pictured objects. The Ishihara test [3] is widely used for studying color perception. Stimuli are represented by circles of small diameters with figures and backgrounds which differ from each other only by color so that the patient with impaired color vision is unable to distinguish the figure. Another visual test operating with incomplete images is the Gollin test [4]. The fragmented contour images of familiar common objects are used in the test. The percentage of contour removed is varied, which lets investigators find the threshold percentage sufficient to image recognition. Unlike other mentioned visual tests, the Gollin test is applied to many fields of research. It is used in studying perception thresholds, signal extraction from noise, learning, and memory. In addition, it provides a quantitative measure of object recognition efficiency. These advantages include wide usage and the possibility of the development of the Gollin test technique. Thus, considering the Gollin test, the neurophysiological mechanisms of its potential for application in different fields of science and medicine are discussed in this review.

Initially, Gollin drew contour pictures to form an incomplete image by partially erasing them [4]. This method of stimuli preparation developed in the 1960s became outdated in the 20th century. A significant step was made in 1987 by Nigel Foreman and Robert Hemmings, who presented the computerized version of the Gollin test [5]. They provided a more accurate measurement of the figure perception threshold by controlling the contour's score and increasing time. The next stage in the development of the program was the creation of a new version of the Gollin test in the laboratory of the physiology of vision of the Pavlov Institute of Physiology [6,7] for the recognition of an incomplete figure as a process of separating a signal from noise.

2. Image Incompleteness with Noise Addition

According to concept developed in the laboratory of physiology of vision of the Pavlov Institute of Physiology, the fragmentation of the image with full-color contour occurs due to the superposition of the mask, which consists of opaque areas identical by color and contrasts to the background and transparent areas. If the fragment of outline coincides with the transparent area of the mask, it is visible, while that with the opaque area is hidden. A gradual increase in the proportion of the contour in such cases is interpreted as the disappearance of the mask. Although this mask is "invisible", it is real for the initial stages of visual information processing and has the characteristics of multiplicative noise. It is filtered out in the lower divisions of the visual system and does not reach its higher divisions. That is why we call it the “unconscious mask”. This unconscious mask is considered noise from which the visual system needs to extract a signal (the image). Such a view on the Gollin test brings it into parallel with the Poppelreuter test. This similarity is reflected in the fact that the performance of the Gollin test correlates more often with the results of the Poppelreuter test than with that of the Mooney test [8]. The advantage of this interpretation, besides its convenience for designing the computerized version of the Gollin test, is that it allows operation not only with the parameters of the image but also with the parameters of the unconscious mask. In particular, we conducted studies on the spatial-frequency characteristics of the mask and their influence on the recognition threshold [9–11]. In these works, it was found that the value of the recognition threshold depended on the similarity of the amplitude spatial frequency spectrum of the original image and mask. The more similar the spectra of the mask (noise) and the image (signal) are, the more difficult it is to recognize the object. At the same time, at the threshold proportion (percentage) of fragmentation, the spatial-frequency characteristics of the mask and the fragmented image become as close as possible. The variability of the parameters of the amplitude spatial frequency spectrum of the fragmented image was also minimal at the threshold stage of fragmentation. The stimuli with the lowest recognition threshold had the highest similarity of the spectra of the original and fragmented images. It is also interesting that the recognition of fragmented images improves not only when the visual system learns the spatial frequency characteristics of the image but also when the corresponding parameters of the unconscious mask are learned. This confirms that the mask is perceived and analyzed by the visual system. Thus, the interpretation of the absence of a contour part as a mask overlay provides convincing explanations for the experimental data.

The deep investigation of stimuli' spatial frequency characteristics reveals their crucial role in the work of the visual system. In the 1970s, Ginsburg suggested that the unification of parts of a fragmented image into a single contour occurs due to low-frequency filtering of the image in the visual system [12,13]. An indirect confirmation of this hypothesis was provided by the gaze movement data of the patients during the Gollin test. When the gaze is fixed on the alleged center of the object, it does not follow the newly appearing fragments of the contour, which helps to observe the entire image as a whole [14]. In Ref. [15], stimulus images (fragmented letters) were filtered in various ways: broadband and narrowband in the low-frequency region and narrowband in the high-frequency region (Fig. 1). Fragments obtained through high-pass filtering consists of a black-and-white edge on a gray background. Such images are called "vanishing optotypes" as they tend to blend into the background when the image is blurred (i.e., low-pass filtered).

With small angular dimensions of the optotype, the smallest error was observed when the fragments were rectangular in filtering at high-frequency and low-frequency ranges and worsened the distinction. This result is predictable as an image constructed from full rectangular fragments contains the maximum spectral energy of the signal. At small angular sizes, recognition strongly depends on the signal energy [9]. However, the possibility of perceiving a complete image when observing "vanishing" fragments allows asserting the combination of fragments into a single hole under observation conditions without a low-frequency component in the image and an envelope function based on a preliminary selection of high-frequency fragments. Low-pass filtering facilitates merging as well mainly for small angular sizes of test images. Thus, the extraction of higher-order features and the determination of the general statistical properties of the image are complementary mechanisms providing the process of fragmented image recognition.

It is necessary to pay attention to the fact that the “unconscious mask” method describes the correlation of recognition, corresponding to the idea of implementing matched filtering in the visual system [16−20], which was experimentally confirmed [21−23]. The difference is the space of description. The method using an "unconscious mask" describes the space of the images and the coordinated filtering in the spectrum. This is prospective for the analytical description of visual recognition of the mathematical apparatus in correlation-extremal pattern recognition systems. In particular, such issues of visual perception can be viewed from the relationship between the recognition threshold and the information characteristics of the standard and presented images. It was shown that the value of the signal-to-noise ratio in the correlation comparison of images is proportional to the ratio of the area of the recognizable image fragment to the area of correlation [24] which is understood as the cross-sectional area of the global maximum of the autocorrelation function at a given level. This ratio, the generalized spatial frequency, serves as a correlation estimation of the information capacity of an image, since it determines the effect of additive and multiplicative noise on recognition efficiency [25–29]. In turn, the ratio is determined by additional filtering due to the limited dynamic ranges of sensors and sensory tracts [30–33]. The influence of distortions of the recognized image relative to the reference one is also determined by the ratio of the the generalized spatial frequency [34].

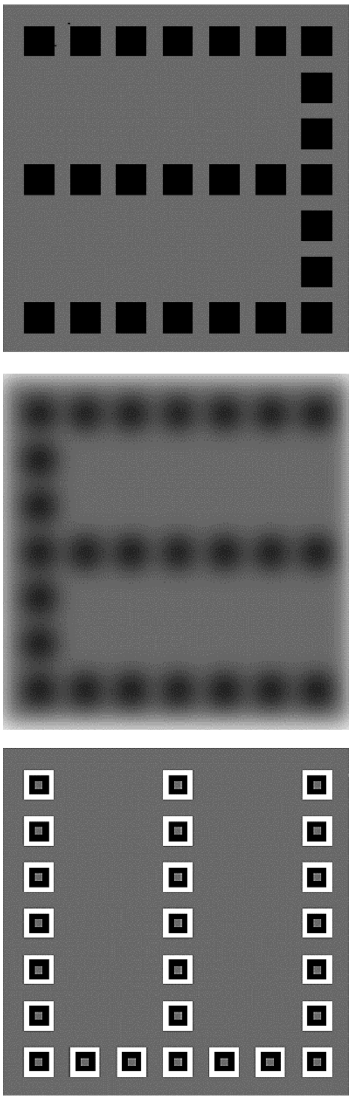


Fig. 1. Examples of fragmented prototypes. At the top, the original image is shown, in the middle, a low-pass filtered image, and at the bottom, a high-pass filtered image.

It is possible to apply the mathematical correlation processing to cognitive phenomena including the fuzziness of assessments characteristic of human thinking [35] and perception through anticipation (predictions or expectations) [36], inductive generalization as a concept formation mechanism [37,38], self-linking of images presented at different times (independently) [39,40], recognition instability [41], and the violation of classical probability theory when choosing alternatives in contradictory conditions. The mathematical apparatus describes biologically motivated neural network architectures and the real properties of their elements (nonlinearity of synaptic sensitivity). In particular, the apparatus corresponds to the concept of a sensation circle that implements the mechanism of stimulus re-entry into the cortical areas of the brain after assessing its subjective significance in structures of long-term memory [42,43]. The mathematical apparatus describing the recognition of visual patterns can be applied to various recognition phenomena in which a quantum-like logic is observed. Reference [44] shows that non-commutativity in making sequential decisions can be explained by the quantum-like model [45] and the framework of the neural network.

3. Gollin Test Using Wavelet Fragmented Images

Taking into account the strong influence of the spatial frequency characteristics of images on the efficiency of recognition, the inconsistency of the impact of visual stimuli with the organization of the receptive fields of the visual system is one of the disadvantages of the standard Gollin test. The contour of the binary visual stimuli gives a wide spectrum of spatial frequencies, while the neurons of the visual cortex of the brain respond to a narrow range of frequencies [46]. The receptive field of the neurons of the primary visual cortex in the range of spatial frequencies is approximately equal to 1.4 octaves [46]. The bandwidth of neurons does not depend on the spatial frequency to produce the maximum response. In addition, most neurons in the visual cortex respond selectively to stimulus orientations. Thus, it is necessary to choose a type of stimulus that selectively activates small groups of neurons in the visual cortex with similar specificity of the orientation and spatial frequency. Such stimuli follow the wavelet function with a clear localization in frequency and spatial area. The simplest variant of the wavelet is the Difference of Gaussians (DoG) function in which the different wavelets of two-dimensional Gaussian functions are expressed with a certain half-width.

$$f(x, y, \sigma) = \frac{1}{2\pi\sigma^2}\exp\left(-\frac{x^2+y^2}{2\sigma^2}\right) - \frac{1}{2\pi N^2\sigma^2}\exp\left(-\frac{x^2+y^2}{2N^2\sigma^2}\right) \quad (1)$$

where σ is the standard deviation and N is the scale factor.

Its spectrum contains spectral components with all possible orientations to achieve the selective excitation of neurons specific to the orientation of the stimulus. Thus, oriented wavelets are defined as a sinusoid multiplied by a Gaussian function.

$$f(x, y) = g(x, y)\sin\left(\omega\left(x\cos(\theta) + y\sin(\theta)\right) + \phi\right) \quad (2)$$

where g(x, y) is the Gaussian function, ω is the spatial frequency, θ is the orientation, and ϕ is the phase.

Another obstacle to the selective activation of neurons in the visual cortex is the overlapping of the spatial-frequency spectra of DoG functions. In this case, a stimulus optimal for one group of nerve cells may activate other cells whose bandwidth only partially overlaps with the spectrum of the stimulus. This problem is solved by using oriented wavelets with threshold contrasts as stimuli based on the assumption that neurons optimal in all characteristics respond to these stimuli with the threshold contrast. The contour images of the stimuli are approximated by wavelets with a given constant. The measurements are carried out following the standard technique of the computerized Gollin test and using threshold contrast wavelets (the threshold contrast is determined individually for each subject) in different sizes of the images and the wavelets that form their contour (Fig. 2). With the above-threshold contrast, the recognition threshold does not depend on the angular size of the image, while the recognition threshold increases with the increase in the image size with threshold contrast. As the stimulus size increases, it goes beyond the fovea to the more peripheral area of the retina, where neurons responding to lower spatial frequencies predominate, and these wavelets are no longer optimal stimuli. At the same time, due to the low contrast of stimuli, the reaction to them is indistinguishable from the noise of the visual system. Images with larger threshold contrast wavelets are recognized better than those with smaller wavelets. As the angular size increases, wavelets become optimal stimuli for neurons with larger receptive fields. The combination of information with the pyramidal representation of information occurs at large angular distances and improves recognition with a smaller number of derived wavelets.

Fig. 2. Examples of incomplete images of the same size from wavelet chains of different sizes.

4. Neurophysiological Mechanisms of Gollin Test Image Recognition

As mentioned above, wavelet-built stimuli are used to activate small groups of neurons in the primary visual cortex (BA17). In this case, it is important to understand which role this area plays in a complex process of incomplete image recognition. Field and Hess suggested that horizontal interactions within BA17 neural network are sufficient for the fragmented contour to be integrated into the image. However, our studies reached the opposite conclusion. Insight is a term for a sudden intuitive understanding of the problem posed and decision-making under uncertain conditions [48]. In this case, the task is to build a gestalt integral image from disparate fragments. The decision is not made in a consistent analytical way but in a sudden way, which represents a heuristic solution for a sensory-cognitive task. At the moment of recognition, the result of unconscious processes passes to the conscious level of decision-making. In Ref. [48], the Gollin test was used as a model of insight, so the insight was considered as a moment of reaching the recognition threshold.

In performing the Golin test using synchronized neuroimaging methods (fMRI), the heuristic type of solving sensory-cognitive problems is provided by the restructuring of large-scale neural networks covering various zones of the occipital, temporal parietal, and frontal areas [49]. Their activation is characterized by the opposition at the moment of making a decision. Thus, at the moment of the maximum activation of the zones BA37 and BA19 (according to Brodmann), there is a relative inhibition of activity in the parietal cortex BA7, mainly in its medial part (precuneus). Dependences shown in Figs. 3 and 4 reflect these relationships when the image recognition threshold (20% of contour fragments) corresponding to the insight effect is reached.

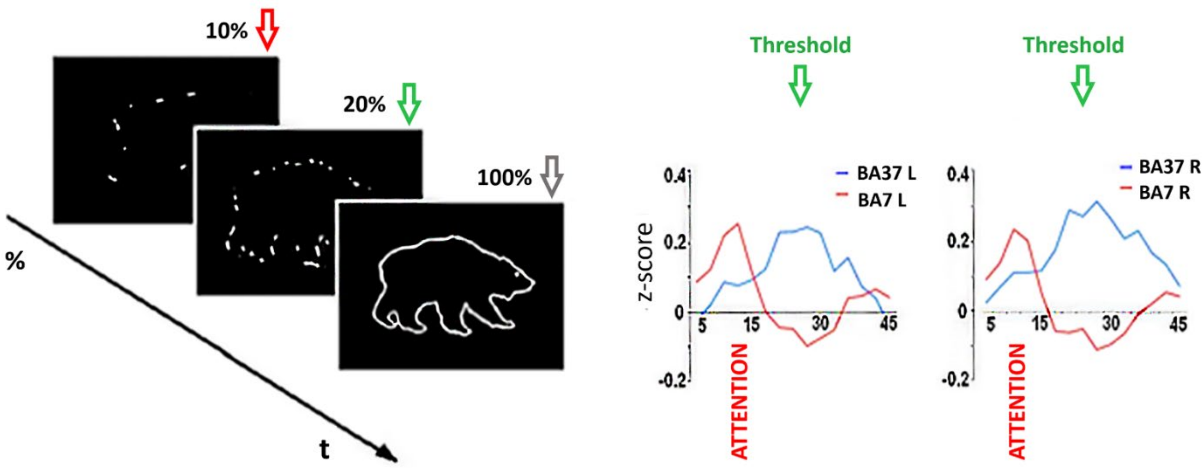
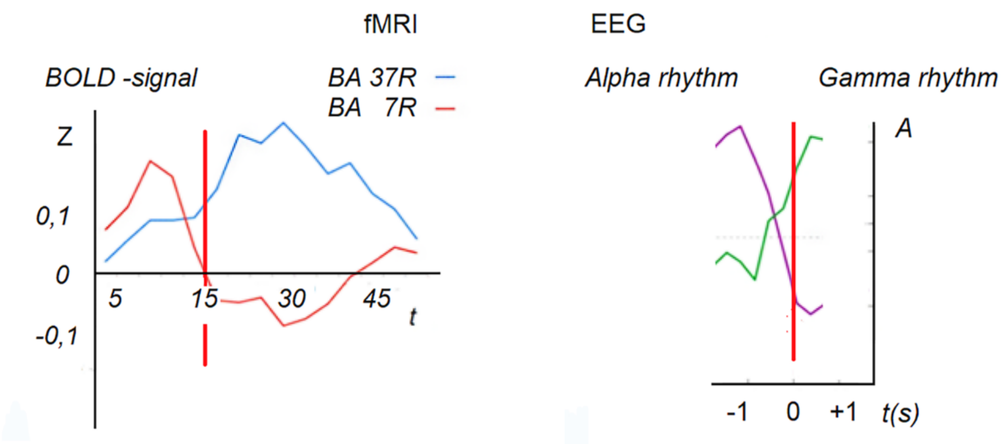


Fig. 3. Dynamics of activation of the BA7 and BA37 regions during heuristic solution of a sensory-cognitive problem in the context of fragmented image recognition (left).



(**a**) (**b**)

Fig. 4. Comparison of BOLD signal dynamic before, during, and after the development of insight with a dynamic in the relative power of the EEG in the alpha and gamma bands. (**a**) fMRI data from [14], the abscissa shows time t(s) and numerically corresponding contour percentage, the ordinate indicates Z-score, blue and the red lines show the BOLD signal dynamic in the areas BA37 and BA 7 of the right hemisphere correspondingly and (**b**) EEG data obtained in the work [50], the abscissa shows time t(s) relative to the moment of insight, the ordinate indicates the relative power of the EEG, the violet and the green lines show the dynamic of alpha and gamma rhythms correspondingly. The red vertical lines indicate the moment of insight.

The data indicate that the activation of the neural network of the modules of the primary visual cortex is insufficient for combining the presented fragments into a single image (gestalt) and its subsequent recognition contrary to the previous studies [51,52]. The zone of holistic perception in the lower temporal cortex BA37 plays a fundamental role. This position is confirmed by the data of clinical practice when the destruction of this zone leads to manifestations of agnosia. Many researchers think that BA37 and BA19 of the brain ensure the formation of concrete image thinking [53]. At the same time, it is important to clarify that one of the basic manifestations of agnosia is caused by a violation of the links between figurative and symbolic representations. In general, the oppositionality of BA37 in the temporoccipital and BA7 in the parietal zone, or BA9 and BA10 in the frontal regions of the hemispheres are correlated with a multilevel decision-making process in a situation of uncertainty. Similar manifestations are in the study of recognition of the visual image of a smile [54]. Thus, the BA37 zone is an area of intersection of several neural networks to evaluate the value of the identified object and its connection with the emotional sphere and ensure the transition from a visual concrete description to an abstract mental form (internal speech). These data support the neurophysiological relationship with visual-lexical associations that accompany the moment of image recognition in the insight model, i.e., the connection of a manifested visual image with its “speech form” (object nomination). This coincides with the study results on the localization of speech and language structures of the brain [55,56] which are associated with the lexical and semantic neural network and the network responsible for visual and spatial perception (with BA37 and BA7). The main part of Wernicke's area covers the areas BA22 and BA21 and also BA41 and BA42. Around its main part, there is a peripheral zone that includes the areas BA20, BA37, BA38, BA39, and BA40. according to neuroimaging data. This allows the existence of an "extended Wernicke's zone". The areas are involved in the production of speech and the formation of the grammatical system of the language in the "extended Broca's complex", combining BA44, BA45, BA46, BA47, and, partly, BA6. In addition, the insula (BA13) located between the anterior and posterior regions of the language network, is actively involved in the coordination of the work of these areas for the basic functions of speech and language. It is assumed to be the important brain center of language and speech [56].

In the context of the general organization of the work of neural networks, brain areas are jointly activated during the performance of one task with a high probability and belong to a common network associated with the function to serve as a filter criterion. This also is involved in visual recognition for which the connection between the systems of visual perception and language (speech nominations) is manifested through the visual-lexical association and semantic categories of images stored in memory. The operation of such relationships is also confirmed in the data we have obtained. The neurophysiological studies are carried out based on the heuristic problem-solving model to confirm the hypothesis of the restructuring of large-scale neural networks for a sensory-cognitive task under the uncertainty and ambiguity of selection criteria. The achievement of visual insight accompanies visual-lexical associations. The tested experimental model is used in the development of heuristic training programs for the elderly to prevent age-related sensory-cognitive dysfunctions.

5. Invariance of Perception

Other than the interaction between visual perception and speech nominations, another phenomenon that enables recognition is important for the invariance of perception. The invariance of visual perception is the ability to identify the same object when its illumination, size, orientation, rotation along the axes, and angle change. This ability is the most important property of intelligence [57] and is manifested in phylogeny and ontogenesis [58–60]. It is used to determine the effectiveness of human behavior in the environment. However, the physiological mechanism providing this function is still not fully understood. The Gollin test makes it possible to quantify the effectiveness of invariant perception by measuring the recognition thresholds of fragmented images by varying their sizes and rotation angles [61,62]. Attention needs to be paid to the study of invariant perception, i.e., various parameters of object images (angular dimensions, rotation angles, and others), in which the quantitative characteristics of perception remain unchanged. The image size is changed by varying the distance of the subject from the screen on which the stimuli are shown. To synthesize fragmented 2D images of 3D objects at different angles, the parallel projection of known 3D objects is created. One group observes images at one rotation angle in all successive experiments, while the other group sees images with an increasing rotation angle by 150º along the x- and y-axis, or both axes (Fig. 5).

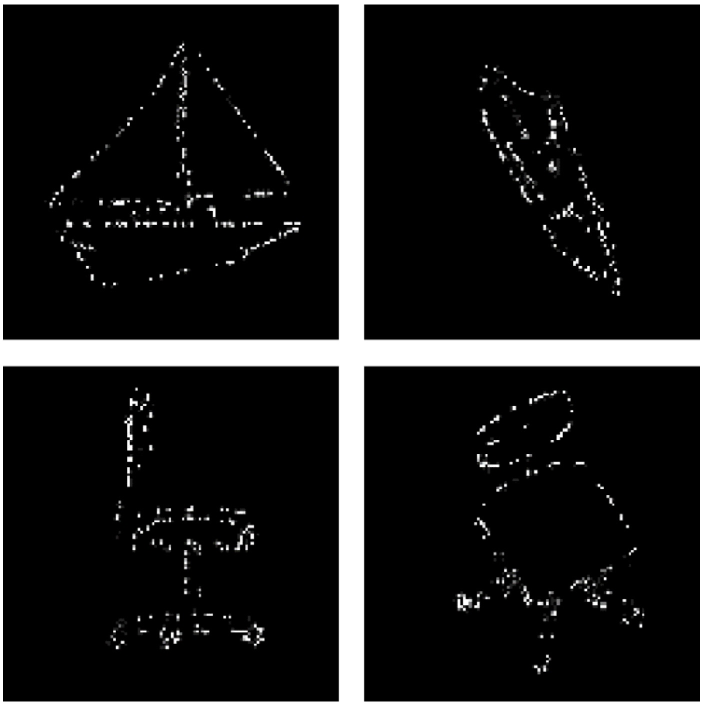


Fig. 5. Fragmented images with different rotation angles along each axis and two axes.

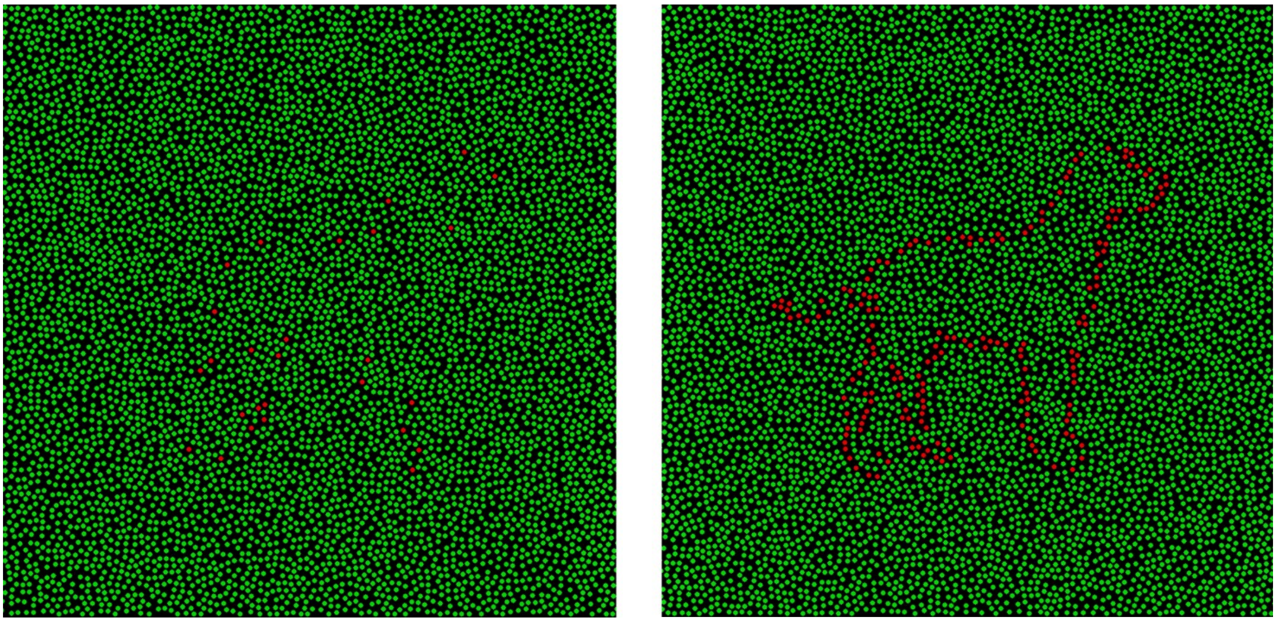
The effect of training and visual acuity on the recognition threshold for fragmented images is also investigated as the range of invariant perception of objects in different scales is determined. The angular size of the image does not affect the recognition threshold in the range of about 1 arc. min. to 50º. Threshold increase and appearance of unrecognized images for a small stimulus size of 0.19º arc. which corresponds to the size of the foveola can be explained by the influence of image blurring by the optics of the eye and internal image sampling noise. When recognizing such images, visual acuity begins to play a significant role. The deterioration of recognition in the case of large images with a size of more than 50º is explained by the fact that under such conditions, recognition without tracing movements of the eyes and head becomes impossible. Acquaintance with the alphabet of stimuli leads to a decrease in the recognition threshold, but the region of invariance remains approximately within the same limits as in naive subjects. In a series of experiments to understand the invariant perception of the rotation of three-dimensional figures, it was found that the recognition threshold drastically decreased and reached a plateau and did not depend on the rotation of the object 15 to 60 arc. deg. This indicates that the invariant template of the object is formed after the first acquaintance with the two-dimensional projection. Interestingly, the studies on localizing the area in the brain for the invariance image formation revealed the crucial role of BA37 [63], which corresponds to the role of BA37 as an intersection of different neural networks to build the integral image.

6. Color Gollin Test

Another modification of the classical technique implemented in our laboratory is the color version of the Gollin test. To expand the range of phenomena in the visual system, we studied using the Gollin test. The main differences in the new version relate to the stimulus material. Traditionally, contour images with a white outline on a black background are used. In such images, the figure differs by the brightness of the background. Brightness is not the only parameter used in the visual system to extract a signal from noise. Theoretically, to recognize a contour image, the contour needs to be distinguished from the background by light intensity and color. To investigate the matched spatial filtering in the observation of purely chromatic images, studies have been conducted [64]. However, up to now, no comparison has been made between the recognition efficiency of color and black-and-white fragmented images. Such a study helps to answer the question of which parameter difference – brightness or color – is more informative for the visual system for recognizing a fragmented image. To answer this question, a new method of the Color Gollin test has been developed. Based on classic images with a white outline on a black background, fragmented images were created to comprise grains with a diameter of 8 pixels. Importantly, the grains forming the background and the outline need to have the same brightness but different colors. Due to this design, the color Gollin test may be considered a developed form of the Ishihara test. While the classic Ishihara test only provides data on the recognized figure, a modified method provides recognition threshold measuring, inherited from the original Gollin test.

To equalize the brightness of the background and the contour, the heterochromatic flicker photometry method is used [65]. In the method, two fields are alternately displayed on the monitor screen – a reference in white and a test one. The test field shows colors with brightness equal to the reference. Two fields alternate with a frequency of 10−20 Hz. By changing the brightness of the test field, a value of flickering which is the least noticeable can be determined. The reference field of the same brightness is used to select the brightness of the background and the outline. We establish the hypothesis about the presence of two genetic subsystems of color vision in the human eye. The conventional system has the color blue-yellow, while the new one has red-green [66]. Volkov and Shamshinova considered that the normal functioning of these subsystems ensures full-fledged color vision in the modern world [67]. Currently, the possibility of using the Gollin test for the diagnosis of color perception pathology has been investigated with five groups of figures. In the first group, figures are presented and recognized by a color anomaly or dichromate. The second group uses blue figures with a wavelength peak of 480 nm on a yellow background with a wavelength peak of 589 nm. In the third group, yellow figures with a wavelength peak of 589 nm are used on a blue background with a wavelength peak of 480 nm. The fourth group uses red figures with a wavelength of a peak of 670 nm on a green background with a wavelength peak of 536 nm. The fifth group uses green figures with a wavelength peak of 536 nm on a red background with a wavelength peak of 670 nm.

Initially, the experiment subject sees a screen completely covered with background (for example, green). The outline of the object appears with a different background color (for example, red) as a part of the emerging outline (Fig. 6). As in the classical method, at the moment of recognition, the subject presses the button to stop the growth of the contour and fix the proportion of the part of the contour. The stimuli of the color Gollin test are not necessarily grains or circles. They can be wavelets to combine different modifications of the Gokkin test. For the neurophysiological mechanism of incomplete colored and black-and-white image recognition, a key role is played by BA19 and especially BA37.

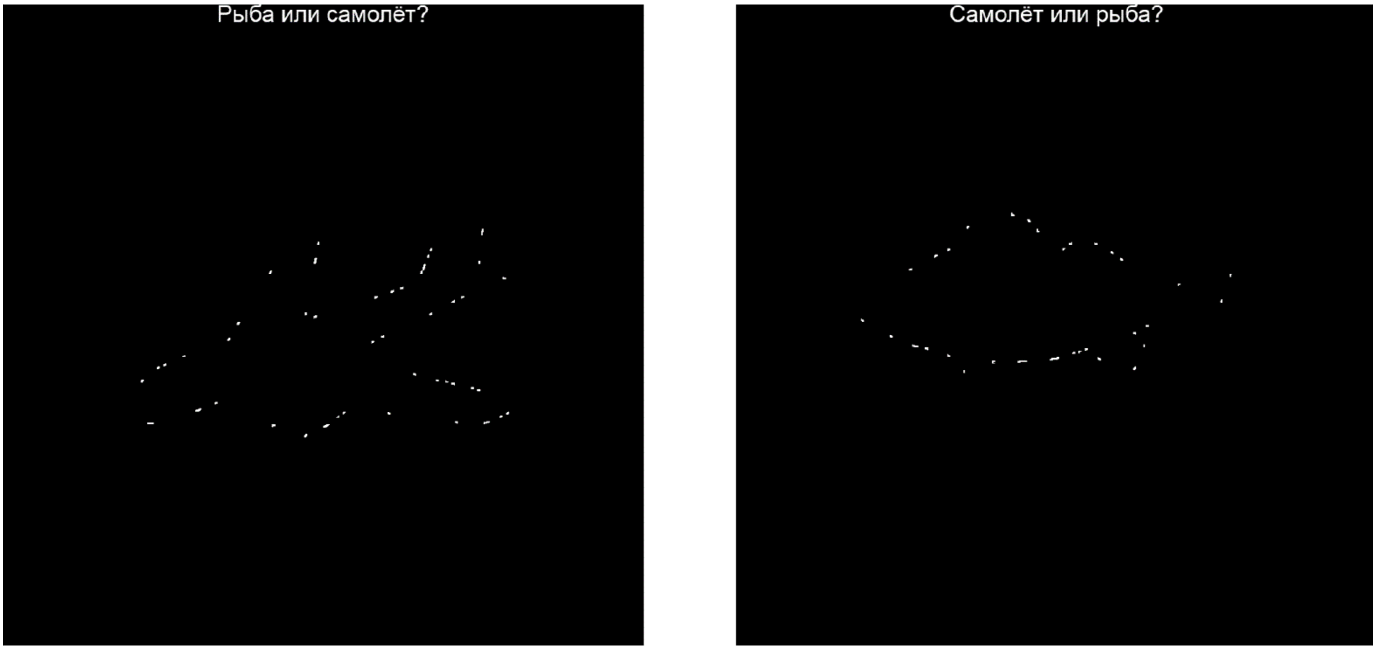


(**a**) (**b**)

Fig. 6. Example of the implementation of the color Gollin test technique with red tone figures (a wavelength peak of 670 nm) on a green background (a wavelength peak of 536 nm). (**a**) Image of the dog with 10% of contour and (**b**) Image of the dog with 60% of contour. In the experiment, the proportion of contour gradually increases from 1 to 100%.

7. Gollin Test with Forced Choice

Despite numerous applications of the Gollin test in solving various problems, the standard procedure still has drawbacks. First, subjects can name the same objects differently, which causes a problem with the correct interpretation. Second, the Gollin test has problems associated with the dependence of the threshold value on the strategy chosen by the subject, which is inherited from the early psychophysical experiment. For example, to minimize the number of errors, he or she can wait for the appearance of a larger contour and, accordingly, the recognition threshold can be overestimated. When they try to reduce the recognition time, the threshold obtained in the experiment becomes lower. To eliminate these shortcomings and increase the possibilities of using the Gollin test for computer testing, we proposed a new design for the experiment with two important differences. First, within the framework of the forced choice paradigm, the subject is asked not to name the object but to choose one of the two proposed options ("correct" and "wrong"). An example of images and answer options is shown in Fig. 7. The main parameter in successful recognition is the proportion of correct answers given by the subjects during the experiment. This method helps to formalize and make the subject's response more acceptable. Second, in this modification, the uniform growth of the contour is abandoned, and the original version introduced by Gollin is used. that is, individual stimuli with a known proportion of contour filling are presented in turn. At the same time, the image on the screen does not change until the subject makes a decision about which objects are seen in the image. This approach avoids the overestimation or underestimation of the threshold according to the choice of a certain strategy by the subjects.



(**a**) (**b**)

Fig. 7. Example of a pair of stimuli used in this of the Gollin test with forced choice. (**a**) an image of an airplane, the question above is “A fish or an airplane?” (In Russian), (**b**) an image of a fish the question above is “An airplane or a fish?” (In Russian), the proportion of contour filling in both images is 15%.

The choice of test images (stimuli) and “wrong” answers is made as follows. For each presented stimulus in the full set of test images, the image most similar to it (“double”) is selected. This "double" image is presented to the subjects as an incorrect answer. Thus, all presented stimuli are divided into pairs that are determined by the maximum similarity. The described changes in the test require additional preparatory measurements to determine which images must be combined into pairs for a choice. The most similar images are selected from the available set of stimuli, for example, an image of a living thing and a non-living thing in one pair. The similarity of images is assessed using cross-correlation analysis in which images are combined into pairs and the square of the correlation coefficient is compared. Providing a choice of two objects is a hint for the subject, the ratio of correct answers, even in the case of subthreshold stimuli, is approximately 50%. Therefore, the results obtained in this experiment must not be directly compared with the results of the classic Gollin test, where options for answers are not provided. This assumption is confirmed in a pilot experiment. With subthreshold contour filling, the ratio of correct answers fluctuates around 50%. As the contour becomes larger, the ratio asymptotically approaches 100% and shows a plateau for 9−10% of contour filling. The range of threshold values for the contour filling is from 4 to 9% in our experiments with 120 tests for 4 subjects (Fig. 8).

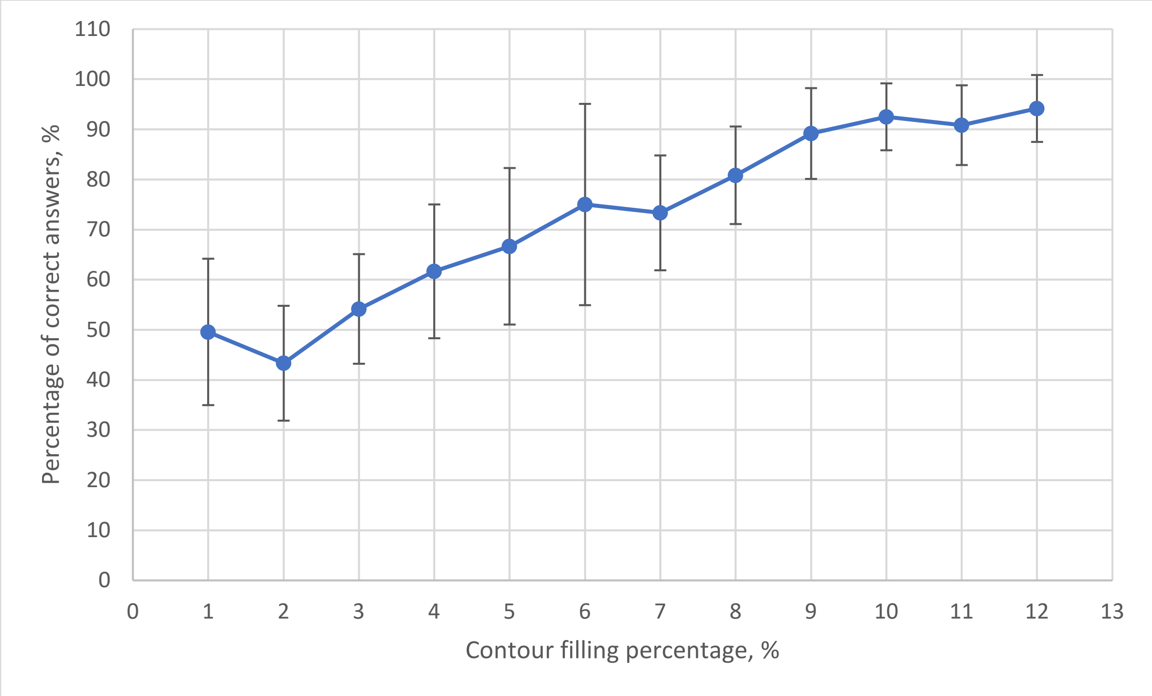


Fig. 8. Dependency of the proportion of correct answers on the proportion of contour filling (with data averaged for 4 subjects and confidence level of $p = 0.05$). The abscissa axis is for the proportion of contour filling, and the ordinate axis is for the ratio of correct answers.

The response time of the subject decreases as the proportion of contour filling increases (Fig. 9), which reduces the variability of reaction time between subjects. The results indicate the possibility of effective application of the new Gollin test design for computer testing on image recognition under uncertainty. This method can also be used for the investigation of learning due to subthreshold and threshold stimuli perception.

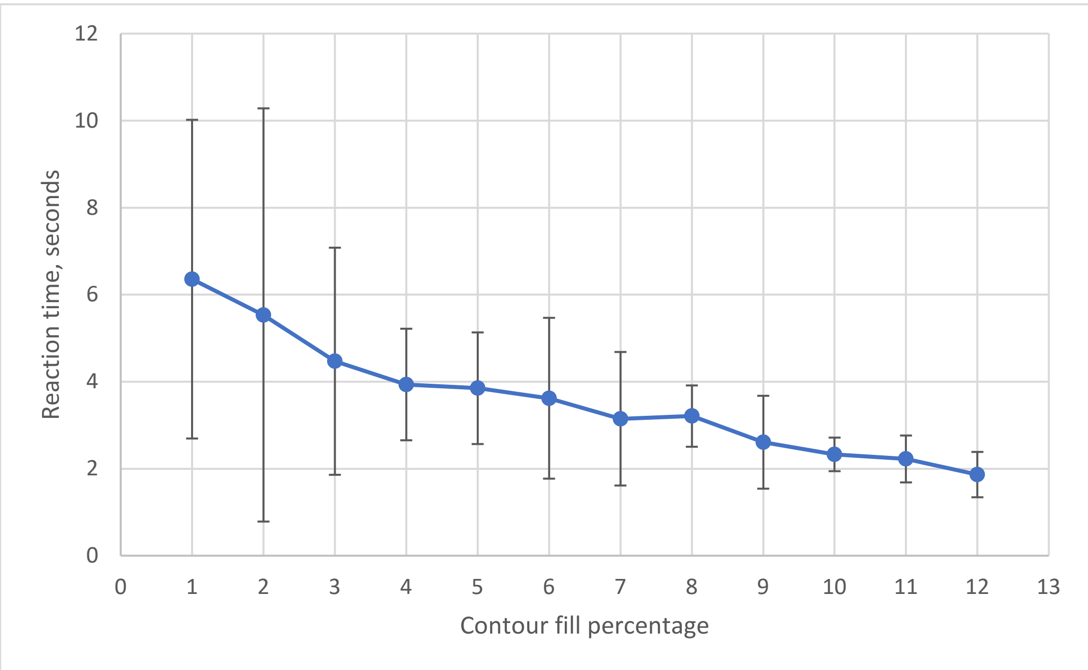


Fig. 9. Dependency of the reaction time on the proportion of contour filling (confidence level of $p = 0.05$). The abscissa axis is for the proportion of contour filling, and the ordinate axis is for the reaction time in second.

8. Clinical Application of Gollin Test

The test was applied to solve clinical problems. In 1968, Warrington and Weiskrantz designed a new Gollin test for studying long-term memory in patients with amnesia [68]. They added images of incomplete objects and incomplete letters in words in the test. Their study included patients with severe memory impairment (with Korsakoff's syndrome and after right temporal lobectomy) and peripheral nerve lesions without detectable cerebral diseases. Patients with amnesia belonged to the control group. Amnesic patients were unable to recall daily events and suffered from retrograde amnesias for 10 to 30 years. 10 image sets with 5 gradations and 10 five-letter words with 4 gradations (1 full contour and 3 intermediate diminishing incomplete versions) were tested. All participants were tested for 5 samples each day for three consecutive days. They examined the test result with images and words. Despite the significantly different results of the group of patients with amnesia from the group of healthy people, the final data showed obvious preservation of the image of objects in the memory on the second and third days. Both stimuli on the second and third days showed better results than the first day. The peculiarity of the reproduction of textual stimuli after 1 and 4 weeks was also studied for 11 healthy subjects. The results showed good retention even after a month. One patient with amnesia was tested at a 3-month interval, and the results showed a retention rate of about 20%. The findings of this study proved that amnesiacs who were unable to remember daily events revealed the retention of information about incomplete images and words between days. After that, the Gollin test began to be actively used in the diagnosis of cognitive impairment in diseases. Thus, in studies of dysfunctions of the right parietal lobe, patients with this lesion were required to present a larger proportion of the contour for recognition [69–71] to screen dysfunction in this area of the brain.

In a new version test, the perception of incomplete images of a wide range of psychological, psychophysical, and clinical tasks was examined. Patients with Alzheimer's disease [72–74], schizophrenia [75], amnesia [76], neuroses [77], and the dysfunction of the right parietal region showed significant differences in the Gollin test. The test was used to study the internal noise of the visual system as a measure of the functional state of the human brain [78,79], insight [14, 48], and age-related changes in healthy subjects [80]. Elderly subjects showed an increase in the recognition threshold for incomplete images. The Gollin test was successfully used in diagnosing cognitive dysfunctions of patients with ischemic heart disease who had coronary artery bypass surgery during the rehabilitation period [81,82]. A distinctive feature of the Gollin test for visual recognition is its length in time. Recognition of an object in the test improves gradually as the contour becomes larger to form an image of randomly appearing fragments. This advantage provides the basis for the successful use of the test in fMRI studies [49]. As known well, magnetic resonance imaging has a high spatial but relatively low temporal resolution. Therefore, standard techniques do not allow tracking the stages of object recognition. The Gollin test enables the adjustment of the rate of presentation of fragments and thus the modification of the technique for the temporal capabilities of tomography.

9. Conclusions

The long-term practice has proven the effectiveness of the Gollin test in solving various problems in psychophysics, psychophysiology, neurophysiology, and medicine. The development of the original Gollin test continues to overcome the existing methodological shortcomings and solve specific problems. As the Gollin test is based on the firm theoretical fundamental, it is used to explain the mechanism of perception and link incomplete image recognition to other phenomena observed in the brain. In the neurophysiological mechanism of perception, the crucial role in recognizing complete and invariant images associated with speech nomination is confirmed in the BA37 zone. With the increasing amount of data and progress in the study of the recognition process, the mechanism of figure formation in the brain still needs to be investigated. The development of psychophysical, neurophysiological, and computational models is also necessary [80]. The techniques used in this area use modified images in varying degrees of transformation in terms of frequency, color, brightness, the addition of noise, and shape transformation in the isomorphism continuum. However, it is difficult to find an alternative method to the Gollin test owing to its dynamic and temporal characteristics, ease of use, and effectiveness in understanding clinical issues of cognitive impairment.

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