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Mechanisms of Recognition of the Outlines of "Vanishing" Optotypes

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The aim of the present work was to study the interaction between the optical properties of images of "disappearing" optotypes and their recognition thresholds. The "disappearing" optotypes were figures with complex outlines and had a unique property – they were close to the threshold of recognition and observation, which increases the accuracy of measurement of visual acuity and the subjects' attention to them. The recognition distances of "disappearing" optotypes were measured. A relationship was found between the recognition distance of "disappearing" optotypes and different optical density profiles on the one hand and the spatial and spatial frequency characteristics of the stimuli on the other. The decisive factor determining the threshold of recognition of optotypes in spatial frequency terms is its spatial frequency spectrum; that in spatial terms is the width of the black/white pair or black-white triad in the complex outline. Regardless of the shape of the optotype, one of the most important limiting factors was the concordance of this test with the scattering function of the subject's eye optics.

KEY WORDS: visual acuity, recognition, "disappearing" figures, outline, threshold, upper limiting frequency.

In natural and laboratory observation conditions, approaching or receding objects have two main thresholds – a threshold of observation of the presence of the object and a threshold of recognition of the outline shape of the object. These two thresholds are characteristic of most objects in natural observation conditions. A given figure is recognized and observed at different distances. For images of normal outline figures, the distance of detection of the presence of a figure and the distance of its recognition are significantly different. In conditions exceeding resolving ability, the observer can only identify the presence and position of a normal image, which is completely blurred by the optics of the eye. The first threshold – the threshold of detection – is limited by the brightness of the figure and its contrast. This threshold is reached on observation of a blurred spot of the object image. Further approximation to the object leads to the second threshold; the test is recognized at this distance. The second threshold is limited by resolution. When the threshold of the resolving ability is exceeded, the observer can distinguish the shape of the figure. The thresholds for the detection and recognition of normal letters in Golovin–Sivtsev tables used for studies of visual acuity have been measured and published previously [21]. The existence of two thresholds poses a significant question in relation to measuring visual acuity, as there is a transitional zone between the recognition distance and the detection distance and subjects have long been known [15–17] to learn to recognize unclear, blurred images close to the detection threshold. The positions of the first and second thresholds depend on the whole series of conditions: contrast, brightness, color, interference, the signal:noise ratio, the concentration of attention, and the state of the observer. Calculation of the magnitude of the thresholds depends on the criterion selected – the percentage of correct responses.

Differences in the angular thresholds of detection and recognition are characteristic for the observation of virtual-

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ly all real objects, including as standard scripts, as well as the optotypes used for measuring visual acuity. The existence of two thresholds is one of the explanations for variability in the results obtained from measurements of visual acuity. Digital image processing methods – iconics [11, 12, 24] – has allowed a method for creating a novel type of image to be suggested – images for which the detection and recognition distances should be the same. These are termed "disappearing" images. This term is used because as the optotype becomes smaller or the distance of the observer from it increases, the observer suddenly ceases to see the shape of the optotype and becomes unable to identify the location of the object in the field of vision. When the threshold recognition distance is exceeded, the observer cannot see the blurred spot at the position of the optotype. Thus, there is a fundamental difference between "disappearing" figures and images based on all other scripts and optotypes.

"Disappearing" optotypes allow the known differences in the thresholds of detection and recognition to be minimized. Different investigators have created various "disappearing" optotypes which satisfy these criteria [2, 3, 8, 22–25, 28–31, 33, 34]. We note that in this context, the term "disappearing" refers only to optotypes constructed on the basis of letters or Landolt rings. Differences between the various "disappearing" test figures which have been proposed relate to the cross-section profiles of the optical density of the optotype outlines (hereafter termed the "profile contour"). Test figures with different profile contours have been created by different investigators on the basis of different approaches to this problem. We have created optotypes completely satisfying the scattering function of the "standard average" eye [22, 23]. Other authors have created "disappearing" optotypes which, theoretically, completely satisfy the "calculated average" weighting function of the receptive fields of ganglion cells in the foveal part of the retina. Optotypes with characteristics concordant with those of the cortical receptive fields have also been created. However, comparative analysis of the optotypes suggested by different authors has not been undertaken, and there are no experimental data on the relationship between the geometrical properties of the outlines (profiles) of "disappearing" figures and the physiological mechanisms responsible for visual acuity. The aim of the present work was to study the optical properties of test images used for determining the recognition thresholds of "disappearing" optotypes.

METHODS

Optotypes. Recognition thresholds were measured by synthesizing test figures (optotypes) in the form of Landolt rings. Landolt rings are used as standard optotypes in ophthalmology and all other optotypes are compared with them (in accordance with the International Standard ISO 8596) [38].

We therefore used Landolt rings as a template for constructing a group of optotypes of the "disappearing" type. "Disappearing" optotypes were constructed with classical ratios of the angular sizes of the bases and breaks in the rings to the total optotype size of 1:5, as described by Snellen. The synthesized test figures had profile contours with different optical density configurations. Firstly, we synthesized standard "non-disappearing" optotypes – single-contour Landolt rings (black Landolt rings on a white background, white rings on a black background, black rings on a gray background, white rings on a gray background). The optical density contour profiles of these optotypes were rectangular and simple. "Disappearing" Landolt rings were also synthesized. The optical density profiles of these optotypes were complex and they could be termed multicontoured, as one of the components of these contours was darker than the background and the others were lighter. The breaks in the ring were in one of four standard positions – above, below, left, and right. The observer was required to identify the orientation of the break in the ring. "Disappearing" and non-disappearing optotypes were synthesized for these increases to be of equal height, width, break size, and contrast. Four types of "disappearing" optotypes were used; a) optotype No. 1 had a double black-white profile with a 1:1 ratio of the widths of the white and black parts; b) optotype No. 2 had a triple black-white-black contour with a ratio of 1:2:1; c) optotype No. 3 had a contour composition of 1:2:3:2:1 (as per Howland); d) optotype No. 4 had a ratio of 1:2:2:2:1. In addition, non-disappearing optotypes with only black (optotype No. 5a) or only white (optotype No. 5b) contours were used. All contoured optotypes were displayed on a gray background.

For comparison, standard (uncontoured, non-disappearing) Landolt rings with simple rectangular optical density profiles with a ratio of 1:5 were also used; the width of the break corresponded to the thickness of the contour of the "disappearing" optotypes. The recognition distance of standard black optotypes on a white background (6a) was measured, along with distances for white optotypes on a black background (6b), black optotypes on a gray background (6c), and white optotypes on a gray background (6d).

Images were printed on a high-resolution inkjet printer onto matte plotting paper. Each sheet of the test card bore an optotype. The size of the contoured optotypes was 72.5 mm, with a break of size 14.5 mm, which corresponded to the size of the optotype in the first row of the Golovin–Sivtsev table, for which the recognition distance is 50 m. The thickness of the contours with different optical density profiles was 2.9 mm for all optotypes. Standard (non-disappearing, non-contoured) Landolt rings had an external diameter of 14.5 mm and a break size which corresponded to the thickness of the contours of "disappearing" optotypes, i.e., 2.9 mm. Test cards bearing these optotypes were placed in a standard Rota apparatus, which is widely used in ophthalmological practice for illuminating paper tests. Optotype illumination was at 600 cd/m^2. The Rota apparatus was located at the end of a long corridor with an illumination level of 10 cd/m^2. Test card sheets bearing images of optotypes were square; each optotype was presented in one of four positions.

Measurements of recognition thresholds. The limits method [1] was used to measure the threshold distance at which the orientation of the break in the optotype could be recognized correctly. Detection threshold measurements were not assessed in the present study. Recognition thresholds were measured using the classical psychophysical limits method, in its stepwise approximation variant, as used by the creators of the classical optotypes in the 19th century. Subjects were sequentially presented with isolated test figures. The test card bearing the optotype was placed in one of four positions. The subject was asked to approach the test card slowly and a record was made of the distance at which the orientation of the optotype was recognized. Despite its apparent simplicity, the method has high angular precision. The difficulty with the method of "stepwise" approximation is the need to make measurements in long locations with fixed illumination conditions.

Subjects. Studies were performed on 22 ophthalmologically healthy subjects aged 17–24 years after prior general ophthalmological examination including standard vision measurements using Golovin–Sivtsev tables [4–6], refractometry, biomicroscopy, and ophthalmoscopy. Refraction in most cases was emmetropic or weakly hypermetropic (to 1.0 diopters). All subjects underwent prior assessment of visual acuity using tables specially prepared by Koskin et al. [9] for measuring visual acuities much greater than 1.0. The mean visual acuity in the subjects, measured using the tables, was 1.53. The results of measurements of recognition distances for standard "non-disappearing" black-white optotypes and recognition distances for "disappearing" figures in different variants were compared.

Image processing and synthesis. Image synthesis was performed using the standard program Corel Draw 11. Image processing was performed using the Spektr program written by S. A. Pronin at the Laboratory of Visual Physiology, I. P. Pavlov Institute of Physiology, Russian Academy of Sciences. Programs written by V. B. Makulov and V. N. Pauk [32] were also used.

RESULTS

Different recognition distances were obtained for "disappearing" figures with different contour profiles. The recognition distance for "disappearing" optotype No. 1 (black-white profile with a 1:1 black:white ratio) was 31.88 m. The recognition distance for "disappearing" optotype No. 2 (with a triple black-white-black profile with a ratio of 1:2:1) was 25.21 m. The recognition distance for optotype No. 3 (with a ratio of 1:2:3:2:1) was 18.81 m. The recognition distance for optotype No. 4 (with a ratio of 1:2:2:2:1) was 21.54 m.

Measurements were also made of recognition distances of different variant "non-disappearing" optotypes and standard Landolt rings. The recognition for optotype No. 5a, which was the outline of a black Landolt ring with a double rectangular profile on a gray background, was 45.13 m. The recognition distance for optotype No. 5b, consisting of an outline of a white Landolt ring with a double rectangular profile on a gray background, was 45.54 m.

For comparison with the results of published measurements, we present data on the recognition of a standard Landolt ring with a simple rectangular profile on black, white, and gray backgrounds. The recognition distance of the standard black Landolt ring (optotype No. 6a) for our subjects and test card illumination conditions was 17.73 m, the recognition distance for the white Landolt ring on a black background (No. 6b) was 17.95 m, the recognition distance for the black ring on a gray background (No. 6c) was 17.74 m, and the recognition distance for the white Landolt ring on a gray background (No. 6d) was 17.80 m. Thus, the recognition distances for optotype No. 5a, the contour of a black Landolt ring with a simple rectangular profile on a gray background, and optotype No. 5b, the contour of a white Landolt ring with a simple rectangular profile on a gray background, were very similar, as also applied to the standard black and white Landolt rings. We therefore selected five optotypes for comparison and plot construction. These are shown in Fig. 1. Plots to the right of the illustrations show the cross-section optical density profiles of one of the contours of the optotypes.

We elected to select two physical criteria for assessing the relationship between recognition distance and optotype profile. The first of these was spatial frequency analysis of optotypes and the second was spatial analysis. For linear optical systems, these approaches give identical results. The linear properties of a visual system are limited, so it is appropriate to use two approaches.

We will first consider the results obtained from measurements in the spatial frequency range. The Spektr program written by S. A. Pronin was used to obtain two-dimensional test image spectra of fixed and identical size for all optotypes. The same program was then used to make one-dimensional sections. The one-dimensional section was used for determination of the peak spatial frequency in the spectrum, including that in which the main energy of the spectrum was located. The following values were obtained: 10 for optotype No. 1, 15 for optotype No. 2, 23 for optotype No. 3, 21 for optotype No. 4, and 3 for optotype No. 5. The relationship between the peak spatial frequency in the spectrum and the recognition distance was virtually linear. We then empirically selected a level at which the upper limiting frequency in the spectrum was measured, and this was compared with the recognition distance. The results of these measurements are shown in Fig. 2. The values for the upper

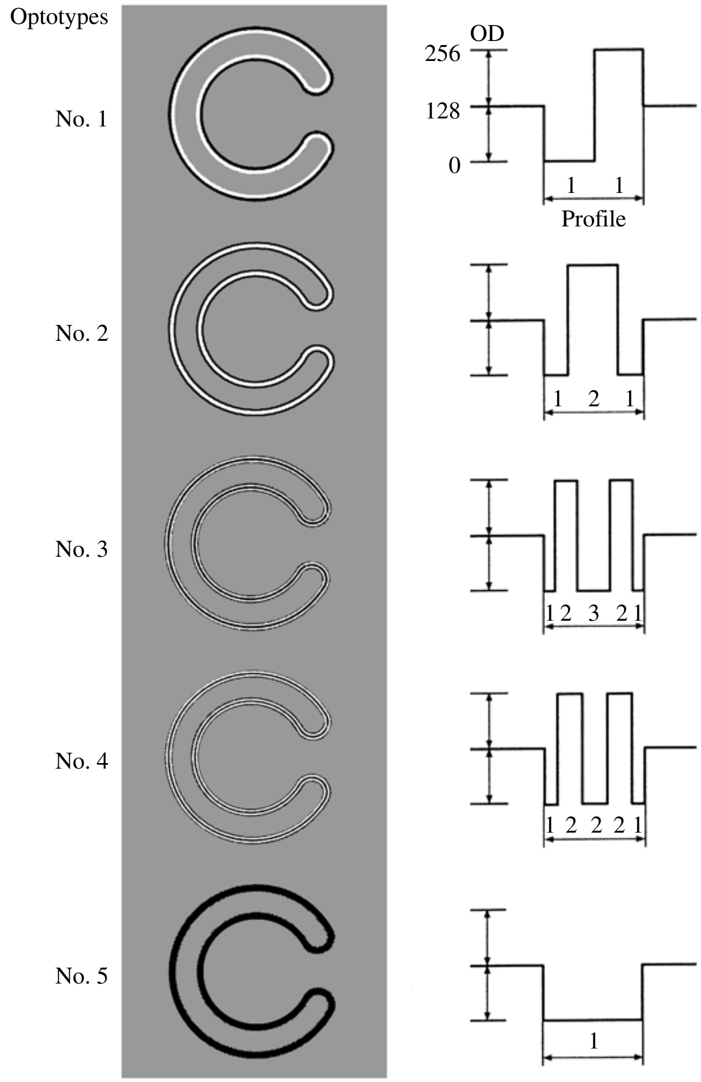

Fig. 1. Left: external appearance of contoured optotypes – “disappearing” (the four upper optotypes) and “non-disappearing” (the bottom optotype). Right: optical density profiles (sections) of their contours.

limiting frequencies and recognition distances had the linear relationship $y = -0.4387x + 46.626$.

Analysis of the spatial properties of optotypes was more complex. This is because comparisons were made of the results of measurements of optotypes whose contour profiles were quite complex in shape. We empirically tested different combinations of sums of the sections of light and dark bands. For No. 5, consisting of one black line on a gray background, the width was doubled, as though selecting a pair. Figure 3 shows the relationship between the recognition distance and the width of one black and one white band counting from the edge of the contour profile of the “disappearing” optotype. As in the spatial frequency analysis, an almost linear relationship was obtained: $y = 0.4379x + 14.983$.

The difference in the signs defining the slopes of the curves in Figs. 2 and 3 correspond to the ratios of the spatial and spatial frequency relationships. The reverse slopes of these functions correspond to the actual determination of the parameters under measurement – the spatial frequency and its inverse, the period.

DISCUSSION

The creators of “disappearing” optotypes deliberately planned to minimize the difference between the detection and recognition thresholds. We did not give this characteristic of “disappearing” optotypes particular consideration in the present study, which focuses on the factors determining the recognition distance of “disappearing” optotypes. We note that the outer and inner diameters and breaks were identical in all the test rings, while the recognition distances

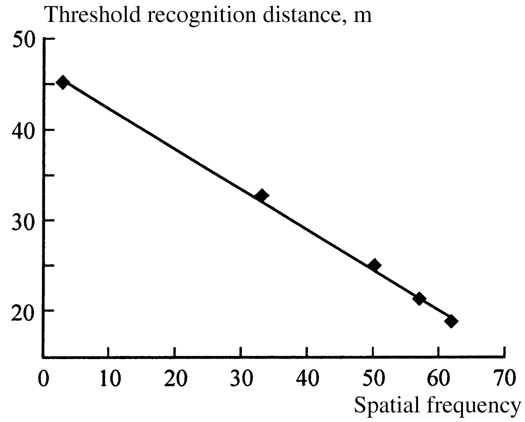

Fig. 2. Relationship between threshold recognition distance and the spatial frequency properties of the optotype. The abscissa shows the upper limiting frequency in the spectrum of the optotype profile, arbitrary units; the ordinate shows the recognition distance for the corresponding optotype, m.

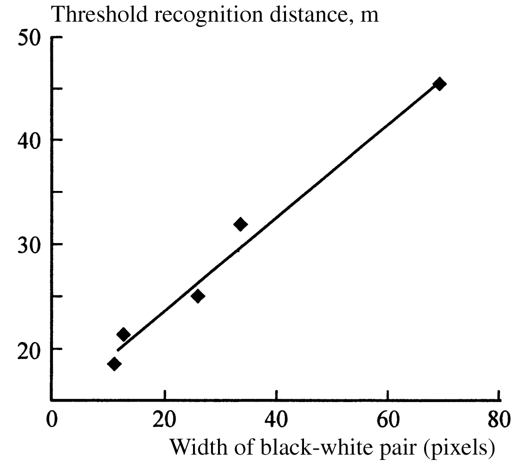

Fig. 3. Relationship between the recognition distance and the spatial properties of optotypes. The abscissa shows the black-white pair in the contour profile of the optotype, arbitrary units; the ordinate shows the recognition distance for the corresponding optotype, m.

were different. The contour profiles of all the rings were different. Analysis of the relationship between the optotype profile shape and the threshold recognition distance was based on both spatial and spatial frequency spectral approaches. Evaluation of the results in the spatial frequency area showed clearly that there must be a critical spatial frequency defining the limiting resolution of a given optotype. The calculation method has been laid out in detail in the doctoral thesis of Yu. E. Shelepin, *Visual Contrastometry and the Neurophysiological Mechanisms of Spatial Vision*, Leningrad (1987), pp. 262–271. We selected the peak spatial frequency in the spectrum and the upper limiting frequency. These frequencies, characteristic of a particular shape of the contour profile, depend linearly on the distance of the observer from a particular test.

The laws of optics indicate that the results of frequency analysis should correspond to the results obtained by analysis of the spatial properties of the images, in this case the size of the combinations of the black and white bars in the complex contour with an optotype ring of fixed external diameter. This optical law also applies to the visual system and for tasks associated with determining contrast and resolving ability [21]. The difficulty in studying the mechanisms determining recognition thresholds of "disappearing" optotypes of quite complex shapes arises from the selection of criteria and image elements appropriate to the investigation. We suggest that the fusion of "disappearing" optotypes with the background may be due to the fact that at the limit of resolution, the parts of the "disappearing" figure which are "lighter" and "darker" than the gray background fall below the effective part of the scattering function of the optics of the eye. If the contour is more complex than a black-white pair, we have to find the combination falling beneath the effective part of the scattering function, which will not produce a response from the receptive fields [19–21, 26, 27, 36, 37]. The effective (at half the height) scattering function of the optics of the eye, according to Raleigh's criterion, is usually taken as one minute. An effective width of the scattering function of a point of one minute is a value close to the mean. Raleigh's criterion is a statistical criterion. The observer, depending on conditions, can select another level for the section of the scattering function. These details are important, because the subjects in our set had above-average visual acuity. Golovin and Kholina showed [4, 14] that visual acuity on average is greater than unity, i.e., resolving ability is less than one minute. It can be suggested that the scattering function and the cone size in this group were minimal. In addition, the observers were not presented with points but with the outlines of optotypes, and could average along the line and thus improve the signal:noise ratio. Overall, resolution on observation of "disappearing" optotypes by members of our set of observers corresponded not to one arc min, but reached 0.5 arc min.

We will consider in more detail the factors determining the signal:noise ratio in these measurements. The scattering function is concordant with the receptive fields of visual system neurons. The weak signals from several receptors are summed in the receptive field to extract the signal from the noise. Increases in receptive field size lead to strengthening of the signal and reduction in interference, as the increase in size allows the signal to be accumulated. Decreases in receptive field size yield maximum resolution and, thus, transmission of more information [7, 10, 11, 13, 18, 19, 24]. The smallest foveolar receptive fields, formed from the smallest cones, provide the highest visual acuity and thus provide the neurophysiological mechanism which sends images of “disappearing” optotypes to the brain at the margin of their recognition. The response of the receptive fields of retinal ganglion cells depends on the local contrast relative to the background – the signal:noise ratio. Within the effective part of the scattering function, this is related to the characteristics of the receptive fields, while at the limit of resolution the light and dark parts of the optotype profile will be averaged. If the result of averaging is equal to the brightness of the background (or, more precisely, the optical density, as in our case the stimuli were presented on paper), there will be no response from the receptive fields and the optotype “disappears.” These are the conditions we selected, at which measurements of the optotype threshold recognition distance were made.

However, the foveolar high-frequency receptive fields of ganglion cells are only a major part of the high-frequency channel. The striate cortex, with orientationally selective receptive fields, is regarded as the neurophysiological basis for the major output of the spatial frequency channels [36, 37]. In the extended receptive fields of striate cortex neurons, signal accumulation occurs along the optimal orientation. Thus, accumulation of signal within the cortical receptive field relative to the background is critical for achieving the threshold. The receptive field is described by a weighting function. The weighting function of the highest-frequency channel is naturally limited by the physical (focusing, scattering function) and physiological characteristics (receptive field structure) of the visual system [19]. The highest spatial frequencies in observed image are also transmitted in the visual system as the response of this channel. The signal:noise ratio in this highest-frequency channel determines the recognition distance of “disappearing” figures. If the angular size of the black-white pair of a “disappearing” optotype is such that it falls beneath the scattering function of the optics of the eye or in the summing zone of the smallest receptive field in the foveola, which is the input for the highest-frequency channel, then there will be no response in this channel, the optotype cannot be seen, and it “disappears.” The optical density profile of the complex contour of the “disappearing” figure determines the spatial frequency spectrum of the image. The spectra of “disappearing figures” lack low-frequency components. As we have established, both the upper limit of the frequency and the peak spatial frequency in the spectrum are related to the recognition distance. Therefore, when the distance from the optotype increases, no blurred spot is seen in its place.

We will consider actual examples of the recognition of different “disappearing” optotypes. Thus, an optotype consisting of a pair of dark and light lines on a gray background can easily be adjusted beneath the scattering function, as the scattering function is arbitrarily taken as constant. In the first optotype, this pair is largest and needs the maximum distance for its “adjustment.” When the optotype contour contains a larger number of bands, the limiting factor is again a pair – the light band with the neighboring dark band (or vice versa). Since at constant total outline width, the width of an individual pair (marginal) in a multi-contour optotype is less, optotypes Nos. 2, 3, and 4 are seen from smaller distances than the first optotype. This distance decreases as the width of the pair becomes narrower. For example: optotypes Nos. 3 and 4 are very similar, though the width of the light part is slightly greater in the fourth optotype, so it is seen from a greater distance. The black-white element of the contour in angular threshold sizes is constant, which follows from the linear relationship between the size and the threshold recognition distance.

CONCLUSIONS

The factors determining the recognition thresholds of “disappearing” optotypes in the present report consisted of measurements of both the spatial and spatial frequency characteristics of the contour configurations of “disappearing” optotypes of different types. The results provided support for the suggestion that there is a relationship between the recognition distance for “disappearing” figures and their spatial frequency spectra, i.e., in our measurements, the peak and upper limiting frequency, and, probably, the width of the spatial frequency spectrum and its position on the frequency scale.

The present article considers only “disappearing” optotypes constructed on the basis of Landolt rings. However, it is evident that numerous attempts to create “optimal” disappearing optotypes on this basis have led to the problem of their adequate description. Therefore, sight should probably not be lost of the simpler (spectrally) class of “disappearing” tests, optimal from the point of view of signal transmission theory – Gaborovskii grids [35]. In addition, the main argument for using Landolt rings – that, supposedly, the observer should be able to recognize them, while grids can only be detected – is not criticized, as both Landolt rings and Gabor grids in the corresponding positions are recognized exclusively in terms of orientation. We note that apart from Gaborovskii grids, sinusoidal and even square-wave grids and chessboards have “disappearing” properties in certain conditions, though they have a number of disadvantages; analysis of these requires separate investigation.

The recognition distances of “disappearing” optotypes of the class considered here, having elements of identical angular sizes but different optical density profiles, were significantly different. The factor determining the recognition distances of “disappearing” optotypes was not the break in the Landolt ring, but the structure of the profile [8]. For these optotypes, the structure of the profile determines the peak spatial frequency and upper limiting frequency of its spatial frequency spectrum, or, in spatial terms, a value inverse to the spatial frequency, i.e., the period (width) of the black-white pair. The greater the upper limiting frequency, shorter the recognition distance.

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