Article

PERCEPTION

Perception
2015, Vol. 44(8–9) 934–951

DOI: 10.1177/0301006615594957
pec.sagepub.com
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Visual Percepts in the Cases of Binocular and Monocular Viewing Stabilized Test Objects, Ganzfeld Stimuli, and Prolonged Afterimages

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Abstract

A thorough analysis of the literature on retinal image stabilization, as well as our own experimental data, present evidence that Yarbus's concept, implying inevitable and irreversible fading of a visible image evoked by stabilized retinal stimulus of any size, color, and luminance in 1 to 3 s after its onset, is not valid in a general case. It has been demonstrated that, even with Yarbus's stabilization techniques, the lifetime of visible images varies from fractions of a second to the whole stimulus duration—up to 30 min in our experiments—depending on many factors: monocular or binocular viewing, stimulus parameters, characteristics of subjects, and so forth. The dynamics of perceived images is determined mainly by the processes at the higher levels of the visual system. In the cases of such unusual visual stimuli as stabilized retinal images, it is problematic for the visual brain to find their proper interpretations in terms of everyday natural experience. Usually, the responses of retinal units are determined by three types of coexisting images: (a) the optical projections of external objects, (b) shadows of the blood vessels and other internal eye structures, (c) virtual patterns caused by the traces of previous stimuli. A task of the visual system is to recognize and visualize only external objects separating their projections from all the entoptic images of the two remaining types. To implement separation, visual brain employs a number of approaches—in particular, the eye movements that cause sliding over the retina but only the projection of the external objects. This means that the peculiar phenomena observed in the cases of stabilized retinal images can be determined not by invariability of such stimuli per se but rather by the fact that stabilization eliminates a powerful cue helping to identify the retinal images belonging to the external objects, thereby increasing the probability to treat them as the entoptic ones which should be ignored or canceled rather than perceived. However, the probability of canceling—image fading—can be essentially reduced in conditions of concordant, large, bright, and sharp binocular stimuli.

Keywords

stabilized retinal images, Ganzfeld, afterimages, image fading, binocular rivalry

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Introduction

In late 70s of the last century, while beginning our experiments with binocularly stabilized retinal images, there was still a great interest in the perception of stabilized retinal stimuli due to seemingly unusual and intriguing behavior of the visual images in conditions of retinal image immobilization—fast fading, partial disappearance, filling-in, and so forth. A majority of the researchers publishing their experimental data before and around that time concluded that complete fading of the perceived images was only possible in the cases of retinal images having relatively low brightness or contrast and blurred contours whereas the images of high brightness and sharpness might produce sustained visual impressions. In most cases, the researches recorded either repeatable fading and recovery of the whole visible image or so-to-speak "fragmentation"—alternating disappearance and reappearance of some image details (Bennet-Clark & Evans, 1963; Ditchburn, 1973; Ditchburn & Fender, 1955; Ditchburn, Fender, & Mayne, 1959; Ditchburn & Ginsborg, 1952; Ditchburn &Pritchard, 1960; Evans, 1965; Evans & Clegg, 1967; Riggs, Ratliff, Cornsweet, & Cornsweet, 1953; Stevens et al., 1976; Wade, 1975, 1978).

As had been summarized by Bennet-Clark and Evans (1963), approximately at the time when Alfred Yarbus was preparing the Russian version of his book for publishing, "most workers observe with their stabilizing apparatus, that targets disappear and reappear at short intervals when viewed for several minutes. Sometimes the whole and sometimes part of the image reappears."

To illustrate a general consensus among the researches who worked much earlier and later than Yarbus, it seems appropriate to present here several quotations from the papers related to the early and late stages of investigations in this area. Some results and statements from these papers are cited below.

In one of the first works (Riggs et al., 1953), the researchers employed a method for compensating retinal image shifts due to the eye movements with presenting the stimuli via a mirror attached to a contact lens. Complete or partial compensation was achieved by adjusting the distance between the stimulus on screen and the mirror on the eye (changing the length of the visual pathway). The stimuli were black lines of varying width (0.1–1.5′) presented for 1 min. Riggs et al. compared the results obtained in conditions of perfect compensation (Condition I—stopping the image on the retina), absence of compensation (Condition II—natural viewing), and overcompensation (Condition III—exaggerated motions of the retinal image). The principal findings were: (I) in condition of supposed stabilization, "a fine black line usually disappeared during the first few seconds of viewing, and failed to reappear" whereas "heavier lines took longer to disappear and often reappeared from time to time"; (II) in condition of "normal" viewing, fine lines were also subjected to fading but "reappeared sporadically" while "heavier lines seldom disappeared"; (III) in condition of exaggerated image motions, "there was scarcely any disappearance of even the finest lines."

Much later, 12 years after the Yarbus's book came off the press, Ditchburn wrote in response to the question "Do perfectly stabilized images always disappear?" put by Arend and Timberlake (1986):

> I do not know of any experiment in which the permanent black field is observed when optics good enough to produce a sharp image was used. Yarbus, for example, used a plano-convex lens for experiments in which a corrected achromatic doublet was needed.... Either the whole or a fragment of the image reappears intermittently. (Ditchburn, 1987)

Somewhat earlier, Tulunay-Keesey (1982) who assessed the rate of disappearance of stabilized images and afterimages as a function of contrast and spatial frequency had found that fast fading was only observed when target contrast was low.

However, the papers by Yarbus (1957, 1960a,b) and his book (1965/1967) which summarizes his studies contain a categorical (unequivocal) statement that stabilization of any retinal stimulus, independently of its parameters, must lead to a fast and irreversible fading of the whole visual image:

> For optimal working conditions of the human visual system, some degree of constant (interrupted or uninterrupted) movement of the retinal image is essential. If a test field (of any size, color, and luminance) becomes and remains strictly constant and stationary relative to the retina, it will become and remain an empty field within 1-3 seconds. (Yarbus, 1967, p. 100)

It is evident that such a disagreement between conclusions of Yarbus and other researches is critical for understanding the mechanisms of visual image processing and needs clarification of its causes.

As it follows from the Yarbus's commentaries to the works of other authors, he reduces all the problems with "violations of his law" to a single cause—imperfect techniques of stabilization. In his opinion, those authors who failed to obtain fast and irreversible fading of visible images evidently could not provide sufficiently good and constant level of stabilization: episodic destabilization led to repeating appearance of the images that were more or less similar to the initial ones depending on the character of the accidental shifting the retinal image. Such a belief of Yarbus was supported by Barlow (1963): comparing the suction cap stabilization technique of Yarbus with contact lens techniques used by Ditchburn, Riggs et al., Barlow concluded that Yarbus's method of retinal image stabilization was the best one. This belief was also shared by some other researchers (Gerrits, de Haan, & Vendrik, 1966) who used suction caps of Yarbus's design.

However, strictly speaking, own experimental results of Yarbus did not contain the indisputable evidence of irreversible disappearance as well as the reliable data on fast fading in the cases of sufficiently bright retinal images. Firstly, in his experimental conditions, it was principally impossible to certify that the image disappeared forever since the duration of the purposeful observations in his experiments was quite short. Usually, the whole experiment, including the time of attaching and removing the suction device, adapting the subject and adjusting the stimulus, lasted 3 to 4 min and only about 2 min from this interval remained for testing (not always leading to the expected results). In the descriptions of his experiments with retinal image stabilization, Yarbus often used reservations and stipulations of the following kind:

> The experiments showed that in every case, 1-3 seconds from the beginning of the experiment *and after removal of all light of varying intensity passing through the sclera,* all visual contours disappeared from the subject's field of vision. These contours did not reappear until the end of the experiment, i.e. for several minutes (*unless something happened to disturb the constancy and strict immobility of the retinal image*). (Yarbus, 1967, p. 61)

Secondly, a success (from the author's point of view) with fading of the bright stimulus has only been achieved by Yarbus in one crucial experiment that seems to be vulnerable for criticism in view of technique and psychophysiology. In this experiment, the stimulus for stabilization was a luminous filament of a miniature incandescent lamp that supposed to produce very bright ("blinding") retinal image. However, in reality, brightness of this image was not so high due to a small aperture and optical aberrations that caused weakening and degradation of retinal projections (actually, if not, the subject could not tolerate stimulation).

In addition, it should be mentioned that, in Yarbus's conditions of stabilization, there was another specific factor reducing the retinal image contrast to a larger extent than in typical natural viewing conditions—the internal ambient (diffuse) light penetrated into the eye through the sclera. Despite the presence of a dark pigment layer, the sclera of the eye is rather transparent, and the amount of "scleral" light inside the eye is proportional to the area of the sclera exposed to light. As one can see from Figure 1, in Yarbus's experiments, this area was essentially enlarged.

More importantly that, even with a weakened and degraded image of the lamp on the retina, Yarbus could not obtain a good fading of the visible image in his initial attempts. As usual, he attributed this failure to imperfections of the retinal image stabilization suggesting that fast saccadic movements of the stimulated eye could make the suction cap to change its position and, correspondingly, move retinal image. To improve the situation, Yarbus proceeded as follows:"... To reduce eye movement*, the subject was given a fixation point for his free eye* ... "(Yarbus, 1967, pp. 62–63).

Due to such a trick, the author satisfied himself (by achieving seemingly expected result) but the description of his finding was far from being convincing for the readers experienced in binocular observations. Consider the following quotation:

> ... During the experiment, the incandescent filament of the lamp disappeared for subject 1-3 seconds after the test field became strictly constant and stationary. *In these circumstances the subject saw only the point fixated by the second eye*. (Yarbus, 1967, p. 63)

What is the most plausible interpretation of this observation taking into account the well known properties of human binocular perception? Let's pay attention to the two principal points:

(1) The author switched from monocular conditions of stimulation (typical of his previous experiments on retinal image stabilization with one eye closed or occluded) to dichoptic conditions when the left and right eyes were presented with essentially different stimuli thus creating *preconditions for binocular rivalry*—alternating observation of the images predominately determined by the left or right eye, the probability of each image being dependent on the stimulus parameters.
(2) The subject was given an instruction to keep his gaze at a fixation point in front of him, that is, the subject's *attention* was attracted to some *real* stimulus observed with his *intact eye* in *natural* conditions of viewing.

Figure 1. Position of lids held by steps of adhesive plaster before fitting the suction cap (Yarbus, 1967, p. 44, Figure 23).

For any researcher familiar with binocular rivalry, it is evident that, in such conditions, the intact eye that is receiving natural stimulation will be dominating practically all the time while the signals from the eye bearing suction cap and having a strange stabilized stimulus similar to a trace of a switched off strong light will be suppressed soon and ignored by the visual brain mechanisms in the process of creating the perceived images of an actual scene.

Thus, it is more likely that, in the experiment discussed, fast fading of the ''blinding'' lamp image was rather the result of binocular rivalry than of retinal image stabilization. In any case, with the second eye closed, the author could not achieve the desired fading.

Such experiments stimulated us to carry out a comparative investigation of the perceptual phenomena observed in monocular and binocular viewing conditions with stabilized retinal images differing in brightness, size, and degree of binocular correspondence. The next sections present the results and main conclusions of the most indicative experiments that were described in a number of our publications, mostly in Russian (Rozhkova & Nickolayev, 1992; Rozhkova, Nickolayev, & Dimentman, 1985; Rozhkova, Nickolayev, & Shchadrin, 1982a,b).

Methods

The following three types of visual stimuli were used in our experiments:

(1) Various binocular and monocular test images stabilized by means of suction devices attached to eyes;
(2) Ganzfeld (''boundless'' and contourless homogeneous light field) presented either to one or two eyes;
(3) Compositions of real objects illuminated by strong flashes and evoking long-lasting afterimages in various conditions of binocular or monocular viewing.

Most important basic information concerning these techniques is shortly given below in conjunction with the description of corresponding experimental results; for more details, see our previous papers.

Results and Discussion

Test Stimuli on Suction Devices

The first binocular series of experiments were carried out with the classic suction caps used by Yarbus. Since the duration of such experiments was limited (because of gradual weakening of suction with time), we tried to achieve fusion in conditions requiring minimal adjustment—with relatively large and blurred stimuli. From the standpoint of similarity to the Yarbus's experiments with retinal image stabilization, the most irreproachable were our experiments with the simplest and the lightest (ca. 0.2 g) caps identical to model P_3 used by Yarbus (1967, p. 32, Figure 15) and having no special optical elements. The opening of each cap frame was sealed up with a thin glass disk having a layer of greenish luminescent dye on its inner surface (Figure 2(a)). To provide visual stimulation, this dye was excited by a weak ultraviolet radiation producing a blurred light spot (1.6 cd/m^2). The visible size of each monocular spot was about 60°.

When the two caps were attached to the eyes and the UV radiation was switched on, the subject usually perceived an image in the form of a light cloud that did not fade essentially during the whole period of observation which exceeded 4 min (Figure 2(b)). If, in similar conditions, visual stimulation was monocular, fading of the perceived image was noticeable

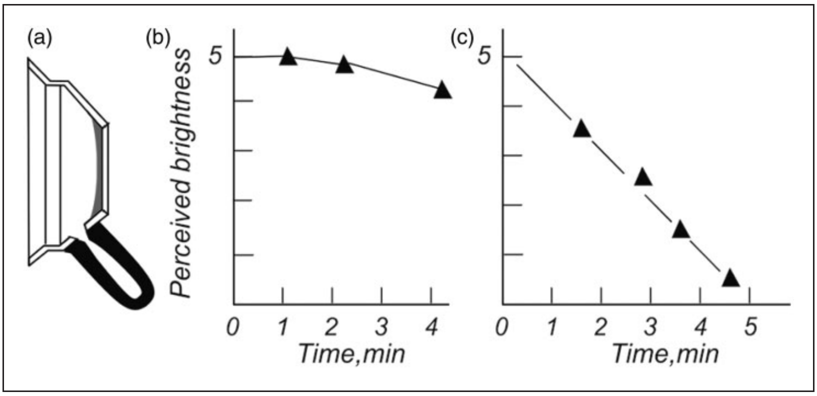

Figure 2. The suction cap with a layer of the luminescent dye on the inner surface of its glass cover (a) and the graphs illustrating changes of perceived brightness with time in one and the same subject in binocular (b) and monocular (c) viewing conditions.

but slow and took several minutes (Figure 2(c)), but not seconds (as should be expected according to Yarbus).

With the technique described, it was difficult to vary the stimulus parameters. To provide a possibility to investigate the dependence of the image fading on the stimulus brightness, we used another method of stimulation where the stimuli were presented by means of the miniature projectors placed on the suction caps (Figure 3(a)). Light intensity was controlled by varying electric current in the micro lamps.

In these series of experiments, suction devices were somewhat heavier than in the first series since they were equipped with micro lamps and had thin wires and plastic micro tubes, which provided connections to the source of electric current and a vacuum pump used to maintain the suction level sufficient for prolonged observation (ca. 30 min: for more details, see Rozhkova et al., 1982a,b).

A typical results obtained in such experimental conditions with the circular stimuli (diameter 40°) of varying brightness are presented in Figure 3(b,c). As one could see, in all cases, a decrease in perceived brightness was not so fast and, in the photopic brightness range (>10 cd/m^2), an essential changes due to retinal image stabilization only became noticeable after 20 s of observation. Even in the case of the lowest brightness level used (1.5 cd/m^2), twofold decrease in perceived brightness took 10 to 20 s. These data are consistent with the data of our "ideal" stabilization experiment where Yarbus's classical suction caps were employed (Figure 2). It is evident that comparison of the two experimental series could only be qualitative, not quantitative, since the stimuli were differing in size and their light spectrum. However, it is not essential for our main conclusion: in the case of sufficiently bright and large stimuli, significant changes of perceived brightness due to retinal stabilization took much longer time than 1 to 3 s.

In view of an adequate interpretation of these results, it is noteworthy to mention that, in normally illuminated rooms, brightness levels of the surfaces usually correspond to tens and hundreds cd/m^2 and, in the open air, one usually deals with hundreds and thousands cd/m^2. Thus, it is evident that, in everyday life, the human visual system is not facing the task to prevent retinal image fading during the phases of gaze fixation with typical duration of 0.25 to 0.4 s.

To give a more complete presentation of the retinal image stabilization phenomenology, we present the results of our experiments that included simultaneous observation of

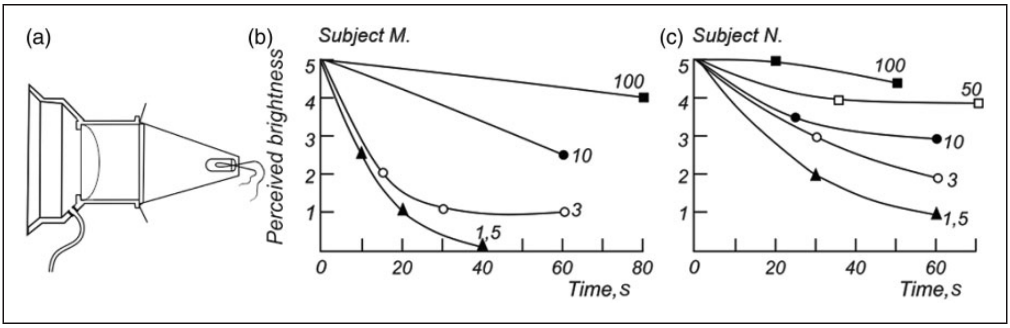

Figure 3. The suction cap with a micro lamp and a micro tube (a) and the graphs illustrating the changes of perceived brightness with time in binocular viewing conditions for the two subjects at several levels of stimulus brightness shown near the curves in cd/m^2 (b, c).

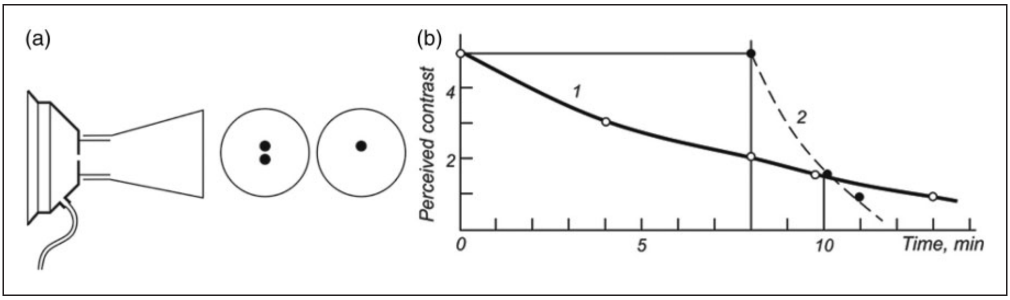

Figure 4. A scheme of suction device and frontal view of the left and right transparent screens with small black disks (a) and the graph illustrating the changes in perceived contrast of the binocularly fused disk (Curve 1) and of the monocularly presented disk (Curve 2) that was attached to the screen later—at the 8th min (b).

monocular and binocular stabilized objects. In such experiments, we used a pair of suction devices similar to the Yarbus's suction cap P_8 (Yarbus, 1967, p. 32, Figure 15) but having a small aperture (diameter < 0.5 mm) and a miniature transparent screen (Figure 4(a)). Such a device which was optically similar to a pinhole camera, provided a possibility to obtain seemingly good images both of very near test objects placed on the screen and, at the same time, of the laboratory interior. To achieve fusion of the stimuli on the two screens, we used the following Yarbus's trick for adjusting stimulus position: one of the stimuli was wetted and moved over the wetted screen with a thin brush under the oral control of the subject signaling successful fusion (the surface tension was strong enough to prevent the stimulus from falling).

At the beginning of the experiment described here, the two identical small black disks were used as the binocular stimulus. The process of alignment resulted in the visible image of a lentil shape hanging in space in front of the subject. This image did not disappear despite retinal stimulus stabilization, and its perceived contrast was decreasing but only gradually and slowly (Figure 4(b), the Curve "1").

After some time (8 min), an additional monocular disk identical to the disks attached earlier was placed on one of the screens. At first, it was perceived as a circle having essentially larger contrast than the binocular lentil image (that appeared to be significantly weakened to this moment). However, the contrast of the monocular image was decreasing much more rapidly than that of the binocular image, and the monocular image vanished before the end of the experiment whereas the binocular image, though essentially bleached at the final stage, was seen up to the moment of removing suction devices. It should also be mentioned that, before its complete disappearance, the monocular image disappeared and reappeared repeatedly (for this reason, corresponding Curve 2 in Figure 4 is drawn with dashed line). These repeated changes could be naturally explained by binocular rivalry: since there was no corresponding stimulus in the second field of view, the subject could only see the monocular test object when this eye temporary dominated; however, when the other eye prevailed in the rivalry, the subject perceived the uniform background instead of the object.

Concluding description of these experiments, it should be mentioned that, in the cases of binocular image stabilization, the visual percepts and perceptual comfort dramatically depended on concordance of the left and right stimuli. In the cases of the apt stereo pairs and successful fusion, the subject could comfortably observe binocular images for a prolonged time. However, when the adjustment failed to eliminate a discrepancy between the left and right retinal images, the subject experienced discomfort, visual strain, and even rapidly developing head ache. Sometimes his feelings were so unpleasant that the subject asked to terminate the experiment immediately. Ditchburn and Pritchard (1960) remarked along the same line in their paper on binocular image stabilization outlining that binocular discomfort was mainly due to impaired functioning of the higher visual mechanisms rather than to image fading.

Binocular and Monocular Ganzfeld Stimulation

Major differences between monocular and binocular perception were also demonstrated in our experiments with quasi stabilized retinal stimuli, namely—with the homogeneous illumination of the retina in one eye and in both eyes (Rozhkova et al., 1985). In these experiments, the eyes were covered with frosted plastic half-spherical caps that were illuminated by diffuse light from outside.

In the monocular conditions, when only one eye was covered with such an opaque damper and the paired eye was occluded, a majority of subjects observed episodic darkening of the whole visual field or of its nasal part. However, in conditions of binocular stimulation, that is, when both eyes were bearing uniformly illuminated caps, the perceived brightness of the visual field did not noticeably change with time.

Some examples of the data obtained in monocular conditions are given below (Figure 5). The mean frequency of darkening was different across the subjects. In the case of the monocular stimulus with brightness of approximately 50 cd/m^2 at the inner surface of the cap, when the other eye was occluded the subject usually observed systematic invasions of darkness into the visible light field. Sometimes, darkness covered the whole visual field, in other moments, —a quarter, a half, or a larger part of it. In different subjects, the rhythms of these events were different. To characterize this phenomenon, we calculated the mean number of dark periods per minute in three trials. The results of examining 50 subjects (100 eyes) are presented in Figure 5(a) which displays a histogram of the individual mean rates for all subjects. The peculiar column "1/2" corresponds to the cases when the perceived image consisted of light hemifield on the side of the illuminated eye and dark hemifield on the side of the occluded eye, and this percept did not vary with time.

A pair of histograms presented in Figure 5(b) corresponds to the numbers of darkness invasions recorded in two selected individuals with significantly different dynamics of percepts (the subjects were tested repeatedly 50 times). The schematic illustrations of Figure 5(c) show the parts of the visual field invaded by darkness in different subjects and

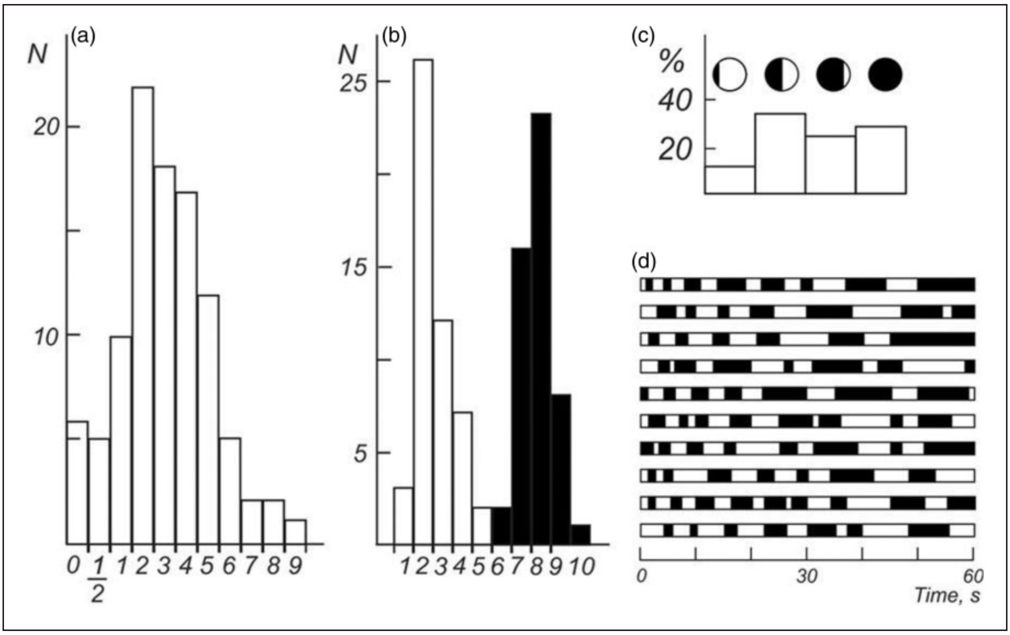

Figure 5. The histogram of the individual mean numbers of dark periods per minute (in three trials) obtained for 100 eyes (a), the histograms of the numbers of dark periods obtained for the two selected individuals (white and black columns) as a result of 50 trials (b), percentage of cases corresponding to different areas of darkness invasion (c), distribution of light and dark intervals in 10 trials of the same subject (d).

the percentages of such cases. Figure 5(d) presents the examples of dark and light interval distributions registered in one and the same subject in the course of 10 trials.

As could be seen from Figure 5(a), on average, the invasion of darkness was observed about three times per minute. In each individual, the results were somewhat varying from trial to trial, and interindividual differences were also present (Figure 5(b)).

It is noteworthy that, only in three subjects (six eyes) from 50, the whole visual field remained light throughout all the experimental session with monocular stimulation. Two of these three subjects were relatives (father and son) suggesting a possible genetic predisposition toward a powerful dominance of the stimulated eye. Probably, in these subjects, the influence of the cognitive level was very strong, and contribution of the occluded eye to the formation of visual percepts was effectively blocked due to the knowledge that this eye was not stimulated. In most subjects, however, such knowledge could not prevent participation of the occluded eye in visual processing and in formation of the perceived images. Similar "inefficiency of knowledge" was also evident in other experiments indicating that, in subjects with normal binocular system, in supposedly monocular visual conditions, visual perception was always binocular even if one eye was closed, that is, saw "nothing" or darkness.

This conjecture received additional support from the results obtained in three subjects with visual impairments. Two subjects, who lost one of the eyes 15 and 19 years before participation in our experiments, never saw darkness invasion in the course of Ganzfeld stimulation. In the third subject with congenital ptosis of the right eye, the influence of this eye was also never seen when it was occluded.

It seems paradoxical that, in monocular conditions of stimulation, many subjects with normal binocular vision could observe that darkness had invaded the whole visual field including the extreme temporal area of the stimulated eye (the subjects thought that "the absolute darkness" took place) despite the fact that the occluded eye could not see this area in principle (due to nose) and, therefore, could not send information to the brain about darkness here. Such observations suggest that binocular rivalry could lead to the total suppression of the inputs from the illuminated eye.

In the experiments with monocular Ganzfeld on cross-eyed children, it was found that the frequency of darkness invasions depended on which of the eyes was stimulated—fixating or squinting. Moreover, it was shown that the difference between the two frequencies could be used as an indicator of the squinting eye suppression: this difference correlated with the results of treatment aimed at recovering normal interocular relationship (Ploskonos, 1989; Rozhkova & Ploskonos, 1988).

Historically, the first description of alternating light and dark phases in conditions of a gomogeneous monocular stimulation, evidently, belongs to 19th century: in the paper devoted to the alternations in perceived color of a white screen when it was observed via red–green glasses, Rapoport (1962) mentioned that, a century ago, Shen and Mosso noticed episodic darkening of the uniformly illuminated surface in the course of its prolonged observation with one eye (the other eye being closed).

The occurrence of fast darkening of the visual field in binocular conditions of Ganzfeld stimulation was only reported by one of our subjects in 1994. Probably, in this case, some central influence could block all the afferent stimuli like in the case of syncope.

In 1980s, the experiments with monocular and binocular Ganzfeld stimulation were also performed by Bolanowski and Doty. These authors had never observed darkening of the visual field in binocular viewing conditions and outlined this fact in the title of their paper (Bolanowski & Doty, 1987). The results obtained in conditions of monocular Ganzfeld stimulation were in a good qualitative concordance with our data (some not principal quantitative differences, evidently, were caused by differences in experimental details). From the fact that there was no loss of visual sensation when Ganzfeld was viewed binocularly, Bolanowski and Doty made definite conclusion that transient inputs due to eye movements might not be required for continuous maintenance of visual perception. Later, Knau and Spilman (1997) performed measurements in conditions of binocular Ganzfeld stimulation and found that perceived brightness decreased slowly and finally reached constant level (on average after 5–7 min), the total brightness loss being equivalent to a 1.2 log unit reduction, independently of the stimulus intensity.

Binocular and Monocular Afterimages

Afterimages evoked by the traces of the preceding stimulation represent another type of the visual phenomena having a direct relation to the issue discussed in this paper. At the time of an afterimage developing, the light is already switched off but the responses of the retinal cells and of central visual neurons are still lasting. One could say that, for some time after the light stimulus offset, the retina could keep a stabilized virtual imprint of this stimulus in the form of the residual neuronal activity and local adaptation patterns.

Most commonly, to evoke an afterimage, the researcher employs either a prolonged fixation or a short and strong illumination of the test stimulus. When the experiments are carried out in darkness and the subjects are dark adapted, the afterimages can be rather long lasting. As an approach to study perception of the stabilized retinal images, the method is advantageous in view of its simplicity in practical realization and suitability for presentation of large natural stimuli—in particular, real interior of the laboratory.

We performed our experiments in complete darkness—in a laboratory room having no windows and light sources—and evoked afterimages illuminating the test stimulus with short flashes of light using a standard photoflash device. The test stimulus looked like a composition of several geometrical objects placed on a dark background (Figure 6(a)). The principal moment was the presence of a very small red fixation point (F) provided by LED in the center of the test stimulus. The subject was instructed to direct his gaze to this point just before the flash and keep the gaze on this point after the flash during all the time of the afterimage developing and destruction.

Such an instruction forced the subject to retain the same eye positions in the course of viewing real and virtual images. The angular sizes of the observed scenes were in the range 30 to 60°. Light protection of the room guaranteed a complete absence of the scattered (ambient) light and, due to this condition, afterimages were always positive, that is, corresponded (in local contrast signs) to the real images and only were fading slowly. In all the experiments, the task of the subjects was one and the same: to report the time of viewing clear images in various conditions. To do this, each subject kept a mechanical stopwatch in his hand and switched it on and off. The stopwatch should be switched on at the moment of the afterimage appearance as a clear natural composition and should be switched off when the afterimage lost its structure. Both stimulation and observation could be accomplished in monocular and binocular conditions of perception in various combinations, for example, during flash, right eye was open, left eye was closed; after flash either right or left or both eyes were open, and so forth.

Summarizing the results obtained in 40 subjects, it is easy to reveal the main tendencies providing an insight into the difference between monocular and binocular processing of visual information as well as into the interference of the output signals coming from various levels of retinal image interpretation.

All other stimulation parameters being equal, the following factors have a noticeable influence on the perceived image: (a) voluntary eye movements deflecting gaze direction from the fixation point and returning it to the initial position, (b) eye states (open or

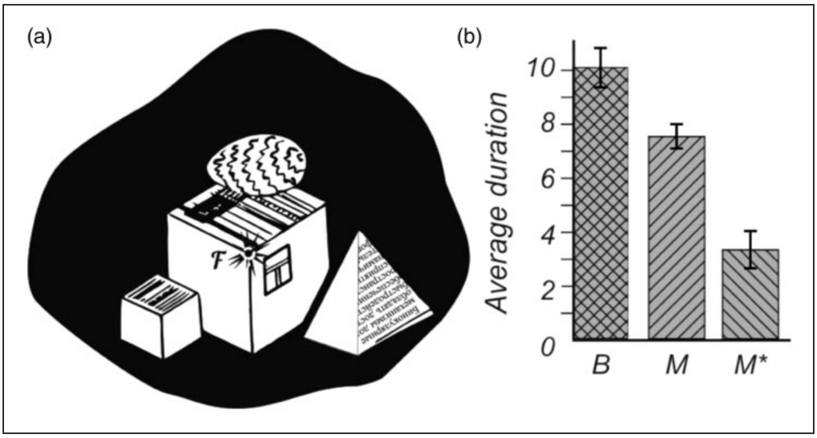

Figure 6. The test composition (a) with a fixation point F(LED) in its center and the diagram (b) showing average duration of the afterimages (seconds) in conditions of binocular (B) and monocular (M) stimulation and observation, and in conditions of monocular stimulation followed by binocular observation (M*).

closed) during and after the flash, (c) covering (closing) or uncovering (opening) the eyes during observation of an afterimage.

Before presenting the data and commentaries supporting these statements, it should be noted that, in certain conditions, some principal and reliable interindividual differences were evident suggesting that corresponding differences in individual peculiar setting and tuning of the whole multimodal (sensory, oculomotor, accommodation, etc.) physiological system were present and manifested systematically.

(1) In all cases, the voluntary eye movements leading to deviation of the gaze from the point of fixation in the center of invisible test composition resulted in a rapid fading (deleting) of the afterimage. Similar observations were also reported by other authors (Fiorentini & Mazzantini, 1965). However, it is equally important that returning of the gaze to the fixation point led to a partial recovering of the afterimage. These two phenomena evidence that, each moment in the course of the visual image creation, the brain is trying to coordinate information received not only from the visual pathways but also from the oculomotor mechanisms signaling current eye positions.
(2) In most subjects, the "lifetime" of the binocular afterimages was significantly larger than of the monocular ones (Figure 6(b)). It is natural to think that the presence of concordant information entering the brain from the two sources increases the likelihood (or the weight) of the hypothesis that the current visual signals are determined by the real objects but not by the entoptic sources. However, in some subjects, the difference between binocular and monocular conditions was small or even absent. It was usually true of the subjects with a short lifetime of any afterimages and could be due to the excessive eye movements each of which contributed to the perceived image fading (see (1)).
(3) Interesting phenomena were observed in conditions when, during the flash, one of the eyes was closed and covered with a palm but the subject was asked to open this eye after the appearance of the afterimage. In most cases, uncovering of this unstimulated eye, not having the stimulus trace on the retina, led to a specific sequence of events: an instantaneous vanishing of the image, its recovering in a weakened form, and more fast fading in comparison with the case of a purely monocular observation (compare the columns M and M* in Figure 6). More than that: uncovering of the unstimulated eye evoked significant physiological and psychological discomfort. The subjects described it in such expressions: "the eye became blind," "the eye felt as being knocked," "it seemed that the eye failed to open," "it seemed that something like a veil prevent seeing with this eye," and so forth. Sometimes, unsuccessful efforts to see the test objects with unstimulated eye evoked tearing. All these sensations could be considered as physiological manifestations of the visual brain attempts to verify various hypotheses explaining why the second eye could not see the bright image clearly visible to the first one.

Besides confirming the anticipated differences in the lifetimes of the monocular and binocular afterimages, these experimental series revealed another interesting effect—a significant influence of the actions, seemingly not related to the information processing, on the perceived images. In particular, this concerns covering and uncovering or opening and closing of the unstimulated eye in complete darkness after the appearance of the afterimage. Such influence evidenced that one and the same pair of the left and right images (traces of a strong flash in one eye and darkness in the other one) might be interpreted differently depending not only on the visual information. It seems likely that the cause of such variability is a striving of the human brain to coordinate all the information available: it means reconstruction not only of the visual scene content but also of the eye and eyelid positions, and the eye optics states that could determine the appearance of the current retinal image pair.

Earlier, Forde (1971) presented some data on fragmentation of monocular afterimages in individuals with and without normal binocular vision that indicated the influence of binocular disorders on the character of afterimage fading (from Wade, 1975):

> Fragmentations and disappearences of the afterimages occurred less frequently in the strabismic than in the normal subjects; they were also less frequent in the dominant (nonamblyopic) eyes of the strabismics than in their amblyopic eyes. The afterimages remained visible for longer when presented to the dominant eyes of the strabismic subjects, and a similar effect was found between the sighting dominant and nondominant eyes of normal subjects.

These data have demonstrated that structural and functional asymmetries of the visual and oculomotor systems are also among the factors that are taken into account in the process of search for the most likely interpretation of the retinal images.

General Discussion

From the very beginning of the experiments with stabilized retinal images, it became clear that the curious phenomena observed in such conditions have direct relation to some general principles of visual information processing. At those time, due to the enhanced interest in information theory proclaiming that "constant signal doesn't contain any information" and surprising discovery in the visual neurophysiology that many visual neurons are silent when the eyes are exposed to constant illumination (even very bright), it was concluded that image fading means eliminating constant signals as the unnecessary ones. In fact, such argumentation has sense for information *transmission* over far distances (in view of economizing power) but not for the image *analysis and interpretation*. In this aspect, it is remarkable that many models of visual information processing that were based on the idea of stationary image fading, implied cancellation of constant image at the first stage, and the inverse operations for its reconstruction at the higher stages (Bongard & Golubtzov, 1970; Losev & Shura-Bura, 1981).

Here, we prefer not to consider possible neuronal basis of the phenomena discussed, in particular—information processing in photoreceptors and other retinal layers. There are two reasons for such an omission. First, despite a huge amount of literature on the neuronal mechanisms of visual information processing, the data available are far from being exhaustive for creating more or less complete picture of functional operations taking place in the course of viewing both natural and stabilized retinal images. Second, retinal mechanisms have been mostly studied on patches of retinal tissues extracted from the eyes of certain experimental animals, and it is beyond reason to believe that the data of this kind are sufficient to predict human visual behavior in normal conditions. The former head of our laboratory, Alexei Byzov—the author of the monograph "Electrophysiology of the retina" (in Russian)—had often demonstrated us serious difficulties encountered in obtaining reliable data as well as a strong dependence of the experimental results on many factors (microelectrode parameters, physiological state of preparations, minor changes of the ambient light, etc.) that could be ignored a priori. Since we are specialists in visual psychophysics but not in neurophysiology, we have doubts in our possibility to extract a plausible and relevant information from the someone else's data.

By now it has become evident that a number of various mechanisms functioning at several levels of visual information processing contribute to the phenomenology of stabilized image perception: active deleting of false images, subtraction of successive frames to eliminate additive noise, local and global adaptation, binocular rivalry, suppression of improbable hypotheses at the cognitive level, and so forth. Perceptual filling-in of the area inside the stabilized contour is likely to be not an automatic operation but the interpolation process similar to those taking place in the blind spot (Spillmann, Otte, Hamburger, & Magnussen, 2006). Many authors dealing with retinal image stabilization had mentioned contribution of higher level and cognitive influences. For instance, the idea of attributing the phenomenology of stabilized image perception to binocular rivalry was expressed at the very beginning of studying binocular perception of stabilized retinal images. Thus, Ditchburn and Pritchard (1960), in the paper "Binocular Vision With Two Stabilized Retinal Images," discussed a possibility that the alternate fading and regeneration represented *a form of retinal rivalry* between the eye which is seeing the stabilized image and the occluded eye.

It seems strange that, until the present time, the simplest and less likely idea that fading is mostly due to adaptation or fatigue, and that eye movements are needed to prevent fading remained the prevailing matter in discussions despite a lot of contradicting data.

Our investigation provided a basis for the more complete explanation of the phenomena observed in various conditions of viewing stabilized retinal stimuli and in conditions of the uniform illumination of the retina that could be considered as a partial case of the stabilized stimuli. This explanation proceeds from considering a general task of the human visual system and takes into consideration some peculiarities of its structure and the properties. All the results obtained by many researchers (but not all author's interpretations of the results) seem to be in agreement with the following conception briefly presented below.

In natural conditions, responses of retinal units are determined by the three types of coexisting images: (a) optical projections of the external objects, (b) shadows of the blood vessels and other internal eye structures, (c) virtual patterns caused by the traces of previous stimuli and manifested itself as afterimages and local differences in sensitivity. The task of the visual system is to reconstruct the observed real visual scene on the basis of the external object projections separating these projections from all the overlapped retinal images of the two remaining types that should be treated as noise or false signals. At several levels of the visual system that is functioning in linkage with the oculomotor and accommodation systems, there are special mechanisms helping to delete noise signals, eliminate false boundaries, or discard the erroneous images.

The peculiarities of perceiving the stabilized retinal stimuli are mainly determined not by the *invariability* of such stimuli per se but by the fact that stabilization rules out one of the most important and powerful cues helping to identify the retinal image as the projection of the external object, namely—its sliding over the retina in correspondence with the eye movement. (In this respect, it is noteworthy that artificial movements of a stabilized image do not lead to formation of an adequate full-fledged percept (Gerrits & Vendrik, 1970).) Stabilization increases the probability of treating the external stimuli as the entoptic images that should be deleted but not visualized. In the case of small and weak stabilized monocular projections of the external objects, this probability might reach 100%, and corresponding perceived images could fade irreversibly. However, this probability can be essentially lowered in the case of concordant binocular stimulation, especially if the projected images are large, bright, sharp, and contrasting whereas the level of the ambient retinal illumination is low.

Proceeding from the idea that only the retinal images that are treated as belonging to the object of the external world should be visualized, one could formulate a set of the hypotheses that could be accepted by the visual brain to "permit visualization" of the stabilized retinal image:

(1) the external object was moving in synchrony with the viewing eye;
(2) the viewing eye was immobilized because the eye muscles were paralyzed;
(3) the central visual mechanisms involved in control of eye movements and in prediction of their consequences were impaired.

It is important that, in the case of normal binocular viewing, a pair of retinal images provides information sufficient both for the visual scene reconstruction and for simultaneous calculation of the current eye positions. Therefore, in binocular conditions of viewing, the

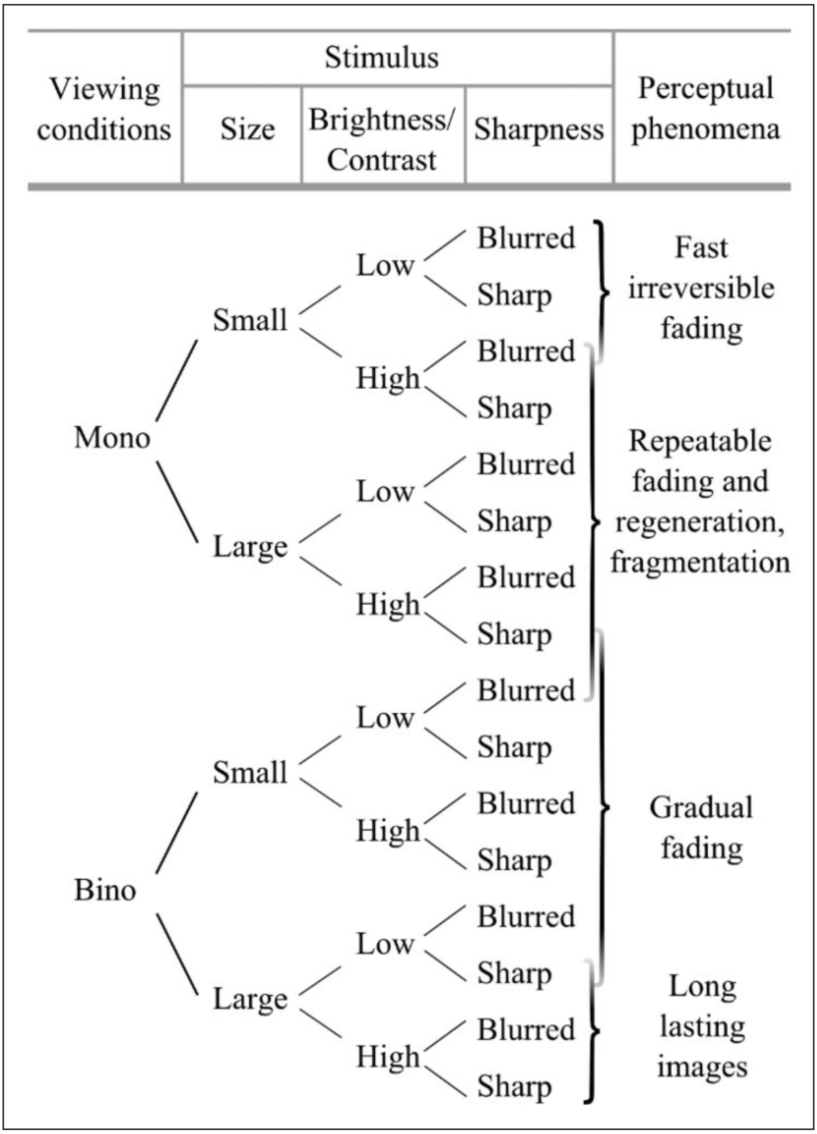

Figure 7. The experimental conditions and stimulus characteristics leading to different perceptual phenomena.

visual brain can ignore all oculomotor and proprioceptive signals associated with eye movements. Moreover, when the stabilized retinal images are not only large and bright but also duplicated (represented in both eyes), the absence of image sliding over the retina in correspondence with the eye movements might be "forgiven" by the interpretation mechanisms since the intraocular structure can not give birth to such powerful and concordant images. For this reason, observation of relatively bright and coordinated binocular stabilized images—stereo pairs or boundless stimuli—does not lead to a rapid fading of the visible images or to sudden changes in brightness or contrast: the percepts remain almost invariable during many minutes. Evidently, in such cases, it seems more plausible for the "brain homunculus" to decide that something is wrong with the oculomotor system.

The images evoked by sufficiently large and bright monocular stimuli can also be visible for many minutes but they are fading faster than similar binocular images and, in addition, sometimes they disappear, and the visual field is seen as completely dark or significantly darker in the nasal half. This invasion of darkness into the visual field is naturally explained by the temporary dominating of the occluded eye (i.e., the eye "stimulated with darkness") in the process of binocular rivalry.

Varying the parameters of stabilized retinal stimuli and going from small and weak monocular images to the large and bright binocular ones, it is possible to obtain the whole spectrum of the visual impressions described in the literature: from complete and irreversible fading of perceived images in a fraction of second or in few seconds to prolonged existence of almost unchanging images for many minutes and tens of minutes. The schematic graph of Figure 7 summarizes this situation.

It shows that one can obtain uniquely determined results in the extreme cases only: fast and irreversible fading in the case of monocular viewing relatively small stimuli of low brightness, on one side, and almost normal long-lasting images—in the case of binocular viewing large and bright stimuli, on the other side. (It should be noted that, at present, due to technical progress, any researcher could find relatively simple and noninvasive means for obtaining own experience in perception of stabilized retinal stimuli with various parameters.)

Retrospective, it became clear that Yarbus based his fundamental statements on the data obtained in the conditions close to the first extreme case and illegally treated these statements as universal laws. However, due to his inventiveness, clear formulation of the ideas, and persistence in defending his position, Yarbus greatly promoted investigations aimed at revealing the general principles of visual information processing.

Acknowledgements

The authors are grateful to E. Krutsova, M. Gracheva, and A. Terekhin for technical assistance.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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