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INTRODUCTION

Although vision constitutes the most important element of our orientation in the surrounding environment, it is only one of many such elements. The properties of the perceived object create separate mental categories. In spite of the generally accepted belief that these categories constitute inherent properties of the environment they are, in fact, pure products of brain activity and cease to exist outside the brain. This concerns colours, separation of contours in the distribution of light-generated excitability on the surface of retina that is stronger than that suggested by the properties of reflected but constantly scattered light, and finally our conviction that space exists. Collaboration of vision with other senses improves adequacy of the created mental representation of an image. However, vision dominates all senses not only as far as the amount of information is concerned but it is also equipped with the best capabilities to adapt. Included in the overall activity of a human being it works together with highly developed forms of mental functions. On the one side vision depends on these functions and on the other it supplies them with selected information that is most essential at the current level of intellectual interpretation (Młodkowski, 1998).

The process of seeing is characterised by an alternate cycle of receiving signals. Optical axes move synchronically within the field of vision and draw up in such a way that the selected object is optimally mapped on the retina. A relative freezing of the eyes takes then place followed by an input of optical information and its partial analysis. This cycle is repeated so that the process of seeing is of successive-simultaneous character.

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The formation of a mental representation of an image begins at the level of physical phenomena. A visual signal, i.e. light either directly emitted by the source or reflected from the objects of the scene limited by the field of vision and carrying information concerning this scene in an optical code, enters the eye. An initial stage of processing the signal is of an optical nature, takes place in the eye and consists in focusing light by means of the lens and forming an image on the retina. Due to the properties of deeper layers of the retina the distribution of optical stimuli is transformed into the distribution of electrochemical activation. In this form the signal is transmitted to the brain by means of the optic nerve. At a small distance behind the eyes the optic nerves cross each other in order to arrange nerve fibres in such a way that signals from one side of the field of vision enter the opposite side of the brain. At a certain point a number of nerve bundles leave the optic nerve. These are the bundles responsible for supplying the central nervous system with the following signals: 1) concerning the amount of radiation entering the eye – in order to control the pupil, 2) concerning resolution of details optically mapped on the retina – in order to control the lens, and 3) concerning the overall distribution of excitations on the retina – in order to control the position of the eye. The principal signal, carrying visual information, is transmitted to sections of cortex specialising in its analysis. The aim of the transformation taking place in these areas is to select the most important characteristics of the signal necessary for the recognition of the objects present in the field of vision. The cortex analysis of the visual signal carried out by means of neural mechanism is accompanied by the mental analysis of visual information. At this level names are assigned to objects selected in the initial stages of the process. Emotional states are generated and they represent visually symbolised values connected to particular objects. At the next step connotations are added and in this way symbolic information is transformed into semantic information. Although it loses its initial properties, such information can be further transformed in the process of thinking (C o h e n, 1977).

The concentration of cone cells also decreases with the increasing distance from the centre of the retina. As a result a ''granularity'' of the screen increases bringing about the deterioration of the optical quality of a retina image. Classical studies of the overall sharpness of human vision show that the image resolution at the distance of 2.5° from the centre amounts to 50% of that of the centre, at the distance of 5° amounts to 33% of that of the centre, and at the distance of 10° – to maximum 10% of that of the centre. This phenomenon has been traditionally attributed to the density distribution of photosensitive cells and cones in particular. Therefore, there are both anatomical and functional reasons for a separation of two zones in the retina: one narrow **central zone** characterised by a maximum of resolution and a broader **peripheral zone** situated toroidally around the central one. In the photosensitive layer of the central zone there are only cones and no horizontal cells. Therefore, no spatial summation of excitations occurs there. Any of the photosensitive cells of the central zone has its own bipolar cell and its own ganglion cell transferring the excitation farther. Therefore, the transferred information concerns the activity of a given receptor and this enhances the ability to resolve details in the representation fragment entering the centre. We deal exclusively with the photopic vision which gives an impression of colours. This is a result of about 1000 times lower sensitivity to light of cone cells than that of rod cells, as well as their different sensitivity to different wavelength of light (Keidel, 1971; Młodkowski, 2004).

When summarising the remarks concerning the processing of an optical image reaching the retina it is worth stressing that the quality of a retina image is lower than one would expect. First of all we deal with significant losses of luminous energy. The quality of optical elements of the eye is also far from perfect. The shape of the lens contributes to the spherical aberration that differs with the changing accommodation ability. The whole system is also chromatically aberrated and this lowers resolution in natural light illumination. Almost hemispherical morphological shape of the retina contributes to the distortion of image geometrical parameters. The shape and the structure of the lens compensates for this disadvantage but not within the entire range. Finally, we deal with the uneven distribution of sensitivity and resolution on the retina surface, with uneven amplification of contours, with higher sensitivity to the moving elements in the representation as well as with the traces of previous representations (so called after image, usually in a negative form). And all this is inverted with regard to the object in the frontal plane, it is parallel to the forehead. Due to the adaptation effects on the higher levels of the nervous system we do not notice these defects as well as, perhaps, certain other faults. Since they may contribute to the formation of errors, however, some of these optical deformations are significant for the process of recognition (Lindsay, Norman, 1977; Młodkowski, 1998).

TYPES OF EYE MOVEMENTS AND THEIR FUNCTIONS

Eye movements condition the creation, maintenance and transformation of retina representation as well as the whole visual representation. Several types of eye movements are known. They are all necessary and some of them enable the combination of several segments of individual acts of perception often made in a twinkling of an eye (sufficient for the identification of details) into a complete act of complex perception leading to the identification of the whole object. Eye position dynamics is an unconscious phenomenon and it may be either complemented or substituted by movements of the head or even of the whole body.

Eyeball movement is a change of its position in the socket driven by peripherally innervated eye muscles. Each eye is equipped with six muscles together with which it constitutes the **oculomotor system**. Simple, alternating or collective contractions of these muscles allow the eyeball to displace in all directions. Eye displacement is defined by means of an angle between the rest position of the visual axis and its current position whereas the rotary motions are measured by means of an angle between the sagittal plane (vertical, perpendicular to the eye surface) of the eye in the rest position and the current deflection of this plane from the visual axis (Młodkowski, Młodkowski, 1979).

Certain movements are alternating, others simultaneous, and all they contribute to the resultant trajectory. Based on the properties of the eye movements and considering their different functions, two basic types are distinguished today: macro- and micromovements.

Macromovements, particularly significant for complex perception, concern simultaneous and identical motions of both eyeballs. Both the coordination and the precision of the control are due to the brain mechanisms located in subcortical nuclei and in frontal lobes of both hemispheres (mainly in the field 8, according to Brodmann). A reflex level of macromovements control is constituted by specific **orienting reflexes** – they set the position of the eyes in such a way that the visual representation of the most important object in the field of vision appears in the central zone of the retina – and by specific **fixation reflexes**, maintaining the stability of these settings.

More important but much less understood, however, is the nonreflex control system of integrated eye movements, which is of a mental nature. Its functioning depends on both external conditions and individual predisposition and experiences of the observer. It is affected the strongest, however, by the aim that is realized with the assistance of visual perception.

One can distinguish **saccadic** and **continuous movements** among macromovements. Their names usually refer to the character of the resulting trajectory but they differ from each other with their functions. Saccadic movements shift the fixation points and their amplitude stays usually within the range of 1–15°, although it can reach 40° in extreme case. Lasting time of these movements also varies and amounts to: from 10 to 20 ms for 1°, to 60 ms for 10°, to 70 ms for 20°, to 90 ms for 30°, and to 120 ms for 40°.

Therefore, the velocity of saccadic movements amounts to several hundred degrees per second whereas the numerical values of the acceleration are still several dozen times larger (Yarbus, 1967; Ditchburn, 1973).

Continuous movements can be divided into **pursuit movements**, i.e. those which compensate changes of spatial position of the observed object with the fixed position of the head and body, and **compensating movements**, which respond to the changes of the position of the observer's head or of his whole body with the stable position of the observed object. The magnitude of continuous movements depends on the kinetic parameters of the objects that have to be compensated. The lower velocity limit of the continuous movements amounts to 5–6'/s and the upper limit equals 25–50°/s for the pursuit movements and about 100°/s for the compensating movements. Above these levels continuous movements are substituted by saccadic movements.

Convergent-divergent movements allowing the eyeballs to change their position in a horizontal plane constitute a special instant of continuous pursuit movements. They are characterized by close synchronisation of the work of both eyes and by equal amplitude. In contrast to the other macromovements, however, the direction of the turn of both eyes is opposite. When the object remains at the distance larger than 6 m from the eyes the visual axes are basically parallel. When the object approaches the eyes the convergent movements will direct the axes concentrically so that the representation will be formed on the corresponding elements of the retina. The smaller is the distance the greater is the angle between visual axes. When the object is carried away the angle will decrease due to divergent movements.

Micromovements determine the formation and relative stability of the retina representation and they are characteristic for each eye. There are three types of these motions: **tremor**, **drift**, and **microsaccades**.

Drift is an extremely slow movement. Typical displacement amounts to 2–20' and the observed rates range from 0.02 to 0.5°/s with an average value of about 0.1°/s. Drift trajectories are either bow- or S-shaped with the usually centrifugal direction with respect to the fixation point. The function of the drift is very likely to help the analysis of the representation through the optimization of its position with respect to the receptive fields (Kulikowski, 1969; Padgham, Saunders, 1975).

Microsaccades occur alternately with the drift. They are characterized by straight segments of the trajectory and the direction opposite to the drift. They are the motions which shift the fixation point towards the middle of the retina. Angular amplitude of the microsaccades remains in the range of 2–50', but usually stays within that of 5–20'. Lasting time equals 10–30 ms so that the velocity changes from about 3 to 25°/s. The numerical values of the acceleration are several times larger. Compensation of the drift, that is the maintenance of the retinal image fixation within the tolerance range determined by the drift parameters, constitutes the principle role of the microsaccades.

Tremor constitutes the finest existing movement of a character of an oscillation. It is superimposed (modulated) on the drift and its amplitude ranges from 10'' to 1', though normally it amounts to 20–40''. Its frequency stays within the range of 30–90 Hz but this range can be doubled. It has been found that the tremor frequency increases with the increasing illumination of the field of vision and decreases with the increasing amplitude of the motion itself (A d l e r, 1965; Y a r b u s, 1967). This suggests that its function is connected to the mechanism of the regeneration of photosensitive material in receptor cells. Optical activation of the retina is due to the radiation of usually different intensity. Because of the retina oscillation the exact spot of the illumination moves from one set of receptor cells to another, which results in short changes in their stimulation. This is easy to prove by means of eliminating tremor. It can be achieved either by the application of pressure on the eyeball or by the stabilization of the optical representation (through mounting the projection device directly on the eyeball, for instance). In that case the illumination of particular receptor cells does not change and the degree of biochemical conversion of the photosensitive substance is a function of the intensity of incoming light. Since, due to the lack of illumination changes, the photosensitive substance is not regenerated the excitation disappears in the course of several seconds. When we are looking at the sun or at another similar bright object then, due to slight shifts of the representation that the tremor is able to induce, the regeneration takes place but only on the image contour. Thus only the perimeter of the disc can be seen and the image of the centre of the observed object disappears. Tremor does not occur in certain species. An immobile frog, for instance, sees only these objects in her visual field that are moving. The representation of these objects moving along the retina brings about the regeneration of photosensitive material in appropriate spots.

THE MEANING OF THE EYE MOVEMENTS FOR THE PROCESS OF RECOGNITION

Saccadic movements are of particular importance in the process of recognition. This relationship is bidirectional: the movements influence the perception process and depend on it at the same time. This means that the control process of eye displacement contains in its feedback data acquired from the forming image. This process is carried out at two levels. At the lower level it is driven by the reflex mechanisms which differentiate contrasts, displacements, intensive colours etc. corresponding to the properties of the objects present in the field of vision. At the higher level, on the other hand, transformation processes take place (thinking, imagination) due to which the relations between information acquired visually at different fixation points are of semantic character. Therefore, the knowledge concerning eye motions can supply information about coexisting mental processes (Młodkowski, 1998).

Saccadic movements occur alternately to the fixation of the eyes. Fixation times amount to 200–400 ms that is 3 to 5 fixations take place within one second. In the course of 24 hours the human eye exercises about a quarter of a million of motions out of which some 15–20% takes place during dreams. But even in the conscious state we do not quite realize this. It is not too hard to observe saccadic motions of somebody else's eyes but it is very difficult to do it directly with your own ones. The process of acquiring signals from the retina representation takes place during a fixation only. Due to fast eyes displacement the representation between fixations is blurred and characterized by distorted contours and colours. This effect is similar to that of observing the environment with immobile eyes while rotating on the merry-go-round. Such representation is useless for the further cortex analysis. That is why the cortex inhibits retina excitations during saccadic movements. The fact that we do not lose a continuity of visual perception at that time is due to the maintenance of the excitation from the previous fixation by memory (iconic) processes. Such excitation is no longer a result of a retina representation but it constitutes a higher form of brain transformation.

Saccadic movements surmount the effect of the so called **lunette vision**, typical for a human eye (Keidel, 1971). This effect, connected to the distribution of photosensitive cells in the retina and to the work of receptive fields, consists in the formation of much sharper image in the central area of the retina and that of a lot worse quality in its peripheral zones. Due to saccadic movements the retina representation of all elements of the field of vision that are significant for the current act of perception is successively aimed at the visual acuity area. On the other hand the peripheral representation, of a quality deteriorating in the centrifugal direction, only coarsely presents the spatial distribution of the particular elements of the observed scene. These elements, however, may be represented on the central vision zone in the very next moment.

All the conceptions presented above have been indirectly confirmed by the results of the studies aimed at finding the boundary between central and peripheral vision and their role in the process of perception (Yarbus, Rozkova, 1977). The methodology of these investigations was based on the elimination of central vision with the help of coaxially located nontransparent round diaphragms. They were mounted on a specially constructed rack immobilized on the eyeball. About a dozen diaphragms of a diameter ranging from 0.5–30° were used. It has been found that the zones of deteriorating perception correspond well to excitation spots in different areas of the retina. They depend indirectly on the size of the representation, its contrasts as well as on the object category understood from the psychological point of view as the presence of the necessary pattern in the subject memory and its usefulness for the identification process. A person can be recognized, for instance, when his/her face is observed from a natural distance and the area of a diaphragm is smaller than the macula lutea. With the lack of the central 10° of the field of vision the identification of a face is still possible but not its recognition. With the diaphragm of 30° in diameter some persons were still able to identify furniture in a familiar room. The same researches have shown that losses in a central part of a field of vision are compensated with the increased frequency of saccadic movements and with their higher amplitude.

In the process of perception (complex recognition act) the eyes move across the field of vision in a synchronized way following an individual, though similar for a number of subjects, trajectory. Trajectories of eye movements of four subjects recorded with the electrooculographic technique are presented in figure. In this case the task of the investigated patients was to find out how many persons were present in the photograph. In fact, there are a person, a puppet, and a drawing of a person in this photograph. In the initial phase everyone's eyes scanned (with the central vision) the figure of the person for about 4–5 seconds. In the next phase vision was concentrated on the puppet and this phase lasted longer. The drawing and the other elements of the scene were usually ignored by the lunette vision of those under investigation. One might conclude that the peripheral vision sufficed for the recognition of these elements.

Fixation points are usually located on the most important, from the recognition point of view, spots of the observed scene. They are known under the term of **informative points**. These points appear on the contours, particularly on their curves and bends, on the light-and-shade boundaries and on other optically characteristic spots. One can state that, for the successive analysis, the brain receives a series of fragmentary representations in a sequence reflecting the trajectory of saccadic movements. Each subsequent change in the central vision, generated by a saccadic movement, simultaneously contributes to the physiological mechanism of "erasing" the traces of the previous excitations (Klatzky, 1975).

In the studies on the role of eye movements in the hypothetical mechanism of visual recognition, based on oculographic techniques (Noton, Stark, 1972), a number of arguments has been collected to prove the thesis that in the majority of attempts to recognize certain object most of the subjects use the same or similar trajectories of eye movements. The commonness of this phenomenon allows to speculate that the process of visual

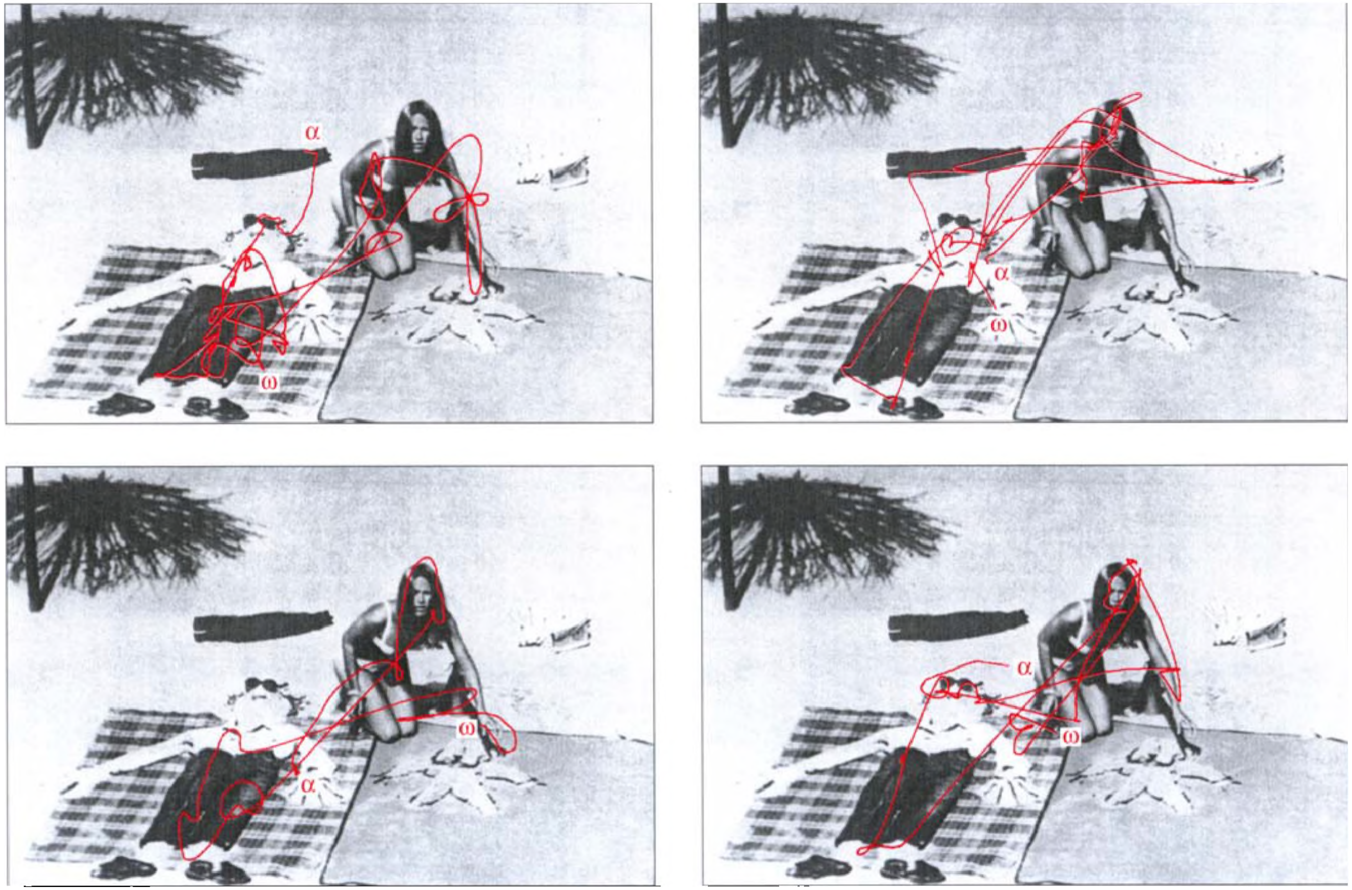

Fig. Trajectories of saccadic eye movements in four subjects (from the author's own research). commentary in text. size of the observed picture: ca 60° x 40°

recognition is based on relatively rigid strategy elaborated for a particular object through the process of learning including a typical trajectory. The recognition strategy consists in the successive scanning of the most characteristic elements of the object (the so called **ring of features hypothesis**). When the entire size of the retina representation is larger then the diameter of central vision then this scanning is realized by means of the oculomotoric system. When the size is smaller, i.e. when the representation of the entire object fits the centre, the recognition strategy is realized through the displacement of the immanent attention concentration.

Independently from the formal parameters of the object and its retina representation discussed above, the location of fixation points may reflect purposive scanning of the field of vision in searching for information significant for the current or planned activity. This is possible because of a program outpacing particular saccadic movements and formulated by them at the same time. This program and consequently also the trajectories of the movements are formed through the consideration of the aims of our current activity. Vision processes subordinated to these aims serve the goal of the preselection of the signals significant for the activity in the field of vision and of active searching for important signals (information). The way of this searching, on the other hand, is related to the previous experiences since the expectations concerning the location of the objects under search in the field of vision result from these experiences. The lack of experience is usually substituted either with concluding processes taking part in the construction of the plan or with the phase of chaotic scanning involved in the trial-and-error search of the desired object.

Information from the peripheries of the retina image, and its fragments important from the recognition viewpoint in particular, constitute another factor affecting the plan. They have a chance to be incorporated into the time-scale trajectory and, at the right moment, become represented in the centre.

The last group of factors is constituted by information acquired in the current fixation point. From the psychological point of view the plan is constructed by notional thinking and imagery processes, that is processes based on memory, with the co-operation of emotional and motivational phenomena.

During the process of collecting experiences a simplification of the trajectory and, consequently, a faster recognition takes place. The number of fixations decreases and their distribution concerns the most significant, strategic for the object, points. The results of the studies show that, in the initial phases of the contact with an object, the oculomotor apparatus guides vision to its principal (''primary'') features (G r a n o v s k a y a, 1974). This leads to the reconstruction of a contour of the object by the trajectory. After several acts of the contact with the same object a reorganization of its memory representation takes place. Elements that are often repeated (those which are present in different planes of projection of the object on the retina or those characteristic for all objects of a given class, for instance) acquire a status of "secondary features". It is then sufficient in the subsequent act of perception that only one such element is selected from the image and the whole memory pattern is activated with the simultaneous recognition of the entire object. Thus the multiplication of contacts with the object results in the reduction of the trajectory of eye movements assisting its recognition and the character of the whole process is shifted from a successive one in the beginning to simultaneous in the mature phase.

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NARZĄD OKULOMOTORYCZNY W PRZETWARZANIU INFORMACJI WZROKOWEJ

Widzenie jest tylko jednym z wielu, choć niewątpliwie najważniejszym czynnikiem orientacji człowieka w otaczającej go rzeczywistości. Proces widzenia charakteryzuje naprzemienny cykl pozyskiwania sygnałów. Na korową analizę sygnału wzrokowego, która odbywa się dzięki mechanizmom neuronalnym, nakłada się analiza informacji wizualnych o psychicznym charakterze.