THE MECHANISM OF THE FOVEA*

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Introduction

In considering the visual acuity of the eye it has been customary to apply the principles of physiologic optics and to visualize image points formed on the retina from object points in the external world. This has led us to believe that these image points form a sharply demarcated pattern on the cones in the retina, and that individual cones can be stimulated separately. From this we have been led to assume that the maximum visual acuity is limited to the size of the individual cones.[1]

This conception of visual acuity is found in our textbooks of ophthalmology, and at the present time occasionally appears in ophthalmic literature. Even fractional stimulation of a single cone has been suggested.[2,3] A moment's consideration will suffice, however, to convince one that this state of affairs does not exist in any eye. Even those versed in physiologic optics admit that the emmetropic human eye suffers from aberrations that prevent the formation of point images on the retina. It has been shown further by a number of investigators, including one of the present writers,[4] that the constant movements of the eye during the most exact fixation are so large that at no time could a point image remain fixed upon a single cone. Finally, the threshold values obtained by a number of workers for the

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detection of a break in a straight line, *i. e.*, the aligning power of the eye, are much smaller than could be accounted for on the basis of the diameter of a single foveal cone.

We are, therefore, forced to conclude that the discrimination of such fine details is not produced by images accurately focused on individual cones, and that our acuity is not, like that of a camera plate, limited to the "grain" of the emulsion.

A number of earlier investigators, not being content with current theories, have attempted to explain why the cones in the fovea afford us such extraordinarily fine discrimination. The work of Weymouth[5] and his co-workers is notable in the experimental proof they have brought to their theory. These investigators believe that the fine, constant movements of the eye during fixation, instead of being detrimental to visual acuity, really aid the eye by carrying the image over a larger number of individual cones, and they point out that a very small break in a contour, stimulating a large number of visual receptors, will yield a percept which could not be obtained if only a few cones were stimulated. They demonstrated that if the effect of eye movements carrying the image over a number of cones was eliminated by exposing the test object for a very short fraction of time, the thresholds of visual acuity immediately rose. Further, in testing depth perception, they found that the length of the test threads considerably influenced their thresholds. Within certain limits depth perception was improved by increasing the length of the thread. This was interpreted to mean that the longer the thread, the more cones are stimulated, and hence a smaller separation between the threads can be distinguished.

Because of the lack of control of fixation during the experiments, the work of these investigators was not entirely convincing. They employed no fixation point when the test object was exposed for a short period of time in order to eliminate the effects of eye movements. They state that after several trials the subject was able to locate the test object immediately, even during such short exposures as 0.15″. We know that such fixation is extremely difficult, and it seemed possible that this was one factor in producing the higher thresholds during such short exposures; hence their results may not have been due, as they claimed, to the elimination of eye movements, but to the difficulties of fixation.

For this reason we investigated the effect on the aligning power of the eye (*i. e.*, the discrimination of an increase in area of one-half of a straight line) of shortening the time of exposure of the test object and, further, of changing the length of the line. The method we employed afforded a constant fixation, and kept the state of adaptation of the eye and the size of the pupil constant, all of which are extremely important factors in any tests of visual acuity.

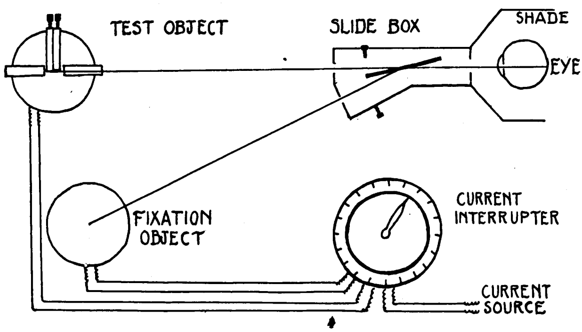


Fig. 1

METHODS

A test object 3 M. distant is viewed by one eye of the subject, appropriately screened. A thin piece of glass is interposed in the visual line at such an angle that the rays of light from this test object are not interfered with. The fixation target is situated at one side. The rays from this target fall on the glass at such an angle that after reflection they enter the eye of the observer. When the test object and the fixation object are both lighted, the observer sees both, and since the rays of light as they enter the eye come from the same direction, both objects are projected by the observer as coming from the same point in space, *i. e.*, straight ahead. Since the glass slide, being somewhat thick, would tend to give two reflections of the fixation target, and hence two images, this slide is made in the form of a prism, base up or down. Therefore, one image is displaced so far that by the time the eye is reached, only one of the two images is in the field of view. This glass slide, or prism, is controlled by two set-screws, so that extremely fine adjustments can be made and the image of the fixation target and the center of the test object be made to coincide or not, at will.

The test object is a black line on a flat white background, formed by opening two slits controlled by separate micrometer screws. Either half of the line can be widened, and the length of each half can be altered by a sliding cover painted a flat white the same as the background.

Interposed in the circuit for lighting the two targets is a mechanism that controls the length of time each target shall be illuminated. With this the fixation target and the test object may alternately be illuminated, the illumination changing at the same instant. Thus, the fixation target only may be illuminated for two seconds, and then the test object alone illuminated for 0.15 second. As the observer views the fixation point he sees in its place the test object for exactly 0.15 second. The illumination on fixation and on test objects is controlled by rheostats, and hence can be made equal. During the whole period of observation, therefore, the eye is afforded a fixation point, and is constantly exposed to the same amount of illumination; therefore the state of adaptation does not change, and the pupil remains of the same size.

In all the experiments that follow the right eye of one subject (F. H. A.) was used.

EXPERIMENTS

1. *The Effect of Using Lines of Different Width.*—Early in these experiments it became apparent that the absolute thresholds were much smaller with narrow lines than when broad lines were used. This was especially true of lines from 0.25 mm. up to 2 mm. Beyond 2 mm. this was not so noticeable. Compare the thresholds of a 0.25 mm. line of four seconds' exposure with those of a 2 mm. line and the

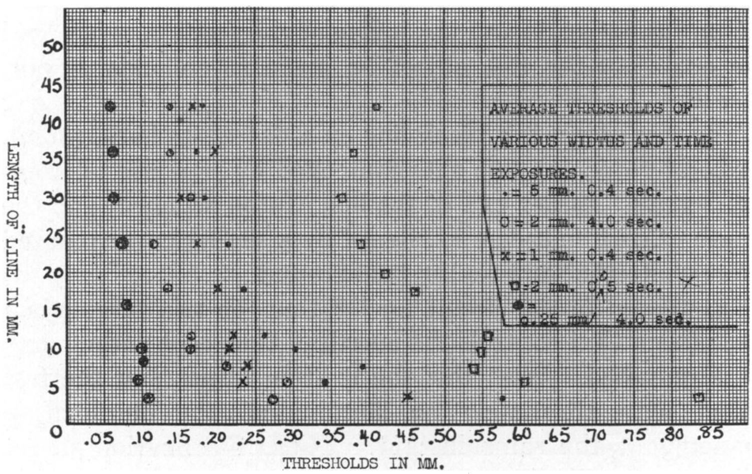


Fig. 2

same period of exposure in figure 2. This proves that the discrimination does not depend upon an absolute increase in area, but upon the percentage increase. This is in agreement with the usual results of sensory phenomena as covered by Weber's law. Accordingly, 0.5 mm. was chosen as a standard width of line for all the later experiments.

2. *Time of Exposure.*—The length of time of exposure of the test object considerably influences the threshold. Even with exact fixation, which our apparatus affords, the thresholds for exposures of 0.44″ are less than half of those when the exposure time is cut to 0.05″ (fig. 2). We have

the impression that exposures of more than one second do not materially improve the threshold. Hence we agree with Weymouth and his co-workers that the acuity diminishes if the exposure time is reduced below a certain minimum; and we have shown that this is not due to the difficulties of fixation which must have been present in their experiments. Whether this reduction in acuity is due, as these writers claim, to the elimination of eye movements during the short exposures, or to other unknown factors, is problematic, and will be discussed later.

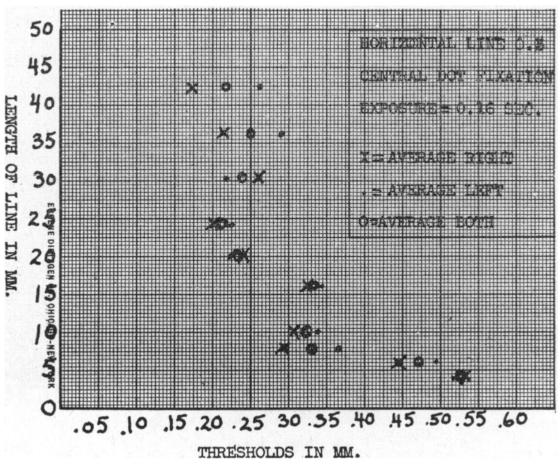


Fig. 3

3. *Length of Line.*—If the thresholds are determined for a line of constant width, but the lengths of the two halves of the line are progressively and equally shortened, very little change is observed in the average thresholds until the total length of the line is less than 25 mm. If the object of fixation is a black dot which corresponds to the center of the test line, where the break in area takes place, we find a marked increase in threshold as the length of the line is still further diminished.

Figure 3 shows the thresholds plotted against length of line when a 0.5 mm. test line is in the horizontal position and a central dot is used for fixation. With test lines less than 25 mm. in length the thresholds increase considerably, especially when the length of the line is reduced to less than 8 mm.

Figure 4 shows the same plotting for a vertical line. In both series the time of exposure was 0.16 second for each observation. This period of time was selected as being sufficient to eliminate the effect of eye movements and to

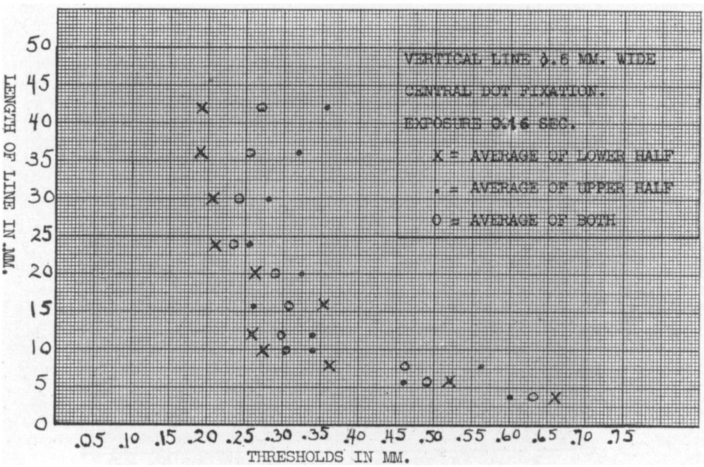


Fig. 4

prevent any shift in fixation that was necessary for the experiments that follow. Each point on all the graphs is an average of 10 or more observations.

This proves that the threshold is influenced by the total length of the test line, especially when the line is extremely short. In other words, it suggests that visual acuity is dependent upon the total number of visual elements stimulated. We found, however, that when the length of the test line was reduced to less than 10 mm., the rise in the thresholds was due partly to an entirely different factor which rise disappeared when this factor was eliminated. By using a central dot fixation between exposures of the test line we were obtaining an after-image effect which lasted through the period of exposures of the test object, and considerably depressed the sensitivity of the retina in a small area around fixation. Hence the thresholds for the extremely short line were considerably increased.

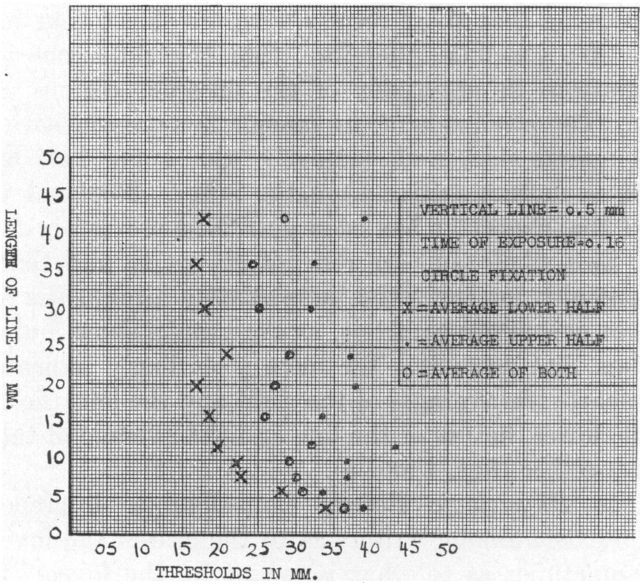


Fig. 5

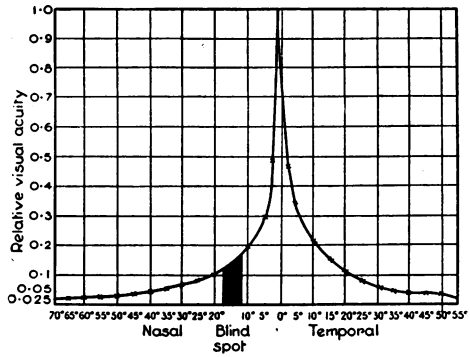
Figure 5 shows the results of observations exactly similar to those of figure 4 except that instead of a central dot a circle 20 mm. in diameter was used for fixation. When this circle was used, the thresholds for the shorter lines were increased, but not nearly so much as previously. The after-image effect of the central dot fixation is negligible when the line is over 8 mm. in length.

4. *Regional Differences in Threshold.*—As these experiments progressed an unexpected factor became evident. When the test line was in the horizontal position, the

thresholds were considerably less when the right half of the line was widened than when the left half was widened; and similarly when the line was in the vertical position the thresholds for widening the lower half were less than those for widening the upper half. In both cases the center of the line corresponded with fixation. By rotating the lines in both cases 180 degrees we obtained the same effect, thus proving that these results were not due to our instrument. We conclude, therefore, that this difference is due to variations in sensitivity of the different regions of the retina. The nasal side of the macula is more sensitive than the temporal side, and, similarly, the upper half of the macula is more sensitive than the lower. Regional variation of this character has been described previously for the retina as a whole, but we did not expect to find that this was true also for the retina immediately around the fovea. It is not absolutely constant, as our graphs show, but must be taken into account. We have accordingly indicated in these charts the averages of the right and the left, the upper and the lower, halves of the line and the average of the two taken together (figs. 4 and 5).

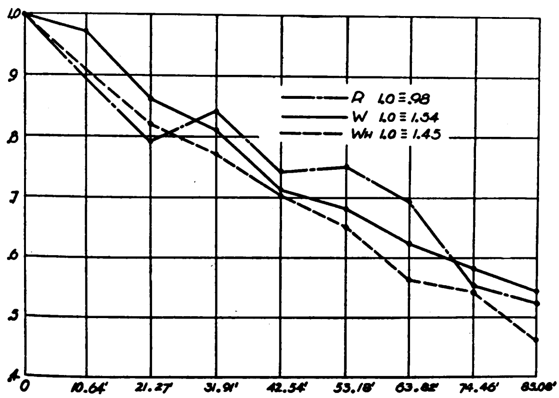
5. *The Physiologic Fovea.*—Considerable difference of opinion exists among writers as to the size of the fovea, or even sometimes as to what is meant by the fovea. Some authors regard the fovea and the macula as one, whereas the majority limit the term fovea to indicate the central depression in the retina caused by the disappearance of all the retinal elements except the cones and their nuclei. No limitation has been set as to the size of the fovea physiologically, and it is usually assumed that the acuity of vision increases from the periphery directly to the central point of fixation.

The earlier writers were generally content with measurements of visual acuity made at 5° intervals from the fixation point. Figure 6 shows the regional variation obtained from the data of Wertheim, which is that most often quoted. It can be seen that no determinations were made from 2½° to fixation. Weymouth's[6] paper, published in 1928, is the only one available to us in which studies have been made of the



Degree's eccentric from fovea

Fig. 6.—(From Duke-Elder, Text Book of Ophthalmology, Kimpton, London, 1932, i, p. 924.)



Angle from axis of fixation

Fig. 7.—(Weymouth, et al., Am. J. Ophth., 1928, xi.)

acuity of vision within this region. As a result of these investigations, Weymouth concludes that visual acuity increases in a straight line right up to fixation. At 21′ from fixation his figure shows a decrease in acuity to about eight-tenths that of the fixation point. This writer has but one determination within this point, *i. e.*, at 10.64′, and here the drop is so small as to be hardly significant.

The essential feature of central vision is the appreciation of small changes in contour, and the method that we have been using in our experiments previously described best tests this discriminatory power. It seemed to be worth while, therefore, to outline the acuity in the foveal region by this method, and to ascertain whether the acuity decreased immediately outside fixation, or whether there was a plateau within which the acuity remained at the same level, and which could, therefore, be regarded as the physiologic fovea.

The test line was kept at a length of 20 mm., as the thresholds for a line of this length are not influenced by the after-images of a central point fixation. The exposure time was kept at 0.16″. This short exposure prevented any change in fixation during the exposure of the test object. The center of the line was then placed so as to coincide with the fixation dot, and the usual series of thresholds was obtained. The line was then displaced 5 or 10 mm. to one side of the fixation dot and a similar series of thresholds obtained. This was repeated at various distances from fixation, to the right, to the left, above, and below.

Figures 8, 9, 10, and 11 show the average thresholds obtained plotted against the millimeter displacement of the line from fixation. They show that the threshold remains approximately the same until the line is about 25 mm. from the fixation point in each direction. Assuming that the observer's eye is of normal axial length (full correction of +1.50 sph. combined with a small cylinder was worn, giving an acuity of 6/5), this corresponds to a linear distance on the retina of 0.125 mm. Beyond this point the acuity decreases rapidly. The area within which we found no change in acuity with the same stimulus measures 0.25

mm. in diameter. This area should be termed the fovea, or region of most acute vision.

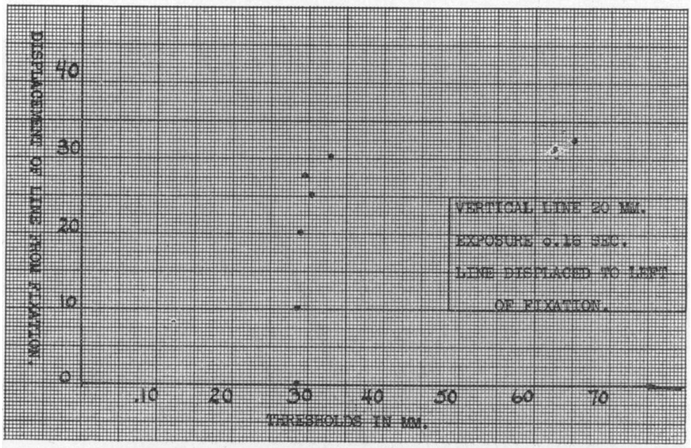


Fig. 8

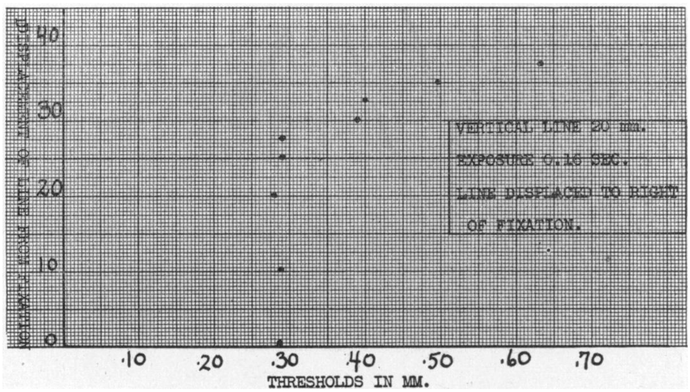


Fig. 9

Summary

We have studied the acuity of vision of the central portions of the retina by a method that permits us to analyze the effect of various factors independently. This consists in widening one-half of a straight line to the point where the

patient becomes aware of the difference in width. The initial width, length, and time of exposure can be varied, as well as the eccentricity of the image from the point of fixation.

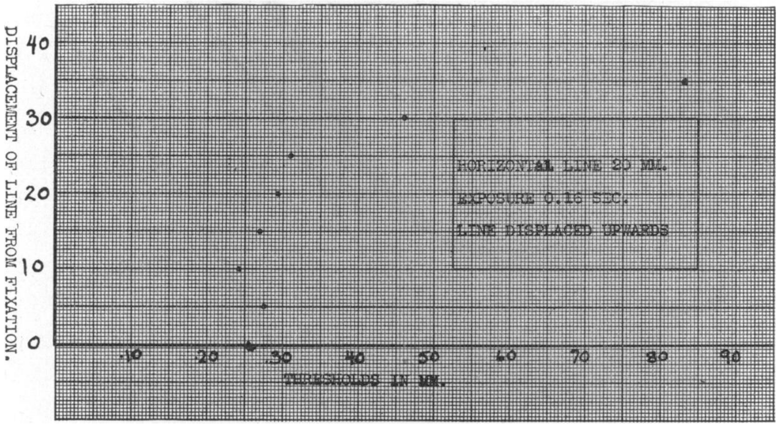


Fig. 10

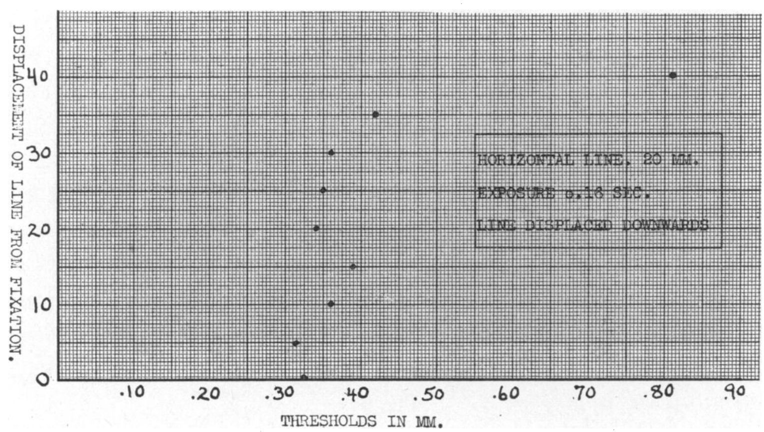


Fig. 11

We have found that the thresholds depend upon the initial width of the line, and are therefore relative. A discrimination between two lines of different width is made only when a certain percentage increase in the width of the original line occurs. Therefore, we conclude that a judgment does not depend upon the stimulation of one visual receptor, or of a group acting as a unit, but probably upon a percentage increase in the number of receptors originally stimulated.

In many cases the thresholds we have obtained correspond to visual angles that are far below the angle subtended by a single foveal cone. The average threshold for a 42 mm. line with a four second exposure is 0.06 mm. (fig. 2). This is a visual angle of about 5″, and corresponds to a linear distance on the retina of 0.0003 mm. The smallest diameter of a foveal cone given by Schultz is 0.0006 mm.—twice that of our threshold. Some individual thresholds were half that of our average.

If the time of exposure of the test object is shortened below a minimum, the thresholds are considerably increased. This may be due, as Weymouth believes, to elimination of the effect of eye movements, which carry the image over more visual receptors. On the other hand, there are additional factors which may account for this. Shortening the time of exposure of the test object considerably increases the latent period of the cortical response, as Bishop has shown. The retina is undoubtedly activated by even the shortest exposures and the longer exposures do not cause the receptors to respond any quicker but only more vigorously. As Bishop suggests, the variation in the latent period is presumably due to summation in the nerve synapses, rather than in the sensory organs. This summation may be the cause of the lower thresholds when exposures of longer duration are permitted.

There is some evidence that the acuity of vision tested by our method increases as the length of the test line is increased from 4 to about 25 mm. Beyond this point there is no increase. In fact, in some cases the acuity decreases. We have ruled out the effect of an after-image from the point of fixation, which considerably lengthens the thresholds for the shorter lines. It is suggestive evidence, therefore, that within this area, which measures 0.25 mm. in diameter, an increase in the number of visual receptors stimulated increases the visual acuity. Beyond this area, stimulation of more receptors does not improve the acuity, and in some cases it is lessened.

Finally, our experiments show that, as long as the same stimulus is used, this area of the retina, 0.25 mm. in diameter, has the same acuity throughout in the four meridians tested. From this area outward the acuity diminishes suddenly and markedly. We have termed this region the physiologic fovea. It is significant that it corresponds in extent with the area previously mentioned, within which we found an increasing acuity when more retinal elements were stimulated.

CONCLUSION

The fovea, *i. e.*, the area of most acute vision, measures approximately 0.25 mm. in diameter. Throughout this area the sensitivity is the same. Within this area the acuity depends upon the number of retinal elements stimulated, and, within certain limits, upon the length of time they are exposed. The limits of acuity are not determined by the size of the individual receptors, for in terms of visual angle the thresholds can be half that size. The extremely low thresholds can best be explained on the basis of summation.

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