genetic research in conjunction with morphological and physiological studies may be of greater value in the investigation of evolutionary theory than morphological and physiological research alone.

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Pupil Size in Relation to Mental Activity during Simple Problem-Solving

Abstract. *Changes in pupil size during the solving of simple multiplication problems can be used as a direct measure of mental activity. The pupil response not only indicates mental activity in itself but shows that mental activity is closely correlated with problem difficulty, and that the size of the pupil increases with the difficulty of the problem. These findings relate to recent Russian research on the pupillary reflex in connection with orienting and brain stimulation.*

We reported previously that while a subject is viewing visual material pupil dilatation serves as an excellent indicator of the interest value of the material to the subject (*1*). In that study, we demonstrated both a differentiation of stimuli (more or less interesting) and a differential interest value of the same stimuli for subjects of different sexes. It was pointed out that this phenomenon is completely independent of pupillary activity as regulated by the external light conditions, under the control of the parasympathetic nervous system, but is instead governed by the sympathetic nervous system, as are other emotional responses. Since Shachnowich (*2*) reports pupillary constriction as being part of the orienting reflex to novel visual stimuli, we thought that the dilatation found in the previous situation could not be attributed to any novelty factor of the stimuli, but must be a measure of a more basic reaction on the part of the subject. Sokolow (*3*) emphasizes the close relationship between the orienting reflex and unconditioned adaptive reflexes, clearly differentiating the two responses.

In reporting on their extensive work on the pupillary reflex, Lowenstein and Loewenfeld (*4*) concluded that the "pupillary reflex does not depend upon the activity of an isolated reflex arc, unaffected by central nervous events, but is a complex function." They also report that one of the factors which leads to deviations from a pupil size which would be predicted on the basis of the amount of light striking the eye is emotional excitation in the subject.

One of the earlier papers indicating that pupil size might be an indicator of the degree of activity of the central nervous system was that of Bumke (*5*) who discussed the work of Roubinowitsch, which was similar to earlier observations made by Exner. They observed the eyes of subjects who were engaged in mental activity, and saw gross changes in pupil size which seemed to be correlated with this activity.

In the experiment reported here, simple mathematical problems were used as the material for mental activity. By utilizing photographic techniques, we were able to determine exact changes in pupil size as well as the exact moment at which changes occurred.

Four men and one woman served as subjects in the experiment. Presumably all were above average in intelligence; one held a Ph.D. degree, two were at an advanced graduate level, one held a B.A. degree, and one was an undergraduate research assistant in the psychology department of this university.

A standard metal head-holder, cushioned with foam rubber, was attached to a laboratory table. Fifteen centimeters from the head-holder was a front-surface mirror on a ring-stand clip. Both head-holder and mirror could be adjusted to the height of the subject. The mirror was always below the subject's line of vision. It was tilted 10 deg from the vertical plane and was at a 45-deg angle in relation to the center of the subject's face and just below the right eye. The mirror reflected the subject's eye into the camera lens 39 cm away. The camera was a 16-mm Arriflex with a 150-mm Kilfitt *f*/3.5 lens in an adapter. The camera was run by an animation motor and took two frames per second with a ¼-second exposure.

The eye was illuminated by a standard 100-watt bulb in a holder with a dulled reflector taken from a gooseneck lamp. Light was directed into the subject's face, with the holder resting on the tabletop and the bulb 45 cm from the subject's eye. Except for this light the room was in darkness. The amount of light falling on the eye was 990 lumen/m^2, making it possible to use an exposure of *f*/8 with Eastman Royal Pan film (800 ASA).

A Pola-Coat screen was 1.45 m from the head-holder. Projected onto the screen from the rear was a 35-mm slide, dark gray, with a white number "5" in the center. The image was horizontal and 16×25 cm in size. A Sawyer projector with a 12-cm lens was placed 100 cm from the screen. The number in the center of the slide was 47 cm from the top of the table and clearly visible to the subject.

The subject entered the experimental room and was seated at the table. Any necessary adjustments were made in the height of the mirror or head-holder. The subject was then told that he would have his head in the holder for 3 or 4 minutes, and was requested to remain as motionless as possible, fixating on the number "5" on the screen in front of him. He was told that he would be given a mathematical problem to solve, and that he was to give his answer orally when he had reached a solution.

While one experimenter operated the camera, a second gave the instructions and the problems. The subject was also told whether or not his answer was correct. A third experimenter recorded the number of the frame at which each question was given and answered from the frame counter on the animation motor. After starting the camera, nothing was said for 30 seconds. The first problem was then given. After each answer, 5 to 10 seconds elapsed before the next problem was given. The problem was always given when the counter was at an even 20-frames interval. Since the time taken for solving the problem varied from subject to subject, questions were asked at different points during the filming with different subjects. The experiment was terminated 10 seconds after the last problem had been solved.

All problems were given in the same manner: (i) multiply 7 × 8; (ii) multiply 8 × 13; (iii) multiply 13 × 14; (iv) multiply 16 × 23. Our unpublished research has indicated that there is a tendency for later stimuli in a series to get a slightly smaller response than earlier responses in a series if the stimuli are equal in value. By keeping the sequence constant, with the problems increasing in difficulty, any adaptive effect in this particular situation would minimize rather than maximize differences between problems.

After the film was processed, each frame was projected individually by means of a Percepto-Scope which was situated on the floor and threw the image into a mirror from which it was reflected onto a screen set into a tabletop. Measurements of pupil diameter were made manually for each frame by means of a millimeter ruler. One person measured while a second recorded the measurements on a standard form. Neither person was familiar with the experiment or the subjects being measured.

Typically, the pupils of each subject showed a gradual increase in diameter, reached a maximum dimension immediately before an answer was given, and then reverted to the previous control size. When the mean size of the pupil of one subject, recorded on five frames immediately before a question is asked, is compared with the mean size of the pupil at the period of maximum dimension, recorded on five frames immediately before the answer is given, the magnitude of the increase in pupil diameter ranges from 4.0 percent to 29.5 percent. Although there is not a perfect agreement between amplitude of response and apparent problem difficulty for individual subjects (Table 1), there is complete correlation between difficulty and the mean response of the five subjects. In all cases of nonagreement, the individual reversals are between two problems adjacent to each other in difficulty (such as between problems 1 and 2, 2 and 3, or 3 and 4). The peak in pupil diameter, together with variations in response latency, suggest that something on the order of "total mental activity" could be postulated. The "total mental activity" would be a combination of both the amplitude and the latency of the response.

Table 1. The percentage of increase in pupil diameter at the point of solution of a problem as compared with the diameter of the pupil before the problem was posed.

Subject	Problem			
	7 × 8	8 × 13	13 × 14	16 × 23
H.H.	15.2	15.8	20.2	22.9
E.K.	9.8	14.1	24.9	21.2
T.H.	10.0	8.9	13.5	23.1
G.B.	4.0	8.8	7.8	11.6
P.M.	16.2	9.1	25.1	29.5
Mean	10.8	11.3	18.3	21.6

While previous research has indicated that pupil dilatation is related to interest (*1*), emotionality (*4*), and mental activity (*5*), this experiment demonstrates that there is, indeed, a correlation between pupil dilatation and problem difficulty.

The situation was designed to eliminate any pressures, sense of competition, or anxiety so far as the subject was concerned. It was felt that these factors were eliminated, since our preliminary research on the problem had indicated that the same type of response curve is obtained when subjects are instructed to mentally pose and answer their own problems without communication between subject and experimenter. The results in Table 1 clearly indicate that the response of the pupil reflects the mental processes which are participating in the problem-solving. Accommodation was not a factor. As a check on this, tests were made with five subjects who alternately fixated on a near object (99 cm from the eye) and a far object (3.14 m from the eye). The mean increase in pupil size for the far object over the near object was 2.1 percent. This is consistent with Alpern (*6*) and indicates that in this experiment there should have been no accommodation effects. The visual field was constant and auditory stimulation was held to the continuous sound of the camera and the voice of the experimenter giving the problems. It is evident that the subject was not responding to the experimenter's voice, for if this had been the case there would have been an immediate increase in pupil size when each problem was presented. In actual fact, the curve went up slowly (and occasionally even went down) from the point where the question was asked, and reached a peak immediately before the solution was given anywhere from 3 to 30 seconds later. Once the answer had been verbalized, there was an immediate drop in pupil size, then a steady and slow decrease to a control level.

It seems evident then, that in this situation the pupil response is a direct reflection of neurological activity and is associated with specific areas of the brain and nervous system. This conclusion is strongly supported by some of the work done in Russian laboratories on the various aspects of pupillary activity. In an extensive review of the Russian literature, Shachnowich (*2*) reports a number of studies of differential pupillary responses in relation to activity in different sections of the brain. With an external light source maintaining the size of the pupil at a constant level, electrical stimulation of the occipital lobes was found to cause constriction in the pupil, while stimulation of the frontal and temporal areas produced dilatation. This is consistent with our findings since mental activity of the type used in problem-solving would be expected to create activity in the association areas.

Smirnow (*7*) also reports differential constriction and dilatation of the pupil in observations of brain damage, with constriction resulting from damage in the occipital area and dilatation resulting from damage in the temporal lobe. If the damage produces increased activity in the remaining tissues, or if the damage itself is a source of stimulation to the area, these results are consistent with those reported by Shachnowich (*2*).

Since electroencephalographs may be used for measuring activity in the brain, it would be expected that mental problem-solving would also produce changes in electroencephalographic rhythms. Lorenz and Darrow (*8*) reported this to be the case when they recorded electroencephalograph waves while their subjects mentally solved the same type of problems used in this study (simple multiplication). Their results indicated a significant decrease in occipital alpha activity during the period of problem-solving, which correlated with increased activity in the association areas. There was more of an "on-off" effect in their results which delineated the solution period regardless of problem difficulty, while in our experiments the pupil responded differentially to problems of greater and lesser difficulty.

These results suggest that the pupil

response will prove to be a valuable tool in the study of problem-solving and other mental processes, which have to date been largely a matter of subjective responses on the part of the subject.

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29 August 1963

Pursuit Eye Movements in the Absence of a Moving Visual Stimulus

Abstract. *Subjects instructed to imagine a beating pendulum develop pursuit eye movements of a frequency comparable to the frequency of a previously visualized real pendulum. The appearance of pursuit rather than saccadic movements supports an "outflow" theory for central control of eye movement and suggests an objective technique for the identification of certain types of visual imagery.*

During sleep, dreaming is frequently associated with a specific low-voltage, high-frequency, electroencephalographic pattern accompanied by rapid conjugate eye movements (*1*). These movements may relate to the content of the dream (**2**). Since visual imagery appears in states other than sleep, for example, sensory isolation (*3*), hypnosis (*4*), psychosis, and drug intoxication, specific eye movements might identify and characterize this activity (*5*).

Eye movement responses to visual stimuli can be classified as "saccadic," when there are rapid changes in the fixation point, or as "pursuit," when there are following or tracking movements (*6*). Pursuit movements have been reported to develop only when there is a moving stimulus upon which the eye can fix (*7*). During a study in which we were attempting to correlate induced imagery with various psychophysiologic responses (*8*), pursuit movements were found during imagining conditions in the absence of such a stimulus.

From the large pool of volunteers studied, ten student nurses were chosen who could be hypnotized, and another ten who could not (*9*). All 20 students were given the same tasks of first following (at beat frequency, 0.5 cy/sec) and then imagining a pendulum, and of having dreams and hallucinations about the pendulum. Table 1 shows the sequence of conditions. The eyes of the subjects were 2 meters from the resting pendulum which was released by an electromagnetic device; its position was established by means of photocells at the extremes of the arc. The angle the eyes subtended while following the real pendulum was 36°50″. Electroencephalographic, electrooculographic, and galvanic skin response data were recorded simultaneously on an eight-channel Grass electroencephalograph (*10*). In recording the electrooculogram, the slow time-constant filter was used (electrocardiogram setting, 0.3 sec). Electrodes were placed lateral to each eye (*11*). Subjective verbal reports were recorded and conjoined to the physiologic data by a time-code signal generator.

Eight of the ten subjects who could be hypnotized and all of the subjects who could not be hypnotized developed pursuit eye movements while imagining the beating pendulum in both waking (WCI) and trance (TCI) states. Figure 1 shows a typical record, with the expected development of pursuit eye movements in *A* when the subject is watching the real beating pendulum (WOR). The unexpected appearance of pursuit movements during the eyes-closed-imagining condition (WCI) is shown in *B*; and, for comparison, the development of saccadic movements during the eyes-open-imagining condition (WOS) is shown in *C*. Pursuit movements were characteristic of the eyes-closed-imagining conditions (WCI, TCI), while saccadic movements were characteristic of the eyes-open-imagining conditions (WOS, TOS).

Nonparametric tests were used to analyze the pursuit movement data across conditions. The results of this analysis are summarized in Fig. 2. No significant difference in the number of pursuit movements was found between watching the real pendulum (OR's) and imagining with eyes closed (CI's).

Table 1. Sequence of conditions. All are of 30 seconds' duration except the rest conditions (2 minutes) and TCD condition (1 minute).

Condition*	State	Eyes	Task
RC	Waking	Closed	Rest
RO	Waking	Open	Rest
WOR	Waking	Open	Following
WCI	Waking	Closed	Imagining
WOS	Waking	Open	Imagining
TOR	Trance	Open	Following
TCI	Trance	Closed	Imagining
TOS	Trance	Open	Imagining
TCD	Trance	Closed	Dreaming
TOH	Trance	Open	Hallucinating
TC	Trance	Closed	Resting
TO	Trance	Open	Rest

* After completion of the entire sequence, conditions RC through WOS were then repeated.

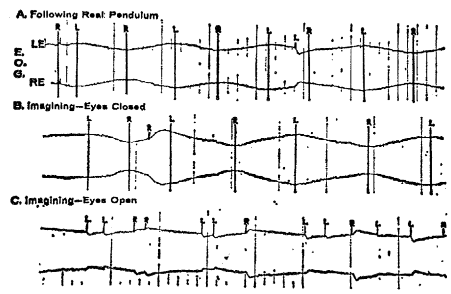

Fig. 1. Electrooculogram obtained during conditions of following and imagining a pendulum (see text). Each record shows the initial 8 seconds of a condition of 30 seconds' duration. (*LE* refers to left eye, *RE* to right eye, *R* to a movement to the right, and *L* to a movement to the left.) The shorter solid line designates a saccadic and the longer a pursuit eye movement.

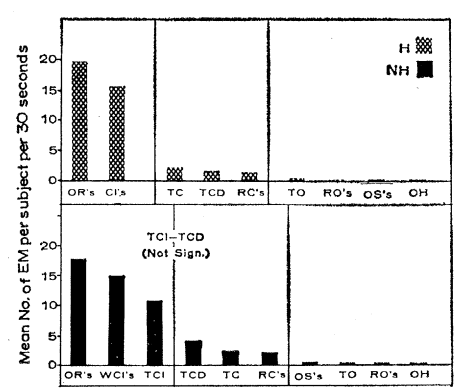

Fig. 2. Significant differences in pursuit eye movements, depending on the conditions. The hypnotizable group is designated *H*, and the group that could not be hypnotized, *NH*. The mean number of *EM* refers to the mean number of pursuit eye movements. For other abbreviations see Table 1. Conditions within a certain block are not significantly different, but conditions across a block are significantly different ($p < .05$; in many instances $p < .01$).