

References and Notes

- U. S. Von Euler and J. H. Gaddum, *J. Physiol. (London)* **72**, 74 (1931).
- F. Lembeck, *Naunyn-Schmiedeberg's Arch. Exp. Pathol. Pharmacol.* **219**, 197 (1953).
- T. Hökfelt, J. O. Kellerth, G. Nilsson, B. Pernow, *Science* **190**, 889 (1975); S. Leeman and E. A. Mroz, *Life Sci.* **15**, 2033 (1974).
- M. Otsuka, S. Konishi, T. Takahashi, *Fed. Proc. Fed. Am. Soc. Exp. Biol.* **34**, 1922 (1975); M. Otsuka and S. Konishi, *Cold Spring Harbor Symp. Quant. Biol.* **40**, 135 (1975).
- J. Hughes, T. Smith, B. Morgan, L. Fothergill, in *The Opiate Narcotics—Neurochemical Mechanisms in Analgesia and Dependence*, A. Goldstein, Ed. (Pergamon, New York, 1975), pp. 1-6.
- J. M. Stewart, C. J. Getto, K. Neldner, E. B. Reeve, W. A. Krivoy, E. Zimmerman, *Nature (London)* **262**, 784 (1976); W. A. Krivoy, J. M. Stewart, E. Zimmerman, in *Substance P*, U. S. Von Euler and B. Pernow, Eds. (Raven, New York, 1977), pp. 195-200.
- N. B. Eddy and D. Leimbach, *J. Pharmacol. Exp. Ther.* **107**, 385 (1953).
- E. P. Noble, R. J. Wurtman, J. Axelrod, *Life Sci.* **6**, 281 (1967).
- G. Henderson, J. Hughes, H. W. Kosterlitz, *Br. J. Pharmacol.* **46**, 764 (1972).
- R. C. A. Frederickson *et al.*, *Life Sci.* **19**, 1181 (1976).
- J. W. Phillis and J. J. Limacher, *Brain Res.* **69**, 158 (1974); S. Konishi and M. Otsuka, *Nature (London)* **252**, 734 (1974); K. Krnjevic and M. E. Morris, *Can. J. Physiol. Pharmacol.* **52**, 736 (1974); R. J. Walker, J. A. Kemp, H. Yajima, K. Kitagawa, G. N. Woodruff, *Experientia* **32**, 214 (1976).
- J. L. Henry, *Brain Res.* **114**, 439 (1976).
- R. C. A. Frederickson and F. H. Norris, *Science* **194**, 440 (1976); R. G. Hill, C. M. Pepper, J. F. Mitchell, *Nature (London)* **262**, 604 (1976); P. B. Bradley, I. Briggs, R. J. Gayton, L. A. Lambert, *ibid.* **261**, 425 (1976); W. Zieglansberger, J. P. Fry, A. Herz, L. Moroder, E. Wunsch, *Brain Res.* **116**, 160 (1976); J. P. Gent and J. H. Wolstencroft, *Nature (London)* **261**, 426 (1976).
- R. C. A. Frederickson, V. Burgis, J. D. Edwards, *Fed. Proc. Fed. Am. Soc. Exp. Biol.* **36**, 965 (1977).
- J. Davies and A. Dray, *Brain Res.* **107**, 623 (1976); J. L. Henry, K. Krnjevic, M. E. Morris, *Can. J. Physiol. Pharmacol.* **53**, 423 (1975); E. Puil, K. Krnjevic, R. Werman, *Proc. Can. Fed. Biol. Soc.* **19**, 20 (1976); J. L. Henry and Y. Ben-Ari, *Brain Res.* **117**, 540 (1976).
- J. B. Malick and J. M. Goldstein, *Fed. Proc. Fed. Am. Soc. Exp. Biol.* **36**, 994 (1977).
- P. Oehme, J. Bergmann, M. Bienert, H. Hilse, L. Piesche, P. Minh Thu, E. Scheer, in *Substance P*, U. S. Von Euler and B. Pernow, Eds. (Raven, New York, 1977), p. 327.
- P. Stern, S. Hukovic, M. Radivojevic, *Experientia* **32**, 1326 (1976).
- W. Krivoy and E. Zimmerman, in *Chemical Modulation of Brain Functions*, H. Sabelli, Ed. (Raven, New York, 1973), pp. 111-121.
- R. C. A. Frederickson, V. Burgis, J. D. Edwards, *Science* **198**, 756 (1977).
- M. Benuck and N. Marks, *Biochem. Biophys. Res. Commun.* **65**, 153 (1975).
- R. Elde, T. Hökfelt, O. Johansson, L. Terenius, *Neuroscience* **1**, 349 (1976).
- R. C. A. Frederickson, *Life Sci.* **21**, 23 (1977).

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Eye Movements of Monkeys During Learning-Set Formation

Abstract. *Eye movements of stump-tailed monkeys were measured during learning of a long series of two-choice pattern discrimination problems. The amount of scanning per trial (shifts in visual fixation from one pattern to the other) and the duration of individual fixations on the patterns increased during the course of learning-set formation and (except for the amount of scanning by some animals) remained high during the prolonged training following learning-set formation. Some of the changes in eye movements were different from those seen during the learning of single discrimination problems, a difference that possibly reflects cognitive processes specific to the learning-set task.*

Primates—both human and non-human—depend on vision for most of their information about the environment. This is surely one of the reasons experimental psychologists using animals as subjects have made such extensive use of visual discrimination tasks in studying learning and memory (1). One might expect eye movements to play an important role in the discrimination process, but little is known about them in this regard because of the technical problems involved in their measurement. During the past few years, we have been measuring the changes in eye movements of monkeys during discrimination learning, using a computerized method that we developed for the purpose. We now describe such changes during the formation of discrimination learning sets. Learning-set formation is of particular interest because of evidence suggesting that the mechanism involved in this kind of learning (which has been variously referred to as "hypothesis," "strategy," or "con-

cept" development) is qualitatively different from that involved in the learning of individual discrimination problems (2), although the question is still debated (3).

Four wild-born, stump-tailed monkeys

Table 1. Mean results on criterion trials of discrimination learning during different stages of the experiment: (i) the first problem when initially presented, (ii) the last five problems of the learning-set series, and (iii) the last 5 days of the repeated presentation of the first problem, at the end of the learning-set series. Data were analyzed with *t*-tests of the difference between correlated means.

Problem	Scans (No.)	Duration of fixations (msec)	
		Preceding	Last
Number 1	0.65	189	287
Last five	1.04	294*	461*
Number 1 repeated	0.72	243	321*

*Significantly different from the mean in the row above.

(*Macaca arctoides*), approximately 2.5 to 3.5 years old, were each given a series of 435 two-choice, dot-pattern, discrimination problems. These were generated on an oscilloscope under computer control and were displayed just behind two circular, clear plastic panels, each 2.5 cm in diameter (4). The monkeys sat in commercial restraining chairs facing the panels. Each animal was trained with the particular pair of patterns that composed a problem until it made 19 correct responses during 20 consecutive trials (criterion trials). Then a new pair of patterns was presented until the same criterion was met. There were 300 training trials per test day, and the intertrial interval was 5 seconds. A correct choice (pressing the panel behind which was displayed the pattern that had been selected at random as the positive one for the particular problem) was reinforced with a 190-mg, banana-flavored, whole-diet food pellet (P. J. Noyes), and an incorrect choice terminated the trial. The details of the eye-movement recording and related training techniques have been described (5-7).

All four animals showed a marked improvement in the rate of learning of the dot-pattern problems over the course of approximately the first 100 problems [$F(19,57) = 15.4$, $P < .001$] (Fig. 1). Thereafter, there was virtually no improvement; learning-set formation had essentially reached asymptote. Hence, the training period would appear to have been of sufficient length to establish any possible permanent changes in eye movements as a consequence of learning-set formation.

Amount of scanning, the number of shifts in visual fixation from one pattern to the other, was one eye-movement variable measured (8). The amount of scanning by all animals increased sharply to a maximum shortly before learning-set formation was complete and then decreased somewhat (Fig. 1) (9). The persisting high level of scanning following learning-set formation would seem to be a major exception to the pattern of scanning that we have observed following the learning of single discrimination problems. In such cases, the amount of scanning also increased to a high level during learning, but then decreased to the minimum necessary for the animal to observe the positive stimulus before making the choice response (7). For a simple, two-choice problem, this minimum is 0.5 scans per trial. In the present instance, however, the four animals fell into two distinct classes of two animals each in terms of amount of scanning, especially during

the final stages of training. Two animals persisted at a high level of scanning; the others scanned less throughout most of the training and, in addition, decreased the amount after reaching the peak, so that near the end of training, they were approaching minimum scanning (Fig. 1). Thus, learning-set formation seems to have a dramatic and persisting effect on this aspect of the visual behavior of some monkeys but not others (10).

The early rise to a peak in the amount of scanning, also seen during the course of learning individual discrimination problems, might be expected to delineate a significant stage in the learning process, but what this might be is not clear yet. It is also unclear whether this type of visual activity is a necessary or important part of the discrimination-learning process. If it were, one might expect more frequent looking at the discriminative stimuli to increase the probability of a correct choice response, but this does not seem to be the case. The probability of a correct response is greater after one scan than after no scans, but further increases in the amount of scanning not only do not increase the probability of a correct response but are accompanied by a decrease in that probability. For example, all animals showed their peak scanning during problems 21 through 60. During the precriterion trials of these problems, the percentages of correct responses made by the group on those trials on which there were 0, 1, 2, 3, or 4 or more scans were, respectively, 69, 78, 74, 69, and 70 [$F(4,12) = 5.09, P < .05$]. The outcome was essentially the same regardless of the stage of learning-set training or the level of performance within single problems (precriterion trials of problems versus the criterion trials). Paradoxically, then, trials in which there are a large number of fixations, though often occurring during periods of rapid learning of problems, are no more likely to end in a correct response than trials in which only a few fixations occur. This could mean that the large number of scans on presolution trials is simply a by-product of the learning process, not an essential part of it. Evidence from human subjects suggests that the frequency of fixations is related to the memory of items fixated (11). Perhaps the amount of scanning on precriterion trials influenced memory of the patterns on later trials.

Duration of an individual fixation on a stimulus pattern was another eye-movement variable measured. During learning-set formation, all animals markedly increased the duration of the last visual fixation on a stimulus pattern during a

trial (Fig. 2). There was also an increase, although much less marked, in the duration of fixations preceding the last one. The durations of both types of fixations remained high for all the animals throughout the prolonged period of training and so appear to have reached asymptote. We separate the two types of fixations because the last fixation on a discriminative stimulus is typically much longer than preceding ones, as was the case here (12). This is so in part because the choice response occurs during the last fixation; the duration of this fixation

thus reflects the time necessary to carry out this response. But the duration of the last fixation also reflects cognitive processing stages immediately preceding the choice response (7). The increased duration of the last fixation during learning-set formation either does not occur during the learning of a single problem of the type used here or is transient (13). Hence, the results for last fixations are compatible with the hypothesis that learning-set formation involves changes in cognitive processes (perhaps reflecting hypothesis or strategy formation) not

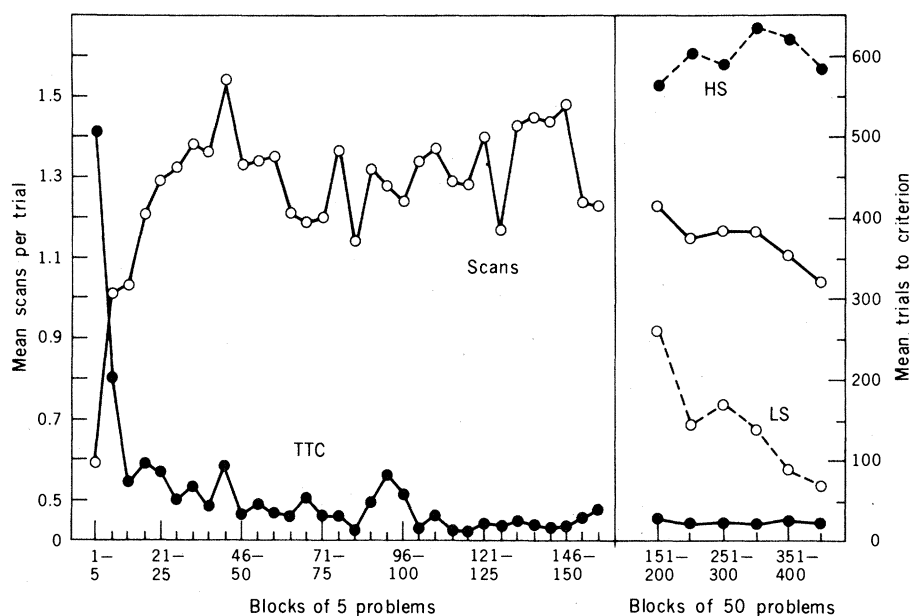


Fig. 1. Mean number of scans per trial (left ordinate) as a function of practice. All four animals are represented by the curve labeled *Scans*; the two animals that showed high levels of scanning (*HS*) and the two animals that showed low levels of scanning (*LS*) are represented separately. Also shown are the mean trials to criterion (*TTC*) per problem as a function of practice. The last block consists of 35 problems, rather than 50.

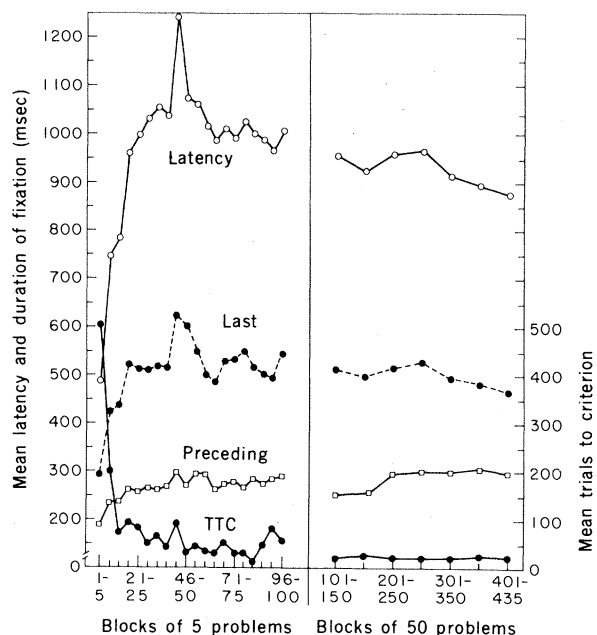


Fig. 2. Mean latency of the choice response, mean duration of the last fixation on dot patterns during a trial, and mean duration of the fixations on the dot patterns that preceded the last one as a function of practice. Latency represents the time from the onset of the two dot patterns to the occurrence of the choice response. Latency is greatly influenced by the number of scans, and so is not related in a simple way to duration of fixations. Also shown is the *TTC* curve from Fig. 1.

seen during the learning of individual discrimination problems.

The animals do not seem to fall into disparate groups with respect to the duration of fixation as they do with respect to amount of scanning. For example, during the last 100 problems, when the difference between the high- and low-scanning animals was greatest (Fig. 1), one of the former and one of the latter were consistently the two highest-ranking animals in terms of average duration of the last fixation.

In addition to the permanent changes in some characteristics of eye movements accompanying learning-set formation, we were interested in determining whether learning-set formation changes the way an animal looks at the stimulus patterns even after the learning-set task is discontinued. Therefore, after each of the animals had completed the series of discrimination problems, the first problem of the series was repeated daily until all measures of eye movements had reached a stable level for five consecutive days (which took 3,500 to 10,000 trials).

Termination of the learning-set task resulted in a decrease in both the amount of scanning and the duration of fixations (Table 1), although these measures do not appear to return to the original levels in all cases. The amount of scanning by the two high-scanning animals remained well above the original levels. Furthermore, the duration of fixations preceding the last remained higher for all four animals after learning-set training than it was originally (Table 1, rows 1 and 3) [means of the log-transformed values: $t(3) = 4.20, P < .05$]. This was not the case for the duration of the last fixation, with two of the animals showing somewhat shorter durations than they did originally. The fact that the duration of the last fixation did not remain significantly above the original level is consistent with the hypothesis that this fixation reflects cognitive processing specific to the learning-set task. Fixations preceding the last may have remained higher because they reflect changes in one or more of the initial stages (encoding, categorization, and so forth) of the visual processing of the patterns, which do not influence the last fixation.

There are, then, marked changes in eye movements during learning-set for-

mation that differ at least quantitatively and probably also qualitatively from those seen during learning of individual discrimination problems. These changes appear to be permanent both in the sense that they persist throughout prolonged training on the learning-set task and in the sense that, in some instances, they persist after the learning-set task is discontinued.

This study is one of many concerned with visual "observing responses" (14). Nearly all of these studies have indirectly measured observing responses, and have either confounded frequency (scanning, number of fixations, and so forth) and duration of observing or have not included the latter. A complete understanding of observing behavior and its role in the discriminative process will require that at least as much attention be given to duration of observing as to its frequency.

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References and Notes

1. A. M. Schrier, H. F. Harlow, F. Stollnitz, Eds., *Behavior of Nonhuman Primates* (Academic Press, New York, 1965), vols. 1 and 2; N. S. Sutherland and N. J. Mackintosh, *Mechanisms of Animal Discrimination Learning* (Academic Press, New York, 1971).
2. D. W. Bessemer and F. Stollnitz, in *Behavior of Nonhuman Primates*, A. M. Schrier and F. Stollnitz, Eds. (Academic Press, New York, 1971), vol. 4, p. 1; A. M. Schrier, *Learn. Motiv.* 2, 173 (1971).
3. D. L. Medin, in *Behavioral Primatology: Advances in Research and Theory*, A. M. Schrier, Ed. (Erlbaum, Hillsdale, N.J., 1977), vol. 1, p. 33.
4. Each pattern was composed of seven dots in a 6 by 6 matrix. The dots were selected at random with the restrictions that the first dot had to be in one of the center four cells of the matrix and that each additional dot selected had to be adjacent to or connected diagonally with a dot already chosen. In addition, no more than three dots of a pair of patterns composing a problem could be in corresponding cells of the two matrices. The matrix size was approximately 4 mm² and subtended an angle of 46 minutes at the eye.
5. A corneal reflection technique was used. The recording and testing procedures were, with two major exceptions, essentially as described by A. M. Schrier, M. L. Povar, and J. Vaughan [*Behav. Res. Methods Instrum.* 2, 55 (1970)]; J. Vaughan [*ibid.* 7, 211 (1975)]; and Schrier and Vaughan (6). The exceptions were the method of head restraint, described by Geary and Schrier (7), and the cue that indicated that a trial could be initiated, which was the brightening of a dim spot of light for 382 msec rather than simply the onset of a spot of light as in all our prior studies.
6. A. M. Schrier and J. Vaughan, *Primates* 14, 161 (1973).
7. N. D. Geary and A. M. Schrier, *Anim. Learn. Behav.* 3, 167 (1975).
8. Zero scans means that an animal looked at only one of the two patterns before making the choice response. One scan means that an animal looked first at one pattern and then the other before making the choice response. Each additional shift in fixation from one pattern to the other added an additional count to the number of scans.
9. For purposes of statistical analysis, the learning-set training was divided into two phases, and the eye-movement data for each phase were considered separately. One phase was composed of the first nine blocks of five problems, which represented the period during which the average amount of scanning rose to the peak level; the other phase was composed of the remaining blocks of problems. The decision to separate the training period into the two phases was based on (i) preliminary data gathered on two other animals that were also given a long series of dot-pattern problems, most of which were the same as the ones used in the main study, and (ii) on the data of Schrier and Vaughan (6). Treatments by subjects analyses of variance were the chief statistical tool. The increase in amount of scanning to the peak level was significant [$F(8,24) = 5.33, P < .001$], but there was no significant change thereafter.
10. For the two animals used in the preliminary study (9), the mean amounts of scanning during the last 50 problems (problems 306 through 355) were 0.56 and 1.56, respectively. These data and those for other animals tested in our laboratory further support the hypothesis that there are two populations with respect to level of scanning, at least when performing learning-set tasks.
11. G. R. Loftus, *Cognitive Psychol.* 3, 525 (1972). We are currently testing the importance of above-minimum levels of scanning more directly by removing information provided by the "extra" scans. This has a marked deleterious effect on discriminative performance.
12. Analyses of variance were conducted on the log-transformed duration data. The increase in the average duration of both the fixations preceding the last [$F(8,24) = 5.22, P < .001$] and the last fixation [$F(8,24) = 9.11, P < .001$] during the first nine blocks of five problems were highly significant, but neither changed significantly thereafter. In separate analyses of variance in which the two types of fixations were analyzed together, the average duration of the last fixation was found to be significantly longer than that of fixations preceding the last during both the first nine blocks of problems [$F(1,3) = 28.1, P < .025$] and during the later blocks [$F(1,3) = 13.4, P < .05$]. There was no significant interaction between type of fixation and practice (blocks of problems) for either of these periods. However, this interaction was significant during the first four blocks of problems [$F(3,9) = 5.05, P < .05$], reflecting the steeper rise in duration of the last fixation during that period.
13. Geary and Schrier (7) found no appreciable change in duration of the last fixation once learning began; additional data collected in our laboratory for the learning of single problems shows either no change or an increase followed by a decrease.
14. The generally accepted definition of an "observing response" is any response that exposes the animal to the discriminative stimuli. Eye movements are the most natural and direct observing responses for visual tasks, but the difficulties of measuring eye movements, particularly in the widely used white rat and pigeon, led investigators, starting especially with L. B. Wyckoff, Jr. [*Psychol. Rev.* 59, 431 (1952)], to attempt to measure visual observing behavior by means of arbitrary, experimenter-selected responses such as lever and panel presses. For more recent findings related to this latter type of observing behavior see M. R. D'Amato, M. Etkin, and J. Fazzaro [*J. Exp. Anal. Behav.* 11, 425 (1968)] and J. A. Dinsmoor, G. W. Sears, and D. L. Doot [*J. Exp. Psychol. Anim. Behav. Processes* 2, 154 (1976)].
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