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was observed for a total of 30 seconds. If a fish showed any movement during this time interval, it was scored positive. All animals with test scores of 15 and above (that is, over 60 percent) were designated as active and those with scores less than 15 were marked passive. This type of selection of the goldfish was found to correlate well with the ability of the animals to learn the float training experiment when the float size was a 0.7-cm cube. The active animals learned the task well, whereas the passive groups made little effort to master the float training task. This activity selection test was used to evaluate the seasonal behavior of the goldfish. The results (for 100 animals at each observation date) showed that in February 75 percent of the animals tested were active. This number decreased to 8 percent in June and to a low number of 2 percent in August. In October the percentage of active animals rose to 24 percent and then progressively increased to the high values of 70 to 80 percent for January, February, and March. Thus, the general activity of the goldfish follows a cyclic pattern with an annual rhythm similar to that of the learning behavior, which suggests that arousal level and not learning is the predominant factor in the behavior.

It is of interest that the periods of low activity and poor learning behavior coincide with the onset of the spawning season of goldfish (7). Moreover, the period of high activity and high performance scores in the learning experiments occur at about the time when there is rapid gonadal development in the animals. It is known that the spawning of fish can be regulated by the photoperiod to which the animals are exposed (8). Thus, animals kept at low light levels can essentially be prevented from spawning. To test this possibility one group of goldfish was placed during the month of May in an aquarium with all sides shielded and with minimum lighting (the light was provided by a 100-watt fluorescent light 3 m above the aquarium). A number of these goldfish were tested in May to establish that high training scores were obtained. The rest were kept until July and then tested in the float training experiment. Animals obtained during July, as well as animals kept under ambient light conditions from May until July, were used as controls. The experimental goldfish achieved training scores of 67 percent, compared to 15

and 25 percent for the two types of controls. The higher learning scores achieved by the May goldfish indicate that a control of the photoperiod may be useful in modifying the behavior. Additional experiments are required before any definitive correlation between the onset of spawning behavior and the decreased learning and activity patterns of the goldfish can be established. The possibility that cyclic hormonal levels as well as cyclic changes in brain biogenic amine levels (9) can play an important role in governing goldfish behavior is suggested by these results.

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Speed-Accuracy Trade-Off in Recognition Memory

Abstract. In a recognition memory experiment, the time allowed for retrieval was controlled by using the offset of the probe as a signal to terminate retrieval and respond. The response latencies measured in the experiment indicate that this procedure effectively eliminated fast-guess strategies. The recognition signal-to-noise ratio, d', grows at a negatively accelerated rate as the allowed retrieval time is increased from 0.5 second to 1 and 2 seconds.

Knowledge of how the accuracy of recognition varies as a function of the time allowed for retrieval of information from the human memory may provide insights not only into recognition performance under pressure, but also into the time course of processes underlying retrieval and into the dynamics of verbal memory in general. This report describes the first investigation of recognition memory to demonstrate a speed-accuracy trade-off which, as a result of a novel experimental procedure, cannot be ascribed to a change in the proportion of fast, random guesses (1). The results show that

recognition accuracy (as measured by d', the signal-to-noise ratio) increases as the time allowed for retrieval of weakly remembered verbal material is extended from 0.5 second to 1 and 2 seconds. This gradual increase in accuracy is negatively accelerated, and when the time allowed for retrieval is further extended to 4 and 8 seconds no consistent increase is observed.

At the start of each trial the experimenter asked the three subjects (2) whether they were ready. If they were, three consonants (3) were shown on an electroluminescent display panel. After the subjects read this trigram aloud,

Fig. 1. Response latency after the signal to terminate retrieval and respond (probe offset), as a function of the time from the onset to the offset of the probe. Standard errors range from 2 to 8 msec.
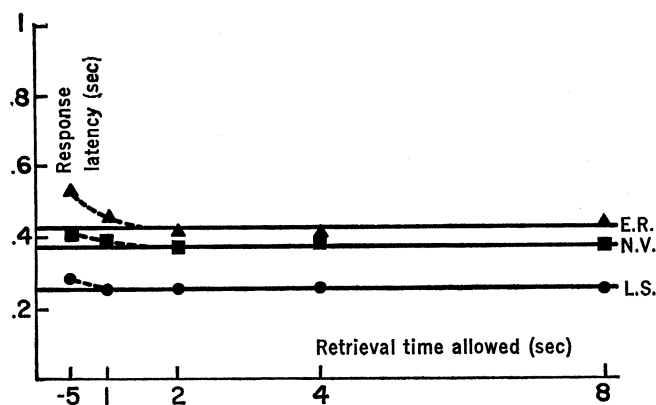
the consonants were replaced on the panel by a three-digit number. After reading this number, the subjects spent 15 seconds vocally counting back by threes, at a self-paced rate which had to exceed one number per second. When a probe consonant appeared on the display panel, the subjects stopped counting and performed the retrieval task. The retrieval instructions were: "When a consonant comes on, stop counting, and start trying to remember whether it was one of the three you saw at the beginning of the trial. If, at the moment the consonant goes off the screen, you think it more likely that it was, press the 'yes' button; if you think it more likely that it wasn't press the 'no.' Try to press the appropriate button as fast as possible after the consonant goes off. Then think back to how you felt about the answer you were about to give. If you felt completely positive, press button '1' on your card punch; if you felt you were just guessing, punch '9.' In between, use the other numbers: the farther away you felt from being positive, the larger the number you should use. Try to use all numbers equally often."

The counting backward by threes (4) was used to prevent rehearsal during the retention interval, and thus to assure a controlled decrement in memory strength. The duration of retrieval was controlled by providing a second stimulus (in this case, the offset of the probe) as a signal to terminate retrieval and respond. This adaptation of the method of forced reaction times (5) was chosen over the alternative method of payoff bands (6) because the former, unlike the latter, does not require that subjects be told in advance how much time is going to be allowed for retrieval on any particular trial (7). Since the subjects did not know how much time would be available until the signal to terminate retrieval was given, they were in the same state during the first τ seconds of retrieval for all conditions with probe duration greater than τ.

Exclusive of training, the experiment consisted of ten sessions of 192 trials each (8). Five probe display durations (0.5, 1, 2, 4, and 8 seconds) were used, and 192 negative and 192 affirmative trials were assigned to each. The conditions were assigned to sessions and trials within sessions by a pseudorandom, multiple Latin square design. Response latencies were measured with Hunter clock counters.
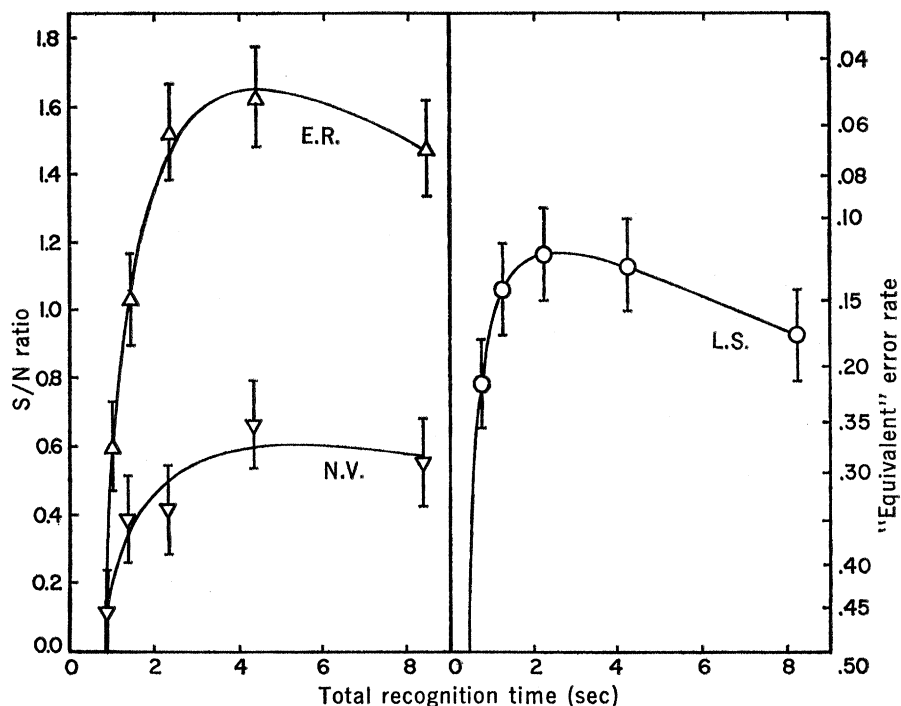
Response latencies, measured from

Fig. 2. Estimated signal-to-noise (S/N) ratio, d_T, as a function of total recognition time for the three subjects. Each point represents a different probe duration. The curves represent Eq. 1. Error bars indicate 1 standard error as estimated from error rates. (For the convenience of readers not familiar with d', a scale of "equivalent" error rates is presented on the right-hand side of the figure. This scale should not be taken literally, since the symmetry assumptions underlying such scales are known to be false.)

the offset of the probe, were first averaged separately for affirmative responses (made with the left hand) and negative responses (made with the right hand). When no consistent differences emerged, the latency data for each subject were pooled for affirmative and negative responses within retrieval time conditions. The standard deviations of response latencies ranged from 35 to 148 msec (9). These values are sufficiently low to preclude any overlap in total recognition time (probe duration plus response latency) between conditions. The mean response latencies are shown in Fig. 1 (10).

It has been postulated (11) that speed-accuracy trade-off in some situations involving choice is caused by changes in the proportion of fast, random guesses. In some visual discrimination experiments (12) the presence of a substantial proportion of fast guesses has been confirmed empirically. In experiments in which the procedure permits the use of fast-guess strategies, low accuracy is associated with low response latencies. The actual response latencies measured in this experiment (Fig. 1) show the opposite tendency. The shortest probe durations, associated with the lowest accuracy

(see Fig. 2), also produced the longest latencies. It appears that fast-guess strategies are effectively excluded by our method. The remaining speed-accuracy trade-off in recognition memory must be due to a gradual improvement in the accuracy of situation-controlled responses with additional retrieval time.

The signal-to-noise ratios measured in this experiment are shown, as a function of mean total recognition time (T) for each subject, in Fig. 2 (10). The measure of signal-to-noise ratio is d_T, an unbiased estimate of d' (the true signal-to-noise ratio) at the moment of execution of the yes-no response. Existing estimates of d' in recognition memory [such as Wickelgren's d_a (13)] could not be used in this experiment, as they are based largely on confidence judgments, which in this case were made after the yes-no response. These judgments could have been based, in part, on additional information not available at the time of the yes-no response. If this were true, the yes-no point would tend to lie below the line fitted to the confidence-rating points in the receiver operating characteristic (ROC) plane. Of the 15 empirical yes-no points, 12 did indeed

lie below the corresponding confidence-rating lines. For one subject (E.R.) all five yes-no points were substantially below the confidence-rating lines, which suggests that this subject had considerable difficulty in complying with the instruction to report her confidence at the time of response. For this reason, d_T was based on an ROC line drawn through the yes-no point alone.

The tables of Elliott (14), which are based on the assumption that ROC lines have unit slope, were not used because the slope may vary with d'. When the slope of the ROC line is a function of d', the d' estimates obtained from the tables are biased. In calculating d_T, the confidence-rating data were used to calculate the most likely slope of the ROC line passing through the yes-no point. First, an ROC line was fitted to each set of confidence-rating points. As in calculating d_n (13), the regression coefficient of ln slope on d_s was computed from these lines for each subject. Each family of lines thus generated includes a unique line through every point in the ROC plane, including a line through each yes-no point. The absolute value (in standard deviates) of the x-intercept of that line is d_T.

The speed-accuracy results shown in Fig. 2 invite a comparison between the detection-theoretic processes underlying retrieval from memory and those previously found in perceptual discrimination experiments (5, 15). In discrimination experiments involving the method of forced reaction times, $(d')^2$ was found to be a linear function of T. The data presented here suggest that the recognition memory d' stops growing when the retrieval time exceeds about 4 seconds. Some experimenters studying perceptual discrimination with other methods found similar asymptotes (12). Although models accounting for this behavior have been developed, their derivation would be out of place in a brief report (16). One model, based on the assumption that the memory trace continues to decay during retrieval, predicts that d', as a function of time, should follow the equation

$$d' = \frac{m[1 - e^{-\alpha\,(T-\eta)}]}{\alpha(T-\eta)\,[\sigma^2 + (T-\eta)^{-1}]^{1/2}} \quad (1)$$

where T is the measured total recognition time, and η, m, α, and σ are constants. Equation 1 is represented by the curves in Fig. 2. This model

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predicts an eventual decrease in accuracy with additional retrieval time, and a small decrease was found when the probe display time was increased from 4 to 8 seconds. The decrease was not significant in this experiment, but the possibility of an optimum retrieval time should be kept open. The method presented in this report should facilitate additional quantitative investigations of accuracy as a function of available time.

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References and Notes

1. In a prior study B. B. Murdock [*Quart. J. Exp. Psychol.* 20, 79 (1968)] investigated speed-accuracy trade-off in paired-associate recall by means of explicit prior limits on reaction time. J. M. Swanson and G. E. Briggs [*J. Exp. Psychol.* 81, 232 (1968)] demonstrated a trade-off in stimulus categorization by manipulating response latency with differential instructions and payoffs, for accuracy and speed. Differential payoffs were also used by B. L. Lively [*ibid.* 96, 97 (1972)] to demonstrate a trade-off in the memory search task described by S. Sternberg [*Science* 153, 652 (1966)]. None of these studies used methods capable of excluding the fast-guess hypothesis (11).
2. The subjects were paid female undergraduates meeting the usual requirements (right-handed, native speakers of English, and so forth).
3. The consonants were chosen from b, c, d, f, g, h, k, l, m, n, p, r, s, t, v, and z.
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7. This is not meant to imply that the two methods of controlling processing time are mutually exclusive. Procedures combining the two methods may be devised, and no doubt will be.
8. The design was also balanced for frequency of occurrence of consonants and order within trigram. Four additional sessions were used for training.
9. This corresponds to standard errors ranging from 2 to 8 msec in the mean latencies shown in Fig. 1.
10. Data are available in tabular form from the author.
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16. These models will be adequately documented elsewhere (A. V. Reed, in preparation). In the meantime a summary of model derivation and parameter fitting will be available from the author. In the model of Eq. 1, $(T-\eta)$ is the retrieval integration time; m is the strength of the memory trace, relative to retrieval noise, at the start of retrieval; α is the decay coefficient of the trace; and σ is the standard deviation of threshold jitter.
17. The author is a National Science Foundation Graduate Fellow. This research was also supported by NIMH grant MH 17958-03 to W. A. Wickelgren. I thank Professor Wickelgren for his advice and supervision of this work.

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Imprinting: Lasting Effects on Uracil Incorporation into Chick Brain

Abstract. *On the first day after hatching, domestic chicks were trained for 20, 60, 120, or 240 minutes with an imprinting stimulus. On the second day, they were all retrained for 60 minutes. The greater the chicks' experience on the first day, the lower the rate of incorporation of tritiated uracil into macromolecules in the anterior part of the forebrain roof on the second day. Such effects were not found in other brain regions, nor in any brain region of chicks that received similar treatment on the first day but were not retrained on the second.*

When split-brain chicks had one eye covered during exposure to a rotating, flashing light to which they became socially attached, incorporation of [³H]-uracil into macromolecules was 15.2 percent higher on the trained side of the forebrain than on the untrained side. No such differences were found in any other region of the brain (1). The forebrain roof has been implicated not only as the site of most rapid incorporation of uracil into presumed RNA during an imprinting procedure, but also as the region where the activity of RNA polymerase and incorporation of lysine into presumed protein first increases after imprinting (2, 3). The results for the split-brain chicks indicate that certain general effects of the imprinting procedure, such as a change in concentration of hormone, are not likely to be solely responsible for the increased incorporation of uracil into macromolecules, since such general effects would be expected to influence both sides of the brain to the same extent. However, the biochemical changes produced by the rotating flash-