Memory consolidation: Probit analysis of retrograde-amnesia data¹

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Probit analysis of retrograde-amnesia data reveals a normal distribution of memory indicant to the logarithm of the consolidation interval. The probit regression lines of three comparable experiments in rats have similar slopes. Conflicts in published consolidation times may arise from differences in learning strengths and artifacts of data handling. Consolidation half-time is proposed to replace consolidation time.

A clue to memory fixation may be found in the consolidation hypothesis, which leads to the inference that the time-course of retrograde amnesia (RA) reflects the kinetics of the rate-determining step of the fixation process. The hypothesis is embarrassed by conflicting values for consolidation time (CT), that contribute to conflicting interpretations of RA experiments (Lewis & Maher, 1965). Probit analysis² of published data suggests an approach to reducing the conflict.

Method

Published RA experiments with rats (Table 1) were selected by four criteria: one-trial learning; interruption by electroconvulsive shock (ECS); at least four trial-to-ECS intervals; and at least 10 Ss per group. The data of Experiment 2 permit a good test of probit analysis because they are based upon: a large, uniform group size ($N=30$); a large number of trial-to-ECS intervals (8); a nearly-geometric progression of the intervals; a high control response (100%); and a wide range of experimental responses (10 to 90%).

The "indicant" of memory is avoidance of foot-shock, quantified as percentage of the control avoidance. The "consolidation interval" is considered to start 0.5 sec. after the onset of foot-shock, because of the evidence that 0.5 sec. establishes avoidance (Chorover & Schiller, 1965). The conventional practice is to measure trial-to-ECS intervals from the termination of

foot-shock, on the assumption that memory consolidation starts only then. The resulting error (0.5 to 3.5 sec. in Experiments 1 to 4) is negligible for trial-to-ECS intervals of 75 sec. or more, but is significant for intervals of 0.1 to 10 sec.

The data are plotted on linear coordinates in Fig. 1A and 2A, and on the probit scale in Fig. 1B and 2B, with regression lines fitted by the method of weighted least-squares.³

Results

The asymptotic rise of the indicant in the linear plots precludes determination of a precise end-point. As a result, published values for RA duration are indefinite and do not lend themselves to comparison of different experiments. The consolidation half-time (CT_{50}), the interval at which the experimental Ss emit one-half of the control response, is a more reliable point statistically. It is proposed that the CT_{50} replace the indefinite "consolidation time." The probit transformation permits precise determination of the CT_{50} and its confidence limits (Table 1).

The four regression lines (Fig. 2B) do not deviate significantly ($p=0.05$) from parallelism with one another, by the Litchfield & Wilcoxon test. The data of Experiment 4, however, are significantly heterogeneous by the chi-square test and have little weight. The constants of the expression for the regression lines, $y = a + \beta \log t$, are given in Table 1.

Discussion

The similar values of the slope constant β suggest that the rise of the indicant reflects a similar consolidation process in Experiments 1 to 3 and that the

Table 1.* Consolidation half-times (CT_{50}), a values, and slope constants (β)

Experiment	CT_{50} (sec.)	a	β
1. Chorover & Schiller	9.1 (7.0 to 11.7)**	2.5	2.6
2. Quartermain***	12.3 (9.0 to 16.8)	3.0	1.9
3. King	1120. (500. to 2530.)	0.6	1.4
4. Weissman****	190. (43. to 860.)	--	--

* Based upon corrected trial-to-ECS intervals.

** The values in parentheses are the 19/20 confidence limits. The 19/20 confidence limits of β for Exp. 1, 2, and 3, are (2.1 to 3.7), (1.4 to 2.8), and (0.9 to 3.9), respectively.

*** The 0.1 sec. datum is suppressed.

**** The data are significantly heterogeneous, therefore the derived values ($a = 3.0$; $\beta = 0.9$) have little meaning.

Fig. 1. Time-course of Exp. 2, plotted on linear coordinates (A) and on the probit scale (B). The open circle indicates a datum at 0.1 sec., suppressed because of uncertainty in the duration of relay-and-timer-lag. The dashed lines show the 19/20 confidence limits of the regression line.

Fig. 2. Time-course of RA experiments, plotted on linear coordinates (A) and on the log-probit scale (B). Exp. 1 - upright triangles; Exp. 2 - circles (A) and dotted line (B); Exp. 3 - inverted triangles; Exp. 4 - squares. (When plotted on an expanded time abscissa, Exp. 1 also shows an asymptotic rise.)

conflicts in published values of CT may arise largely from differences in the values of a . The latter is the y-intercept of the regression line at $\log t=0$,

Fig. 3. Time-course of forgetting, from data of Luh (1922), as given by Bahrick (1965), plotted in ebb units and linear time (A) and in probits and log time (B). Recognition scores are represented by triangles; anticipation scores by circles.

i.e., a is the indicant, in probits, when $t=1$ sec. Determination of a values may provide a means for quantitating learning strength; for consistent results in RA experiments, supra-maximal strengths should be employed.

Probit analysis is facilitated by using the graphical method of Litchfield & Wilcoxon (1949), with two constraints: equal numbers of Ss per group (preferably 30 or more) and a balanced geometrical progression of intervals (e.g., $t/4$, $t/2$, t , $2t$, and $4t$, where $t=CT_{50}$, estimated from pilot experiments).

An application of probit analysis to memory decay is shown in Fig. 3B for comparison with the ebb transformation (Fig. 3A) of Bahrick (1965). It may be inferred that the decrease in the indicant, in probits, is normally distributed with the logarithm of time. The rate of decay, in these terms, is the same for recognition or anticipation performance ($\beta=-0.7$) but the retention half-time (RT_{50}) is 300 hr. for recognition performance and 1.3 hr. for anticipation performance.

References

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Notes

1. Supported by USPHS Fellowship 1-F3-MH-25,443-01, NIMH and the Veterans Administration, Sepulveda, California.
2. Probits are "probability units," equal to the normal equivalent deviate plus the arbitrary value 5.00, added to avoid negative numbers. The rationale, application, and limitations of probits are discussed by Finney (1952, 1964), Litchfield & Wilcoxon (1949), and Riggs (1963). Bahrick (1965) analyzed the variables which affect forgetting and the assumptions which underlie the use of variance units for the indicant of memory, and applied to memory-decay data a Z-transformation that is essentially the probit transformation ($Z\text{-score} + 5.00 = \text{probits}$). The same assumptions apply to the use of probits.
3. I thank R. N. Lane for programming and computing the probit transformation.