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Final Report

STATISTICAL DECISION PROCESSES IN RECOGNITION AND DETECTION

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The following work was completed under AF 49(638)-1710. Patrick A. Lucas's work on low probability signal of free-response data was completed. His entire doctoral thesis was published by the Journal of the Acoust. Soc. of America, Vol. 42, No. 1, pp. 158-178, July 1967. A report of this publication follows.

Also related to the method of free response was work completed by Harold Miller (a graduate student in psychology) on "The FROC Curve." A full report of his work was submitted in Quarterly Technical Summary Report No. V. The report with a few minor alterations is being prepared for publication in the Journal of the Acoust. Soc. of America.

Experiments on time uncertainty in two alternative forced choice (2AFC) of four alternative forced choice (4AFC) experiments using continuous wave (CW) of pulsed correct (PC) cues were completed by Dana Main, Ph.D., Research Associate in Psychology. Results of the continuous wave experiments were reported by Dr. Main at the Acoustical Society Meeting, April 1967. An abstract of the paper and the full text were submitted in Quarterly Summary Report No. V. These results combined with those in which the pulsed carrier cue condition was employed are being prepared for publication in the Journal of the Acoust. Soc. of America.

Ted Cohn, a graduate student in Bioengineering has been conducting neurophysiological research with an emphasis on methodology. An experiment concerning a neurophysiological system is designed so that the data may be interpreted within the framework of the theory of signal detectability. In this way inferences concerning information processing in the neurophysiological system and inferences concerning the experimenter as a receiver are possible. The understanding of the neurophysiology, depends upon the quantification of the effect of the experimenter on the experiment.

Gary Sylvester, a graduate student in psychology has studied sensory code acquisition in the psychoacoustic task with modality effect. His experiments and some of his data were presented in earlier Quarterly Reports. He has subsequently constructed an algebraic model which complements the geometric model discussed in Quarterly Report V.

Essentially, the process of sensory coding is regarded as one of estimating certain parameters. It assumes that each input has an associated representation in the nervous system which can be described statistically as a normal distribution. The decision making process is a function of the comparison of this internal representation with one drawn from the memory. The memory representations are conceptualized as the result of a transform of the associated input distribution. If no (or negligible) external noise is assumed, the uncertainty is due to internal noise (or "input noise") and the effects of faulty memory. Input noise is a random variable which is distributed normally, with the amount of variance reflecting the noise magnitude. A certain amount of variance is assumed to be added in the memory on each observation to the input noise variance. It is the reduction of this memory variance which constitutes coding. The variance should be reduced by the accumulation of greater amounts of information as the experiment progresses. If more information is available to an observer on each trial, then this observer should demonstrate more rapid coding. Such is the hypothesized function of the correlated visual information in the experiment.

The basic parameters of the model are $\Delta\mu$, σ_I^2 (the input noise variance), σ_m^2 (the added memory variance), and d'(n) which is the sensitivity measure on trial n. The involved mathematics and strict assumptive statements will not be described here—however, it may be said that the model incorporates three cases: (1) An observer with perfect memory ($\sigma_m^2 = 0$); (2) an observer with constant memory variance added $\sigma_m^2 > 0$; and (3) an observer whose memory noise fluctuates according to some statistical pattern. Case (3) is a reasonable approximation to Case (2) with d'(n) being given a distribution with small variance. Case (3) may also be regarded as a more complete description of a human observer's performance. Thus, the results for Case (2) were used to analyze the data within the framework of this model. The basic prediction equation may be written as: $d'(n) = \Delta\mu \, (\sigma_I^2 + \sigma_m^2(n))^{-1/2}$.

Theoretical curves were fit to the graphs of d' vs. experimental session number and certain parameters estimated so that σ_m^2 could be determined. Fitting such curves to the data may be justified in that predictions of the model were examined in relation to the empirical results. Through suitable manipulations a linear relationship between ℓn and the natural logarithm of a quantity based upon the model's predicted sensitivity at each n and the empirically determined asymptotic sensitivity was obtained. Log-log plots supported these straightline predictions. This parameter (σ_m^2) was then used to compare the two sets of observers. With this method, the "visual" observers indicated having a smaller variance added in memory. This is interpreted as a reinforced memory due to the added visual information those observers were receiving. These rsults correspond ordinally to the statistics computed on the basis of fitting 2 linear curves to the data, as presented in the earlier report. The implication is that central processing areas appear to be able to utilize any relevant information in constructing suitable hypotheses.

Mr. Sylvester is preparing a paper for the *Journal of the Acoust. Soc. of America* in which the model is described in detail.

Wilson P. Tanner, Jr. has written a paper to be submitted to *Science* on the acquisitions of sensory codes. A draft of this paper follows.

ACQUISITION OF SENSORY CAPABILITIES

Wilson P. Tanner, Jr.

(Draft of paper to be submitted to Science)

ACQUISITION OF SENSORY CAPABILITIES

Implicit assumptions frequently determine the course of scientific investigation. These assumptions, while not always readily identifiable, nevertheless guide the experimenter's selection of seemingly worthwhile experiments. To the extent that such assumptions formalize scientific thinking, they may be regarded as universally accepted. For example, the development of non-Euclidean geometries flourished only after the role of the parallel line assumption in restricting conceptions of space was elucidated. Kuhn[3] cites many similar examples.

By examining the types of experiments which have and have not been conducted in a field, one may discover consistent reasons for rejecting experiments. These reasons may in turn reveal the nature of tacit assumptions which are currently unstated or long since stated and forgotten. Such examination of the field of psychophysics reveals that the initial basis of measurement in the field, the threshold, was an assumed concept which supported confused and conflicting analyses of data.

An alternative basis for psychophysical analysis was provided in the early 1950's by the development of statistical decision theory and the theory of signal detectability. These new techniques and measures were applicable to experimental designs which had previously been analyzed exclusively by threshold techniques. When the two sorts of measures were compared over the same sets of experiments, it was found that the signal detection measure d' eliminated many of the inconsistencies inherent in threshold measurements.

For example, Tanner and Swets[12] demonstrated the invariance of d' in a set of visual experiments which yielded different false alarm rates. Swets[8] demonstrated the consistency of d' over several different types of experiments (yes-no, 2AFC, 4AFC, 8AFC) as well as the generalizability of the consistency to hearing experiments.

Several hundred studies conducted within the framework of the theory of signal detectability are reported in the psychophysical literature. Regrettably, almost all of these studies have been concerned with topics which had previously concerned threshold theorists. It is undeniable that most the problems to which signal detectability analyses were directed required attention. Nonetheless, there have been too few attempts to employ signal detection paradigms to expand psychophysics beyond traditional bounds.

Among the efforts to extend the field of psychophysics have been Egan *et al.*'s,[1] development of a method of free response, which generalized signal detection analyses beyond fixed observation designs and those designs in which detection and false alarm rates are directly determinable. Lucas[5] applied the method of Egan *et al.*,[1] to infrequently occurring signals in a "vigilance" task. Tanner and Norman[11] were concerned with selective attention, and the former used the results of these experiments to develop a theory of masking.[9] Tanner[10] investigated the role of memory in detection tasks. Norman[6] has extended Tanner's techniques to apply to the analysis of short term memory of verbal signals. Considerable attention has been directed toward the development of signal detection techniques for analyzing data collected by the rating method (e.g., Pollack,[7] and Watson[13]).

While the list is not exhaustive, it is too large a fraction of the total research in new problem areas to be encouraging. Models developed within the framework of the theory of signal detectability should be more prolific in enhancing the scope of psychophysics. Unless the reasons for the relative unproductivity of signal detection models are discovered and corrected, the theory may soon outlive its usefulness in psychophysics.

At least one argument advanced from a position of scientific naivete may have restrained the more widespread development of signal detection models. This argument, that data should be reported in raw forms, has led some investigators to revert to reporting percentage correct responses as did experimenters working with the threshold concept. Unfortunately, percentage correct responses varies with experimental designs while d' tends not to vary in this way. Given that one knows the experimental design in which the raw data has been collected, one can convert d' to percentage correct as readily as one can convert percentage correct to d'. This misunderstanding has diverted some investigator's attention to trivial psychophysical problems.

A second possible restraining influence on the use of signal detectability analyses in new problem areas has been the traditional separation of psychophysics from other areas of psychology. The isolation of psychophysics may well be due to an implicit assumption that sensory systems may be studied as independent entities, without considering their interactions with other functions of the nervous system. Firm belief in this assumption leads experimenters to produce _a_ sensitivity curve as _a_ function of frequency, _a_ curve on the judgment of the magnitude of weights or sounds based on data collected from nonpost office personnel, a curve of frequency discrimination as a function of the frequency of one of the tones, and many similar relations. The preoccupation of many workers in signal detectability with old problems may have served to perpetuate the assumption that psychophysics or sensory psychology may be divorced from the rest of psychology. The threshold is no longer to blame. What then is to blame?

It is possible that current attitudes toward the doctrine of the specific energy of nerves underly the problems to which this paper is addressed. The inference that Johannes Mueller's specificity of the nervous system is innate seems to have permeated the structure of psychophysical and psychological theory. It is inconsistent, however, to assert simultaneously that the human animal is the most flexible of all animals and that the human is also completely rigid and nonadaptable.

From the point of view of a signal detection theorist, a psychophysical response represents a report of an accepted hypothesis rather than a report of the makeup of the sensory input, and probably rather than a report of the output of a sensory system. In fact, the report may be of an hypothesis accepted on the basis of inputs to several sensory systems. The idea that responses represent hypotheses accepted on the basis of testing data received through several senses was presented by Licklider[4] in a discussion of auditory localization. Licklider suggested convincingly that the artificial environment of the laboratory may lead to theories which adequately describe laboratory behavior but which have little relevance in real life situations. In discussing Licklider's presentation, Davis (1967) stated that it seemed as though a little green man had been postulated but he said also "that seems to be the way the nervous system works." In spite of these statements, psychophysicists continue to investigate the same old problems, and physiologists continue with the same problems without a new approach.

If the observer does indeed test hypotheses, where do these hypotheses come from. It seems obvious that in the complex form they must be acquired. It is also possible that the basic codes of which complex hypotheses are composed are also acquired. During periods of individual growth and development one may learn to use those cues in the environment which are relevant to his welfare. Thus, the common psychophysical experiment reflects not only the sensory system under study, but also the codes and hypotheses which have been stored as relevant to the individual's welfare in the past. To interpret these results one has to be a learning theorist, a sociologist, a decision theorist and an anthropologist as well as a psychologist.

Speculation on the sources of perceptual hypotheses leads to the issue of whether the sensory areas of the cortex are more nearly like special or general purpose computers. Specifically, is the visual cortex peculiarly designed for processing data relevant to visual hypotheses, or can it process neural data pertinent to any class of hypotheses? Is the degree of specificity of function of the visual cortex innate, or is it achieved gratuitously, merely because it has always received inputs of a particular nature? If the visual cortex were to receive inputs arising from acoustic signals could it evaluate acoustic hypotheses?

Let us assume for the moment that central sensory areas function in a generalized rather than a modality specific fashion. An immediate consequence of this assumption is that the nature of sensory data processing is heavily dependent upon an individual's experience during his growth and development. If such were the case, environmental utility might well dominate genetic specificity in determining the aspects of the environment which an individual would learn to discriminate. Environmental differences would be reflected in differences in patterns of discriminal capacities; moreover, aspects of the environment which are at one time indiscriminable might at another time be rendered discriminable in the interests of biological utility.

METHOD: The current study was intended to test the above assumptions in tasks involving discriminations among signals with which observers had had no prior experience. An attempt was made to devise a set of acoustic signals which encoded information customarily interpreted visually. By analogy with television transmission practices, visual horizontality was represented as time position of an audio frequency carrier and visual verticality was represented by the frequency of a pulse superimposed upon the carrier. A hundred millisecond segment of a 1 kHz amplitude modulated sine wave served as a time reference. The 100 msec sweep of the waveform started at a maximum amplitude in the left ear and decayed linearly to zero amplitude by the end of the segment. The inverse signal was presented in the right ear; i.e., a 100 msec waveform which started at zero amplitude and increased linearly with time to maximum amplitude at the end of the sweep. Only one sweep (one vertical position) was presented diotically on each trial during the first experiment. Superimposed upon this carrier at one of four time delay positions (20, 40, 60, or 80 msec for both ears) was a 10 msec 1 kHz pulse, the amplitude of which was proportional to the instantaneous amplitude of the carriers in each ear. The observers' task was to indicate by pressing an appropriate button which of the four delays occurred on each presentation of the carriers. Observers were informed by lights immediately after each trial which button they should have pressed and whether their decisions were correct. The biological utility of the discrimination task to the observers was a reward of .3¢ per correct response and a fine of .1¢ per incorrect response.

It was acknowledged at the beginning of experimentation that the observers might be unable to develop a capacity to discriminate among the signals for many thousands of presentations. However, even though initial results were discouraging, our intuitive estimates of the magnitude of the number of 'trials' which an individual experiences during development encouraged us to devote an entire summer term to the experiment. About 35,000 observations were recorded for each observer.

RESULTS: The daily correct response percentages for each observer were converted to d' measures from Elliott's[2] tables for M = 4. Figure 1 displays these data as a function of trials. It is clear from the graphs of Figure 1 that while initial performance for all observers indicated no capacity to discriminate among signals (d' = 0), all observers performed in a manner indicating the development of discriminal capacities as the experiment continued. Both the rate and the form of the functions describing progress in developing the capability of discriminating among signals differed among observers. It is difficult to conceive of a typical learning curve applicable to the performance of all of the observers in this experiment.

One model for the improvement of performance with experience (perceptual learning) is to assume the development of a subjective time scale which coincides with the 1000 msec observation interval. The process of development of such an internal time scale entails the establishment of four time constants, one corresponding to each signal delay. Two factors are thought to account for the absence of nearly perfect performance in this model. The first factor is noisy transmission of sensory information to the processing areas of the nervous system; the second factor is a noisy memory for sensory input. The noisy transmission hypothesis suggests that elapsed time between acceptance of the input by the transducer and the arrival of the data at the processing areas is variable. The noisy memory hypothesis suggests that the estimation of the four time constants is not error free. If we assume that the variances of the two factors are additive, it follows that

$$d'_A = \frac{\Delta T}{\sqrt{\sigma_I^2+\sigma_M^2}} \qquad (1)$$

where d'_A is the value of d' at asymptotic performance, ΔT is the time interval between the values of the hypothetical time constants, variance_I is the variance of the transmission time and variance_M is the variance of the memory process at asymptote.

Before asymptotic behavior is achieved,

$$d'_i = \frac{\Delta T}{\sqrt{\sigma_I^2+\sigma_{M_i}^2}} \qquad (2)$$

where the subscript i refers to position of time during the course of the experiment. It will be noted that the value of the transmission noise variance, σ_I^2, is assumed to be invariant during the progress of the experiment. Rather, the change in d' between d_i' and d_A' is due entirely to a reduction of $\sigma_{M_i}^2$ to σ_M^2.

Squaring and taking the reciprocal of Eq. (1) yields,

$$\left[\frac{1}{d_A'}\right]^2 = \frac{\sigma_I^2+\sigma_M^2}{(\Delta T)^2} \quad . \tag{3}$$

Likewise, squaring and taking the reciprocal of Eq. (2) yields,

$$\left[\frac{1}{d_i}\right]^2 = \frac{\sigma_I^2+\sigma_{M_i}^2}{(\Delta T)^2} \quad . \tag{4}$$

Subtracting Eq. (3) from Eq. (4)

$$\left[\frac{1}{d_i'}\right]^2 - \left(\frac{1}{d_A'}\right)^2 = \frac{\sigma_{M_i}^2-\sigma_M^2}{(\Delta T)^2} \, . \tag{5}$$

Since in the model σ_M^2 and σ_I^2 are assumed constants, then σ_M^2 can be written as

$$k(\sigma_M^2+\sigma_I^2)$$

and from Eq. (3)

$$\frac{\sigma_M^2}{\Delta T^2} = k\left(\frac{1}{d_A'}\right)^2 \, .$$

Equation (5) now becomes

$$\left(\frac{1}{d_i'}\right)^2 - (1-k)\left(\frac{1}{d_A'}\right)^2 = \frac{\sigma_{M_i}^2}{(\Delta T)^2} \, . \tag{6}$$

Now since $\sigma^2_{M_i}$ should decrease linearly with the logarithm of i then that part of $(1/d'_i)^2$ which is dependent upon $\sigma^2_{M_i}$ should also decrease linearly with the logarithm of i. It is therefore necessary to determine a value of σ^2_I which permits $(1/d'_i)^2$ to show this linear decrease.

A graphical procedure was employed. First the curves representing d' as the function of the day of observing were fit by eye. From this we obtained values of d'_i and d'_A. We then plotted on log-log paper $(1/d'_i)^2$ as a function of the observation day (Figure 2). Observing that this function was concave upward, a value of σ^2_I was chosen which would tend to remove the deviation and a new curve plotted. A reiterative procedure of choosing values of σ^2_I was followed until one was found which yielded a negatively decreasing straight line. Using this value and Eq. (3) and the graphical value of d'_A obtained above and using the fact that the time positions which were to be discriminated were separated by 20 msec, we could now express these variances in terms of seconds. In the cases where the variances were approximately equal the following table could be used for estimating the standard deviations and variances for this experiment.

TABLE I

d'	p(C)	σ in msec	σ^2 in msec
2.80	.95	1.75	3.06
2.36	.90	2.23	4.97
2.07	.85	2.72	7.40
1.83	.80	3.15	9.92
1.63	.75	3.51	12.32
1.45	.70	4.17	17.39

While the above analysis is presented as support for a model which assumes that the "learning" process is one which involves the development of a scale for measurement of the inputs, we might also suggest that it might eventually be possible to use this or similar analyses as a basis for coordinating psychophysical and physiological data. For example, knowledge of the transmission variance along with a knowledge of the factors which lead to latency variance in the nervous system could lead to a estimate of how far into the nervous system the information must be transmitted before a decision is reached. The memory variance could be used in even wilder speculations leading to hypotheses concerning the factors involved in memory, the capacity of the memory and soforth. It is my feeling that the speculations made in this paragraph are important and should be taken seriously as suggestions of directions in which psychophysics and psychology might follow if one hopes for coordination with physiology. These speculations must also be considered with caution.

One testable consequence of the above model is that the establishment of new time constants on an existing scale should require less experience than the initial development of the scale and establishment of the original time constants. A second experiment was conducted to test this deduction. In Experiment II, similar signal ensembles were presented (i.e., the same increasing and decreasing amplitude modulated carriers in each ear) which differed only in the time delays, which were 30, 40, 50, and 60 msec. The current model predicted a ΔT value of one half of its value in Experiment I but the same σ_I^2 and σ_M^2 values as in Experiment I.

If the cut points for decisions to report each time delay are located midway between the mean time constants assigned to time delays on the hypothetical unidimensional scale, then the percentage correct responses (P(C)) is

$$\begin{aligned} P(C) &= (4-6E)/4 \\ &= 1 - 1.5E \end{aligned} \tag{7}$$

where E is error associated with the proportion of the distribution outside the cutoff. The justification for the figure 6E is that the two interior distributions each lose two tails while the extreme distributions each lose only one tail. The predicted P(C) for the set of time delays employed in Experiment II may be derived by computing the distance (d') between adjacent distributions in the first experiment from observed probabilities of correct responses and then dividing these distances in half.

Table II displays the data from the second experiment. The correspondence between the observed data and the predicted data encourages one to believe that the current model provides a reasonable account of the process of developing a scale of measurement for the inputs.

TABLE II

OBTAINED AND PREDICTED PERCENT CORRECT VALUES FOR SIX OBSERVERS

	Observer (percent correct)					
	1	2	3	4	5	6
Obtained Exp. I	.85	.62	.46	.85	.90	.61
Predicted Exp. II	.61	.43	.33	.61	.66	.44
Obtained Exp. II	.58	.51	.35	.50	.65	.41

We do not imply that the present model constitutes a description of the nervous system. In its strictest sense, the model consists only of a set of functions which are interrelated in a fashion which resembles the input-output relations observed in the two experiments discussed above. If the model provides an adequate description of these relations then in a mathematical sense whatever actually happens in the nervous system must be equivalent to what happens in the model. Thus, even if the same functions are not performed in the nervous system, those which do exist may be transformed mathematically into the functions described in the model.

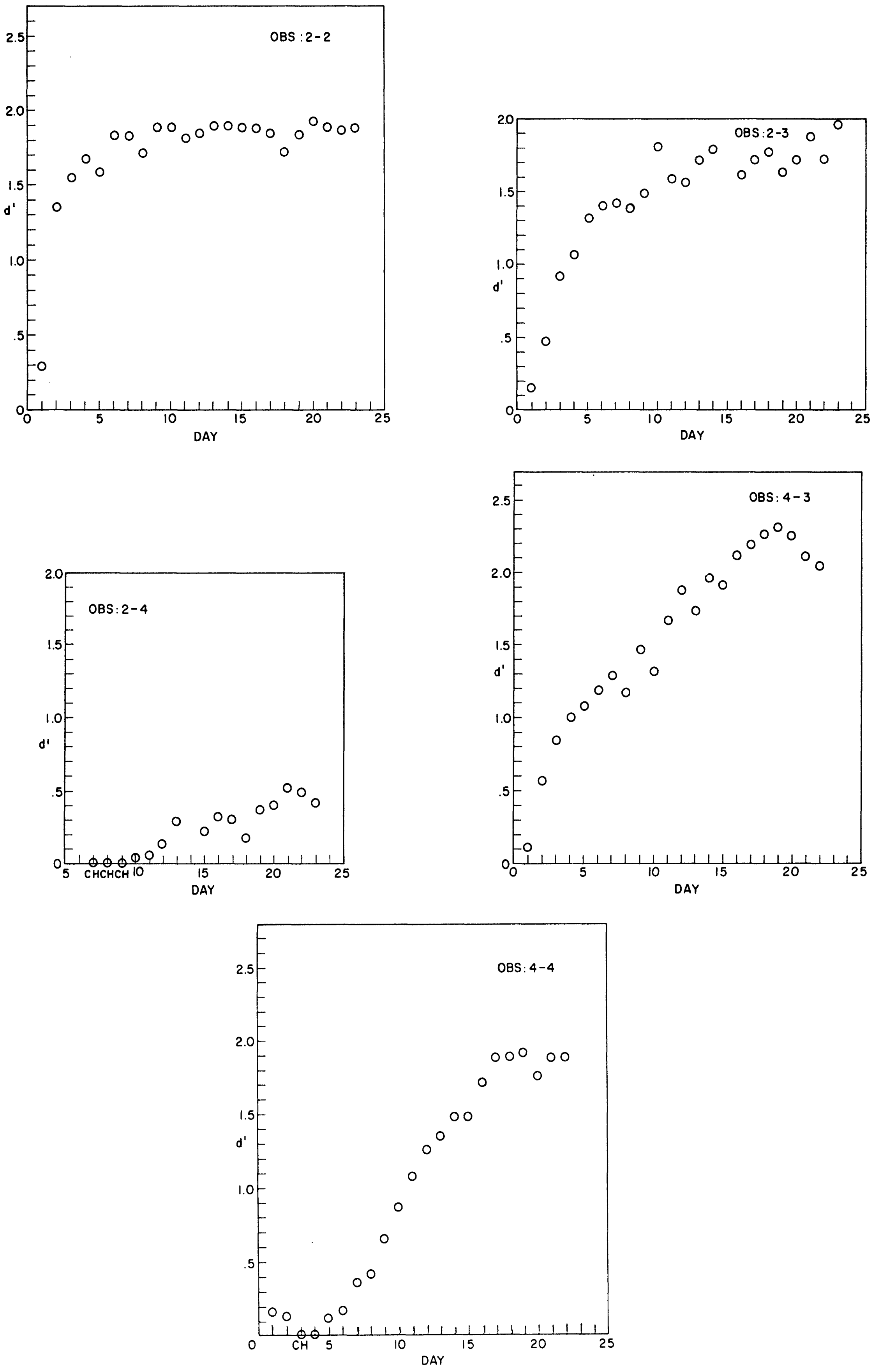

Figure 1. d' as a function of the day of observing.

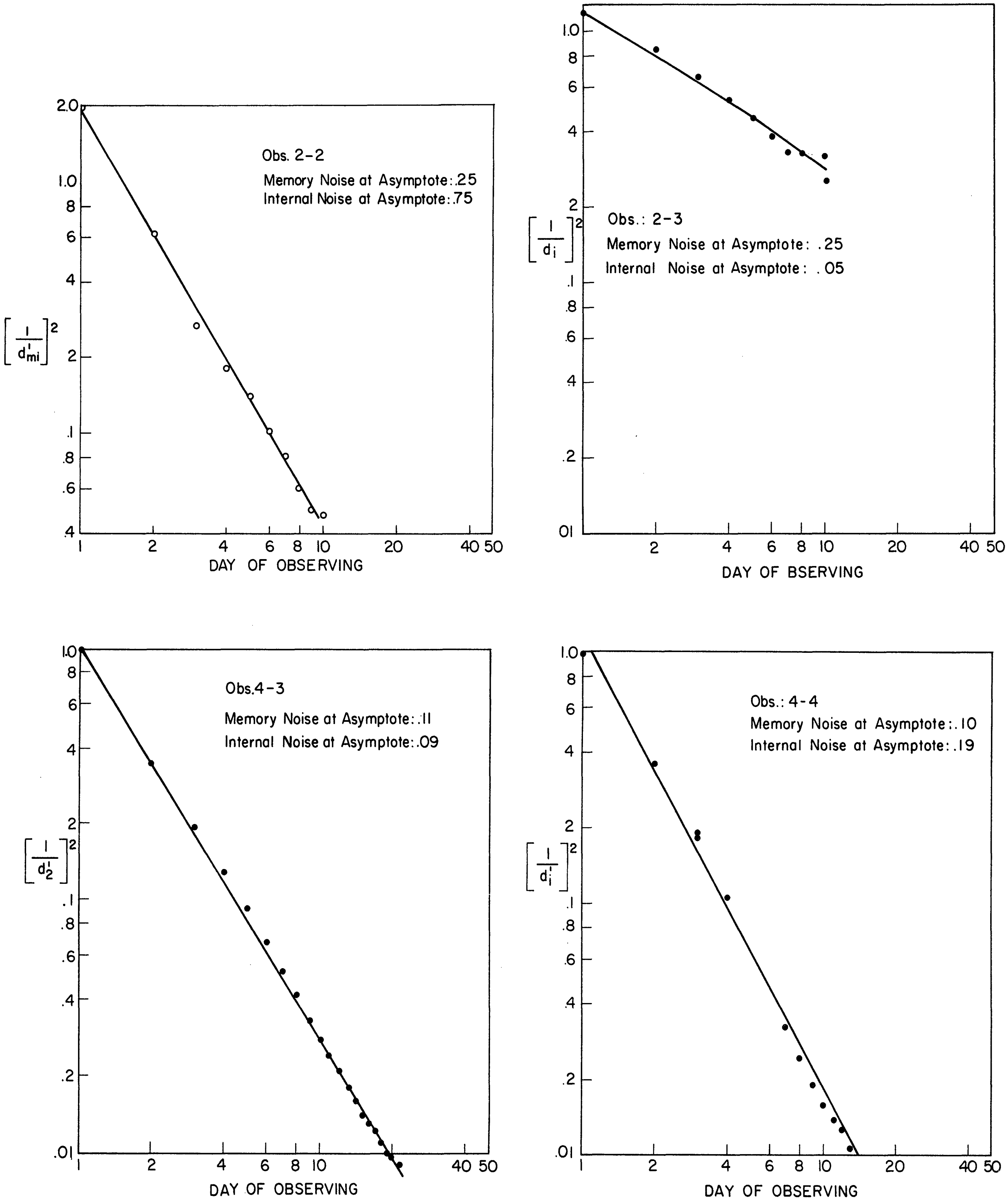

Figure 2. Log-log function of the reciprocal of $(d'_i)^2$ versus day of observing.

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