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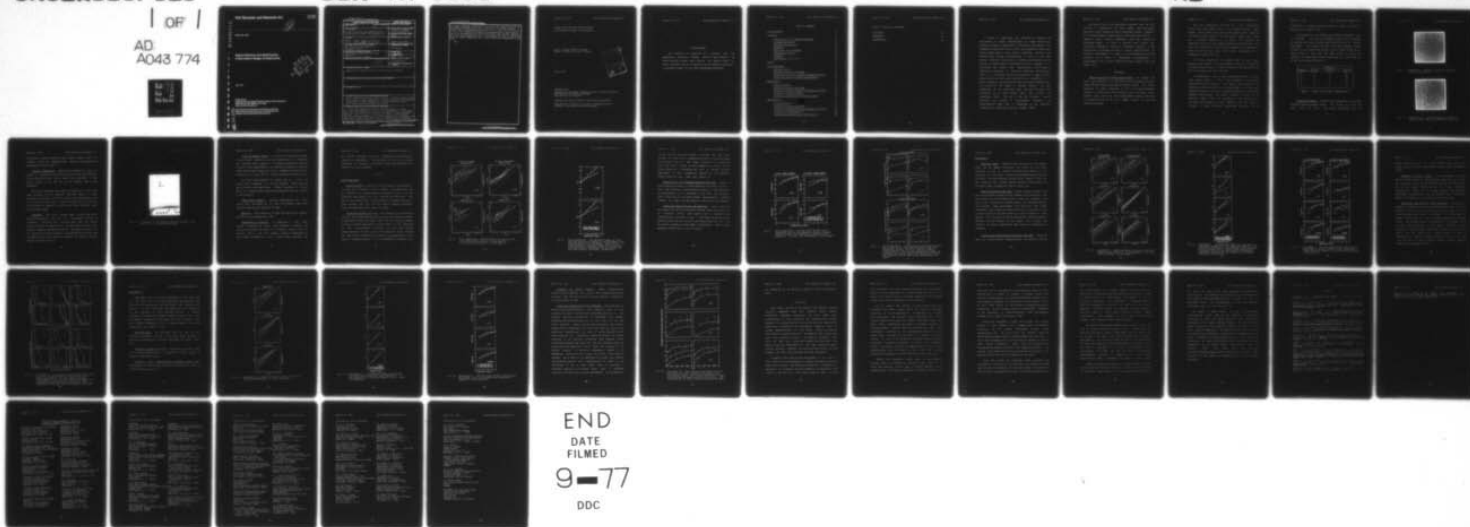
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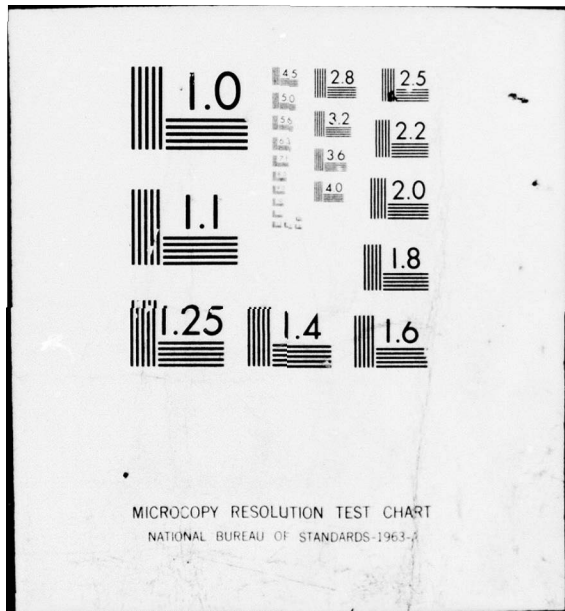
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Report No. 3535

**Signal Detection and Identification  
at Successive Stages of Observation**

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Prepared for:  
Engineering Psychology Programs, Office of Naval Research  
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One model employed conceives of detection and identification as proceeding together over time as parts of a unified process. A second model employed shows how the *joint detection-and-identification ROC*--a Relative Operating Characteristic that relates the joint probability of correct detection and correct identification to the probability of a false detection--may be predicted from the simple detection ROC. Both models were supported by the data.

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Signal Detection and Identification  
at Successive Stages of Observation

John A. Swets, David M. Green,  
David J. Getty, and Joel B. Swets

July, 1977

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A series of experiments was conducted to examine the relationship of signal identification to signal detection at successive stages of observation of relatively long signals. The fundamental theoretical idea is that, with sequential observation of each signal and/or noise pattern presented, detection and identification proceed simultaneously as parts of the same process. Moreover, the accuracy of detection performance and the accuracy of identification performance will grow together in a predictable way (Nolte, 1967). Specifically, at each stage of observation a Relative (or Receiver) Operating Characteristic (ROC) of a form that relates the probability of both a correct detection and a correct identification to the probability of a false detection can be predicted from the simple detection ROC, as a function of the number of possible signals. The main assumptions of the underlying model are that the signals are orthogonal and of equal energy (Starr, Metz, Lusted, and Goodenough, 1975). The use of the ROC provides a way of examining the results of simultaneous detection and identification tasks that is independent of the observer's criterion for a detection response (Lindner, 1968).



The signals used in the experiments reported here met the criteria of independence and equal energy. They were highly idealized visual representations of underwater sounds, suggested by the spectrographic display used in some sonar applications. A companion study, reported separately, used more complex and correlated signals, in order to simulate more closely real (including underwater) sounds of practical interest. In the latter study, an attempt was made to relate identification and detection performances by means of a multidimensional scaling analysis, and by means of developing correspondences of psychological and physical dimensions (Swets, Green, Getty, and Swets, 1977).

#### PROCEDURE

Description of the Signals and the Noise. The signals and noise were generated on a DEC PDP-11/34 minicomputer driving a COMTAL 8000-SA image-processing and display system. The COMTAL generates an image consisting of 512 x 512 picture elements (pixels), in which each pixel can take on any of 256 gray levels between black and white. The raster-scanned image is displayed in an area 24 cm by 24 cm on a CONRAC 17-inch (43 cm) SNA television monitor.

The noise background consisted of a 256 x 256 element matrix, each noise element being a 2 x 2 square of pixels. Each element was assigned a gray value drawn randomly from a Gaussian distribution with a mean of 128 units on the COMTAL gray scale and a standard deviation of 25 units. The contrast and brightness controls on the CONRAC monitor had been adjusted such that the middle gray (128 units) corresponded to a luminance of about 62 cd/m<sup>2</sup> and full white (255 units) corresponded to a luminance of about 308 cd/m<sup>2</sup>.

The noise background was sampled anew on each trial. Signals, when present, were superimposed on the noise background by constructing a matrix of signal values and then displaying the sum of the signal and noise matrices.

In Experiment I, eight signals consisted of single, vertical lines eight pixels in width, which differed in horizontal location across the display. The signal lines darkened the underlying noise background by five gray units (1/5 of the noise standard deviation), and were centered horizontally in successive eighths of the display. The general location of each of the potential signal lines was indicated to the observers by a horizontal strip above the image labelled with the digits 1 through 8 above successive signal-line locations. As an

illustration, a slightly enhanced display of signal #3 (a line in position 3) is shown in Fig. 1.

In Experiment II, the display was divided horizontally into 16 locations. A set of five orthogonal signals was constructed by choosing five sets of three lines from the set of 16, without replacement. The pattern for each of the five signals is given in Table I, and an enhanced display of one of them (Signal #3) is shown in Fig. 2. Each line was eight pixels in width and darkened the underlying noise by three gray units (less than 1/8 of the noise standard deviation).

Signal #	Location		
	Line #1	Line #2	Line #3
1	5	9	12
2	2	7	10
3	4	6	15
4	3	8	16
5	1	11	14

Table I. Signal Line Patterns (Experiment II)

Viewing Environment. Observers sat approximately two meters from the stimulus-display screen. This screen was about one meter from the floor, and viewed comfortably over the

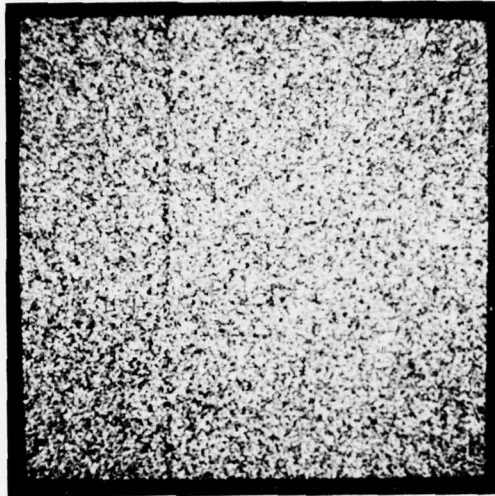


Fig. 1. Experiment I. Enhanced display of signal #3:  
a line in position 3.

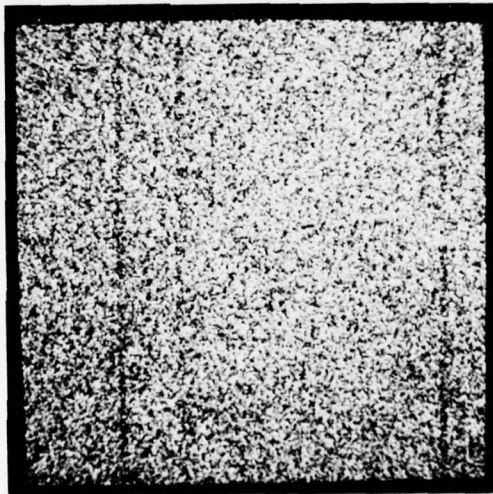


Fig. 2. Experiment II. Enhanced display of signal #3:  
a pattern with lines in positions 4, 6, and 15.



CRT/keyboard computer terminals (Lear Siegler ADM-3A) used for response cueing and response entry. Ambient room lighting was approximately three cd/cm<sup>2</sup>.

Stimulus Presentation. Signals were presented in noise at random on one-half of the trials, and noise alone was presented on the remaining trials. When a signal was presented, it was equally likely to be any one of the signals used in the experiment.

Each trial contained five stages of observation, with each stage followed by the responses described below. A stage consisted of painting a horizontal stripe over approximately the top one-fifth of the screen. Stages followed from top to bottom of the screen in "waterfall" fashion, each stage "pushing down" the preceding stages.

Responses. The first response made at each stage was a detection response in the form of a six-category rating of confidence. Following this response were first and second choices relative to identification, and were made no matter which detection response was made previously. Responses were made via the keyboard of the CRT terminal, with appropriate type and time of response cued by the terminal's display; the complete terminal display is shown in Fig. 3.

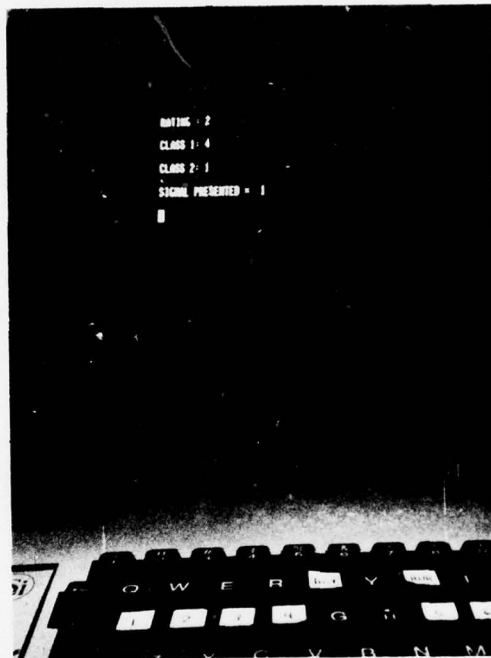


Fig. 3. An example of the complete terminal display at the end of a trial in both experiments.



Trial and Session Timing. A fifth of the screen was painted in ten seconds. The next fifth was painted after all observers had completed their responses. The observer-terminated response interval lasted approximately five seconds, followed by a warning sound that the next stage would occur. Feedback was given at the conclusion of a trial, and 1.5 seconds intervened between trials.

Ten trials were presented in a block, and, as a rule, six blocks were presented in a two-hour session. Thirty sessions were conducted over eight weeks. Certain sessions or initial parts of sessions were designated as practice, and not included in the analyses.

Experimental Control. Stimulus presentation and trial timing were controlled by the PDP-11/34 computer, which also recorded responses and analyzed the data.

Observers. Three observers included two high school students and one of the experimenters (JBS).

Experimental Conditions. In Experiment I, with eight signals consisting of single lines differing in location, two conditions examined the effect of (a) leaving visible, and (b) erasing, each of the five stages of stimulus presentation as these stages proceeded on a trial. A pilot study, employing JBS

and another technical assistant as observers, was essentially identical to Experiment I. In Experiment II, with five signals consisting of variously distributed three-line patterns, only condition (a) was conducted.

## RESULTS

### Pilot Experiment

Detection ROC's. Detection ROC's for each of five stages -- (a) with, and (b) without, "visible memory" -- are shown for the two observers on double-probability scales in Fig. 4. The two conditions were based on (a) 142 trials and (b) 120 trials. The form of the several ROC's -- approximating a straight line with a slope perhaps less than but near unity -- appears reasonable, given the relatively small number of trials.

Detection Accuracy Over Time. The increase in the detection index  $d'_e$  (the normal-deviate index taken at the negative diagonal as described by Green and Swets, 1966, 1974) over the five stages is shown on double-logarithmic scales in Fig. 5. As a reference for the visible-memory condition (a), the best fitting (least-squares) line with a slope of one has been drawn through the data points, representing a growth of  $d'_e$  proportional to the number of preceding stages,  $n$ . As a reference for condition (b),

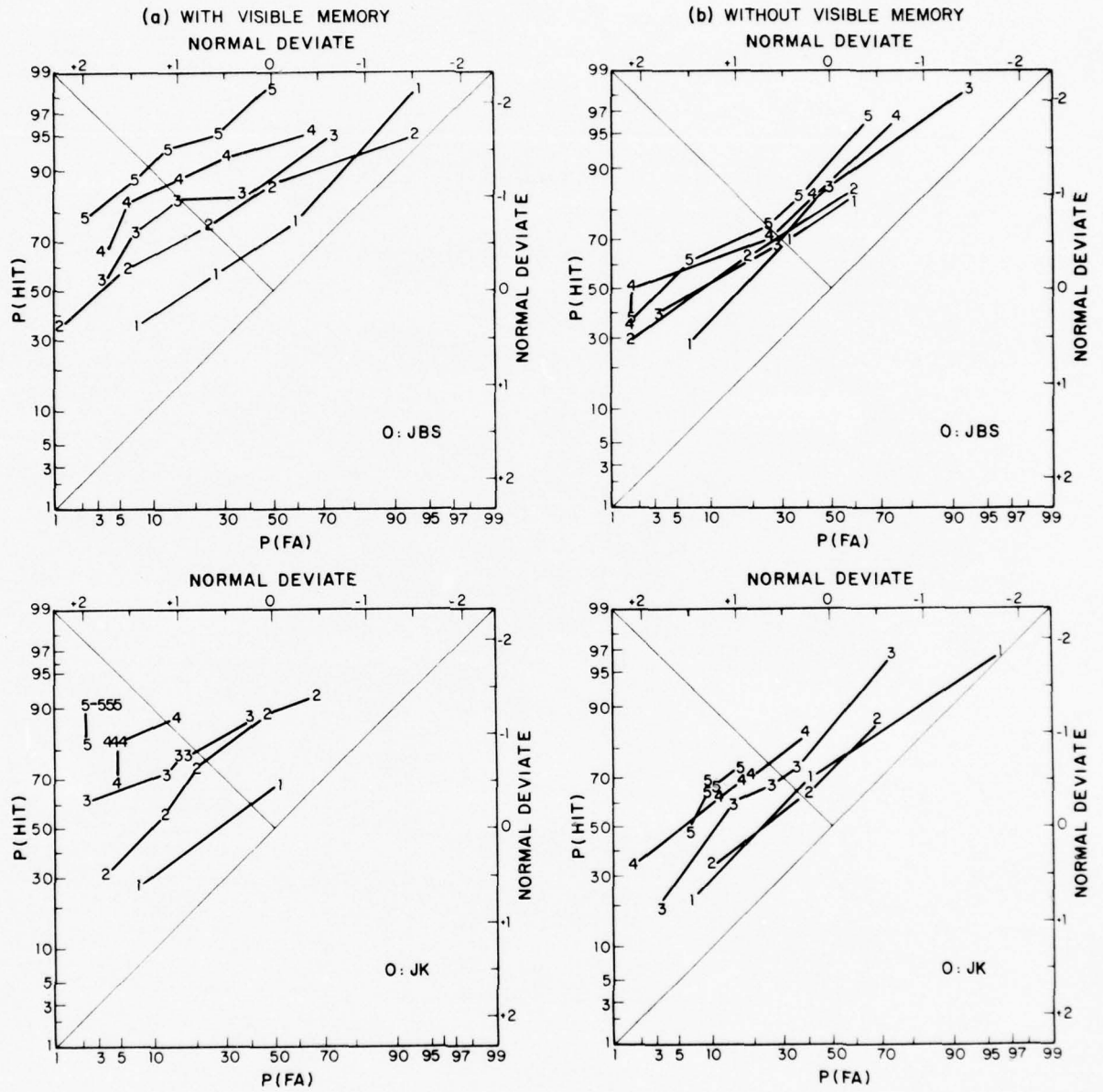


Fig. 4. Pilot Experiment. Detection ROC's for each of the five stages of observation for two observers: (a) with, and (b) without, visible memory.

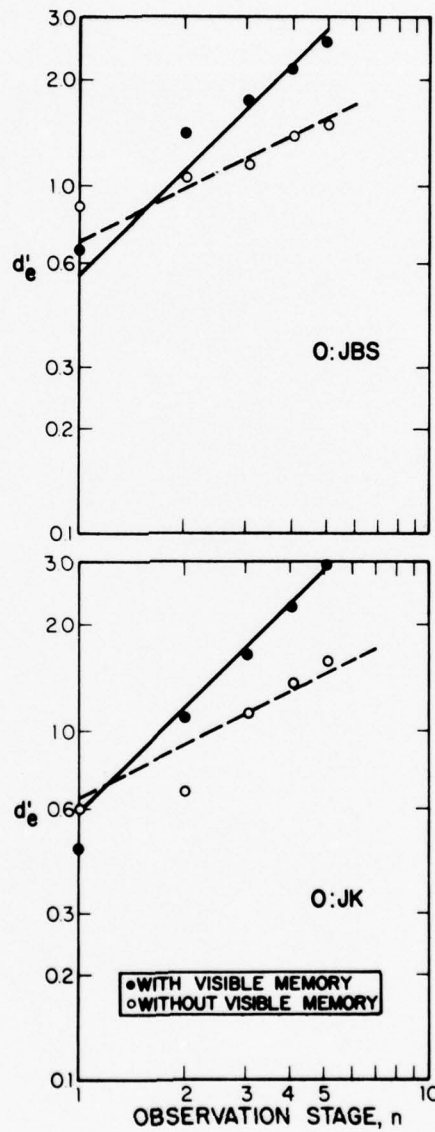


Fig. 5. Pilot Experiment. The detection index,  $d'_e$ , over the five observation stages for two observers, both with and without visible memory. Best fitting (least-squares) lines with slopes of one and one-half are shown as references for the visible and no-visible memory conditions, respectively.



the best fitting line with a slope of one-half has been drawn through the data points, representing growth in  $d'_e$  proportional to the square root of  $n$ . The former prediction is consistent with some other results of areal summation in vision, and the latter prediction is consistent with data of several previous experiments in which integration depended on the observer's memory (Green and Swets, 1966, 1974, Chapter 9).

Detection and Identification Accuracy Over Time. Figure 6 shows detection accuracy -- here indexed by area under the ROC -- over time, along with identification accuracy -- here indexed by the percentage of correct responses -- over time. The indication here is that the two processes proceed simultaneously, spanning together the range from near chance to near perfect performance.

Predicting Identification from Detection. Joint detection-and-identification ROC's, having as ordinate value the probability of responses correct with regard both to detection and identification, are shown in Fig. 7. The figure shows the values predicted from the data points of the simple detection ROC, and the values obtained, at each stage of observation. There is good agreement between the two sets of values.

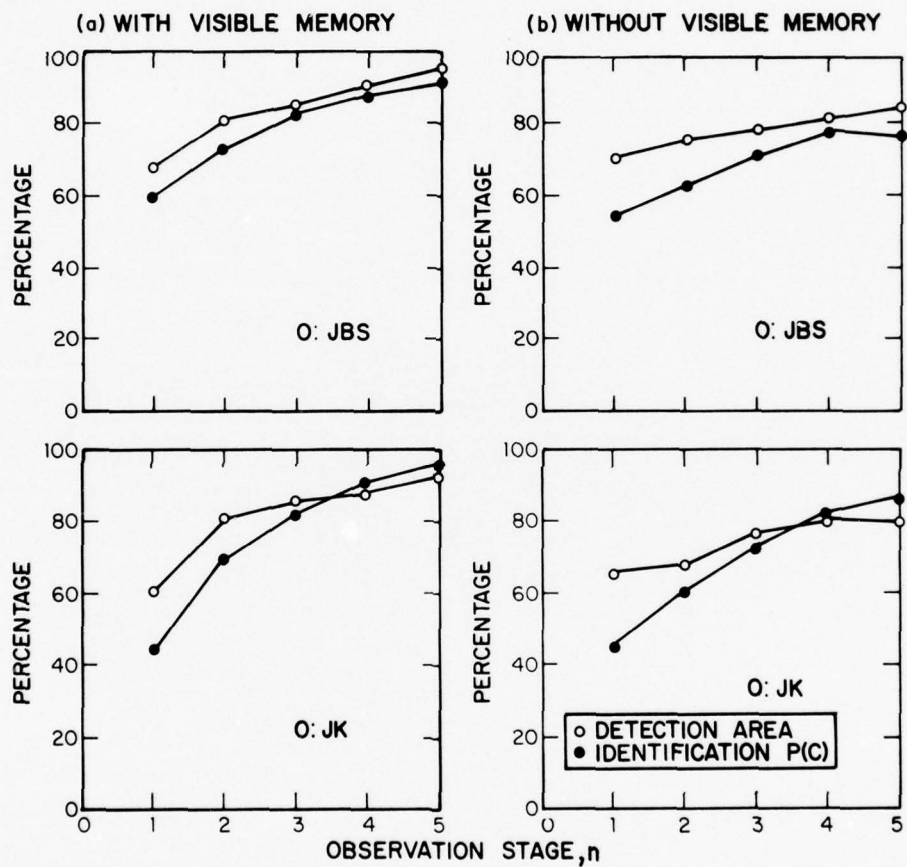


Fig. 6. Pilot Experiment. The area under the ROC curve (detection) and the percentage of correct responses (identification) over observation stages for two observers: (a) with, and (b) without, visible memory.



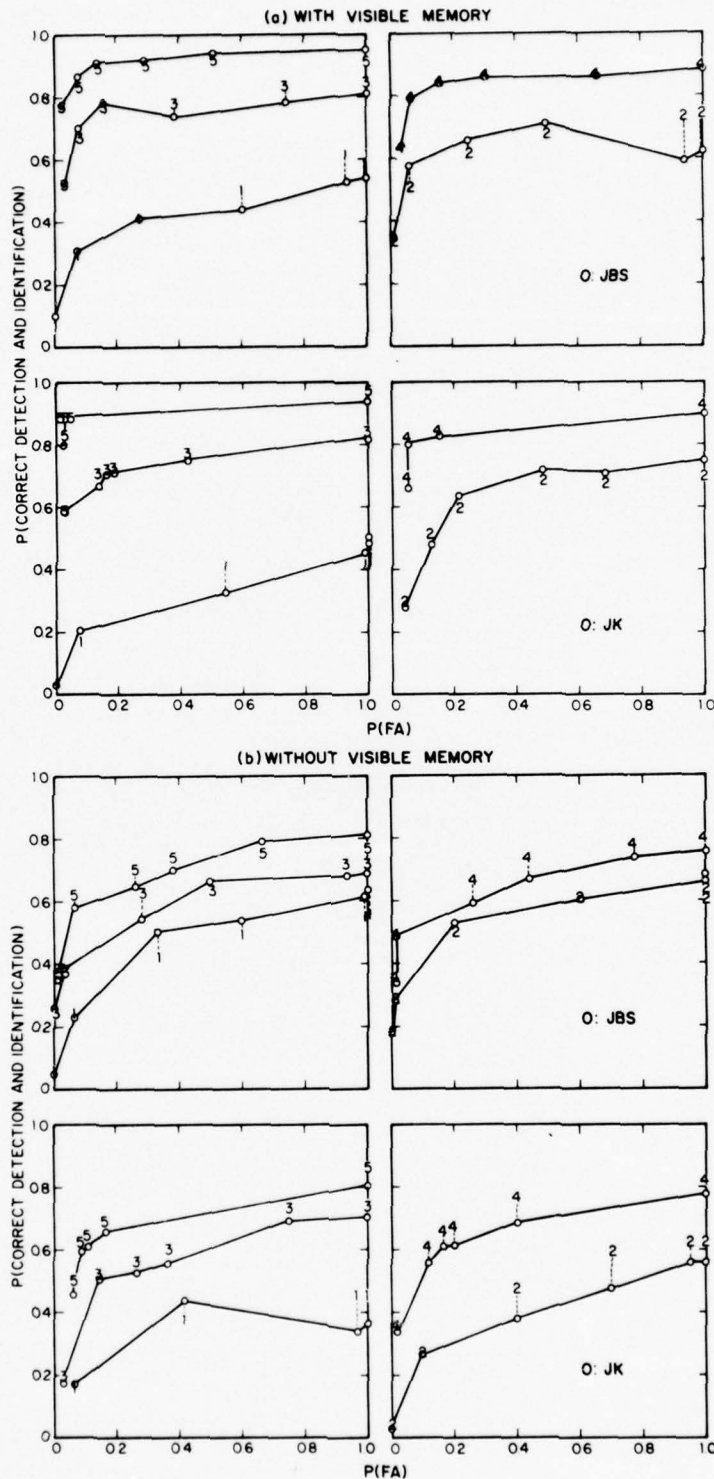


Fig. 7. Pilot Experiment. Joint detection-and-identification ROC curves for two observers for each of the five observation stages: (a) with, and (b) without, visible memory. Odd and even observation stages are presented in separate panels for the sake of clarity. The connected circles show values predicted by the model.

Experiment I

Detection ROC's. Detection ROC's for each of five stages, under the two memory conditions, are shown for the three observers in Fig. 8. The two conditions were based on (a) 126 trials and (b) 141 trials. The more experienced observer yielded tidy data. The new observers yielded fairly regular ROC's for the condition with visible memory; without visible memory the effective signal strength for them was quite low.

Detection Accuracy Over Time. Figure 9 shows a growth of  $d_e'$  with visible memory having a slope somewhat less than unity. The data based on no visible memory have a slope only slightly less than those obtained with visible memory, and noticeably greater than one-half. Swets and Birdsall (1977) point out that signal uncertainty may produce an effect seen here in both sets of data but more clearly in the data based on no visible memory: a slope greater than one-half for early observations, during a phase of zeroing in on the location of the signal, and a slope near one-half on later observations, when locational uncertainty is lessened.

Detection and Identification Accuracy Over Time. Detection area and identification percent-correct are shown for the two

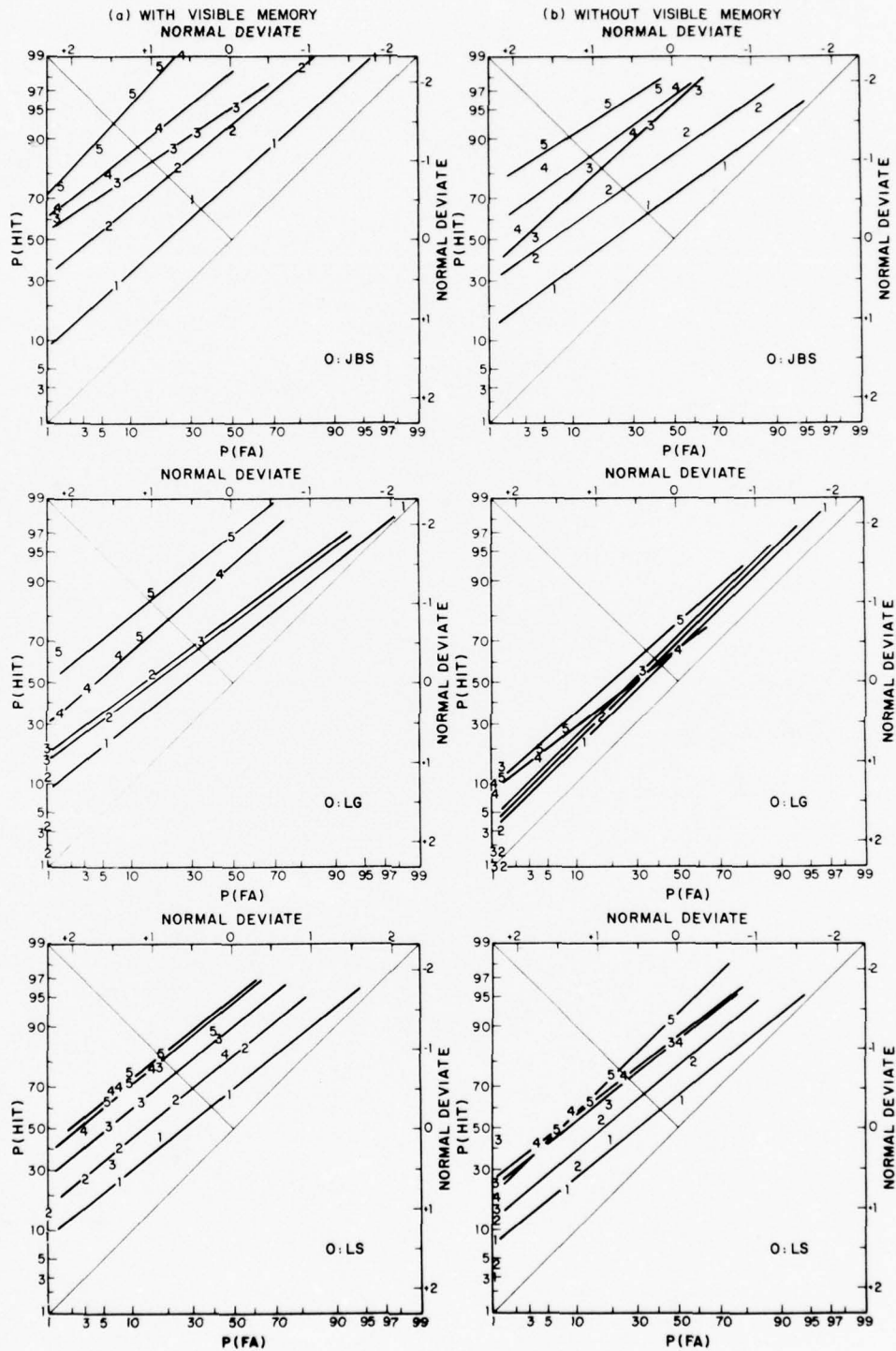


Fig. 8. Experiment I. Detection ROC's for each of the five stages of observation for three observers: (a) with, and (b) without, visible memory.

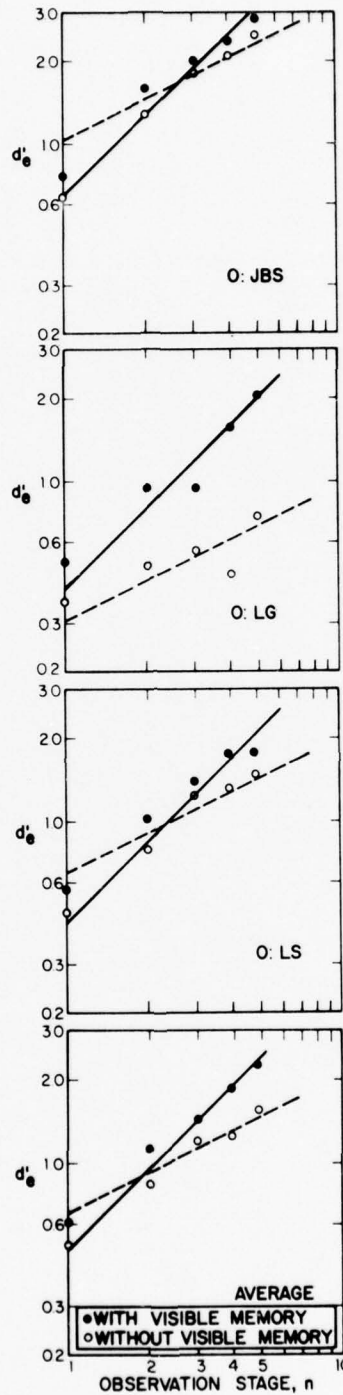


Fig. 9. Experiment I. The detection index,  $d'$ , over the five observation stages for three observers, both with- and without-visible memory. Best-fitting (least-squares) lines with slopes of one and one-half are shown as references for the with- and without-visible memory conditions, respectively.

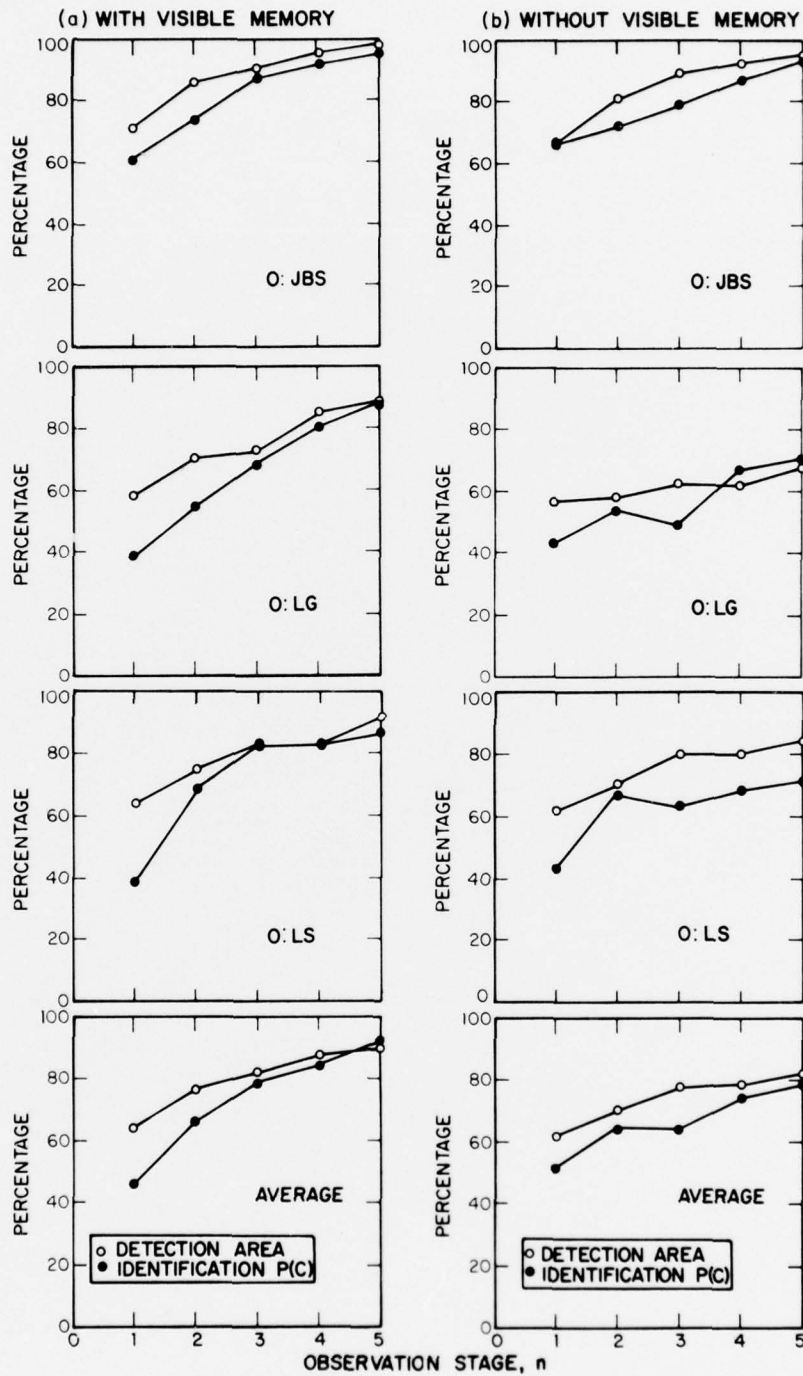


Fig. 10. Experiment I. The area under the ROC curve and the percentage of correct responses over observation stages for three subjects: (a) with, and (b) without, visible memory.



memory conditions in Fig. 10. They proceed apace from near chance (50% and 12-1/2%, respectively) to near perfect performance (100%).

Accuracy of Second Choices. The percentages of correct second choices relative to identification, when the first choice was incorrect, were 59% and 58%, 32% and 30%, and 43% and 35%, for the two memory conditions and the three observers, respectively. These are all clearly greater than the chance percentage of approximately 14%, and indicate that a substantial amount of information is conveyed by the second choice.

Predicting Identification from Detection. The model that predicts the correct detection-plus-identification ROC from the detection ROC is strongly supported by the data shown in Fig. 11 (three observers, two memory conditions). In relatively few cases is there room for a line to connect predicted and obtained points. The average absolute discrepancies in percentage units for the three observers and two memory conditions (listing condition a, visible memory, first) are 2.9 and 4.4, 4.0 and 5.3, and 3.1 and 3.8, respectively. Taking account of sign of deviation, the errors of prediction are -2.5 and +1.4, -0.1 and +3.3, -0.3 and -1.5, where negative numbers indicate obtained values less than those predicted.



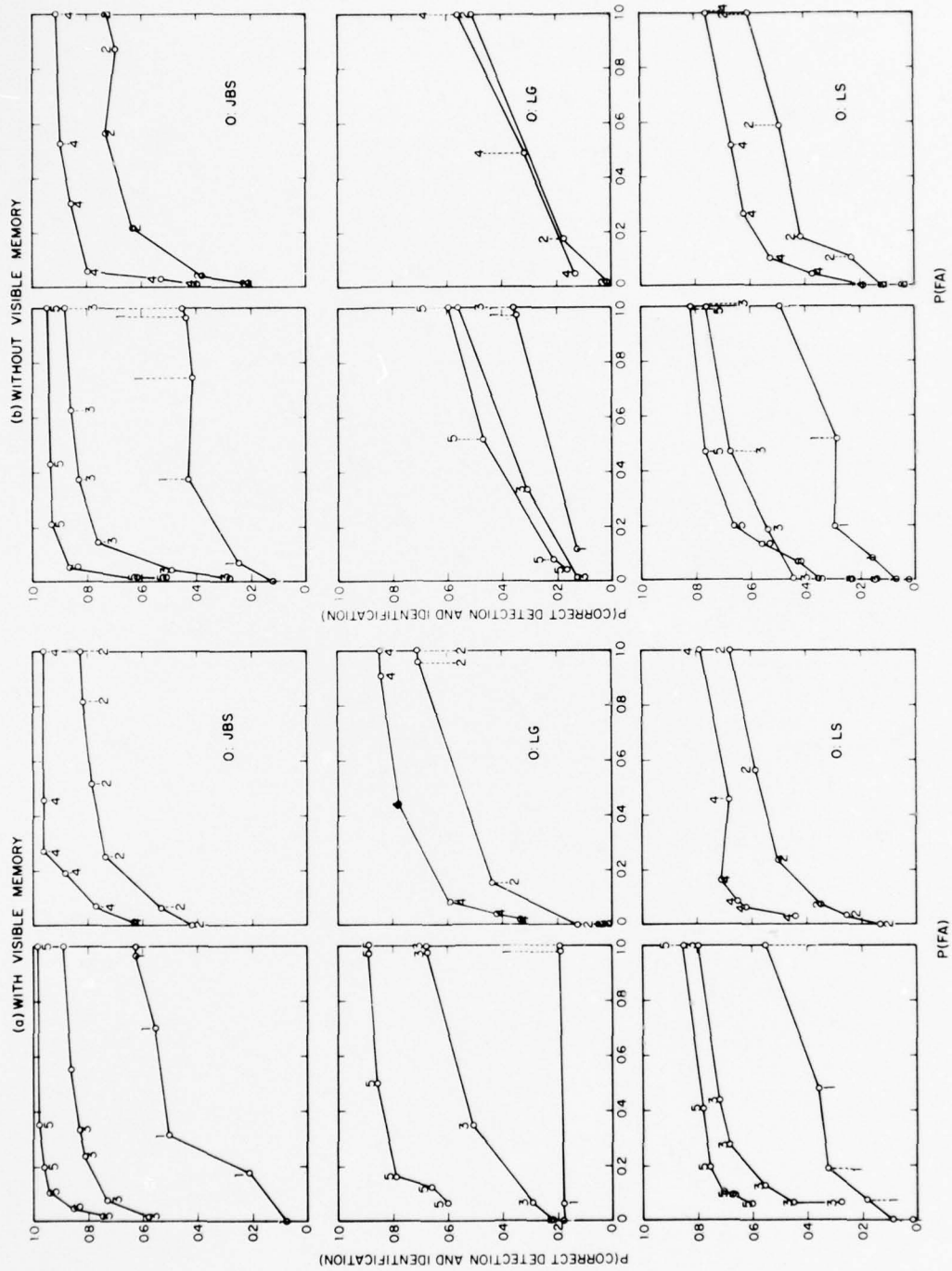


Fig. 11. Experiment I. Joint detection-and-identification ROC curves for three observers for each of the five observation stages: (a) with, and (b) without, visible memory. Odd and even observation stages are presented in separate panels for clarity. The connected circles show values predicted by the model.

Experiment II

Experiment II was conducted to determine if the data look much the same, and if the model predicting identification from detection is as successful, when the signals are somewhat more complex. In this experiment, the signal was one or another of the five patterns of lines described earlier: a pattern consisted of a particular three of sixteen possible lines. Just one "memory" condition was conducted, with each stimulus stage left visible throughout a trial. A larger number of trials was presented in this condition (320).

Detection ROC's. The detection ROC's in Fig. 12 look familiar: reasonably straight lines with slopes tending to decrease as detectability increases (see Green and Swets, 1966, 1974).

Detection Accuracy Over Time. The index  $d'_e$  is seen in Fig. 13 to increase approximately in proportion to the number of preceding observation stages.

Detection and Identification Accuracy Over Time. Performances on the two tasks become more accurate over time in related fashion; see Fig. 14.

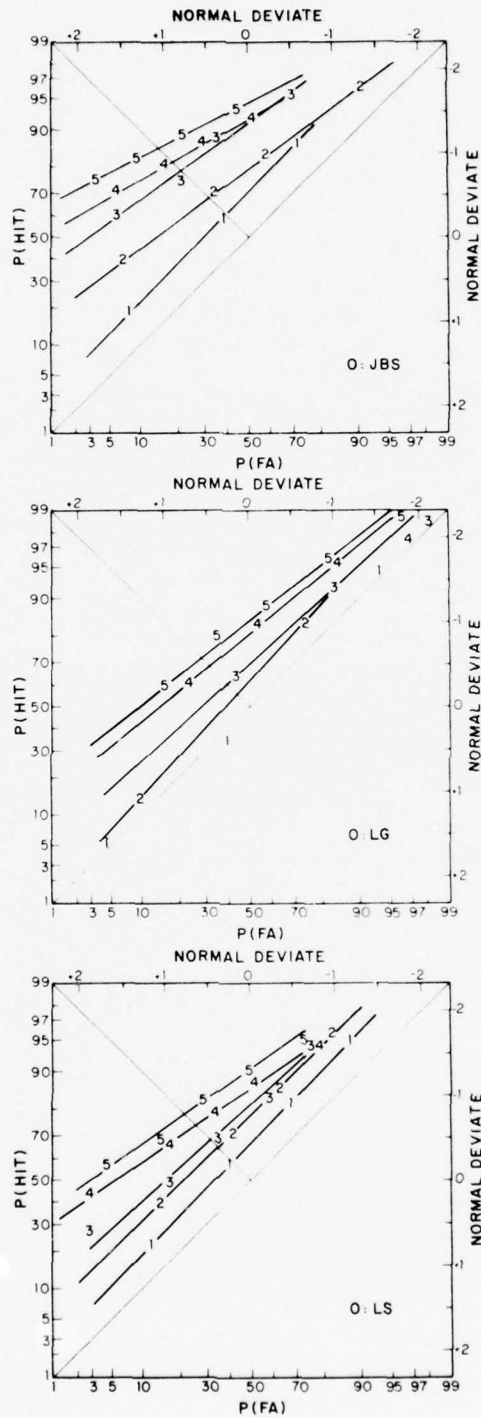


Fig. 12. Experiment II. Detection ROC's for each of the five stages of observation, for three observers.

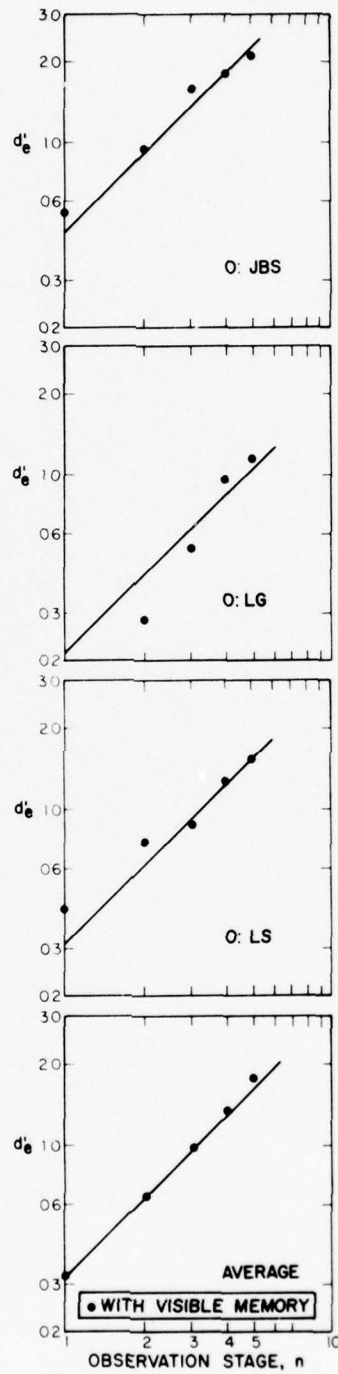


Fig. 13. Experiment II. The detection index,  $d'_e$ , over the five observation stages for three observers. A least-squares-fit line with slope of unity is shown as a reference.

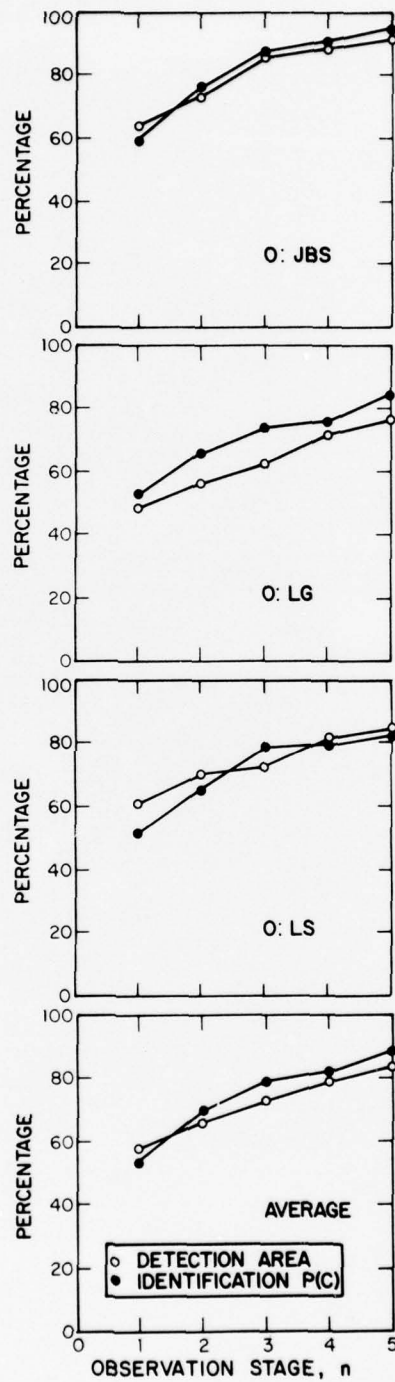


Fig. 14. Experiment II. The area under the ROC curve and the percentage of correct responses over observation stages, for three subjects.



Accuracy of Second Choices. Again, second-choice identification responses are correct with greater-than-chance accuracy: 50%, 41%, and 49% for the three observers, relative to the chance level of 25%.

Predicting Identification from Detection. The prediction of detection-plus-identification from detection alone is less accurate here than in the previous experiment; see Fig. 15. The average absolute discrepancies in percentage units between predicted and obtained points are 5.1, 15.9, and 5.9, for the three observers. These discrepancies are about 2 and 3 points greater than in Experiment I for the first (JBS) and third (LS) observers, respectively, and about 12 points greater for the second observer (LG). The average signed deviations are almost identical to the absolute deviations, with obtained values consistently greater than predicted. Why the obtained values are greater than the predicted values, which are supposed to be optimal relative to detection performance, remains to be determined. One possibility is that the forced identification response can be based on the detection of a single line, whereas the detection response might conservatively be based on the likelihoods of two or three lines. What is relatively a depressed detection performance would yield a depressed prediction of ideal identification performance. This possibility

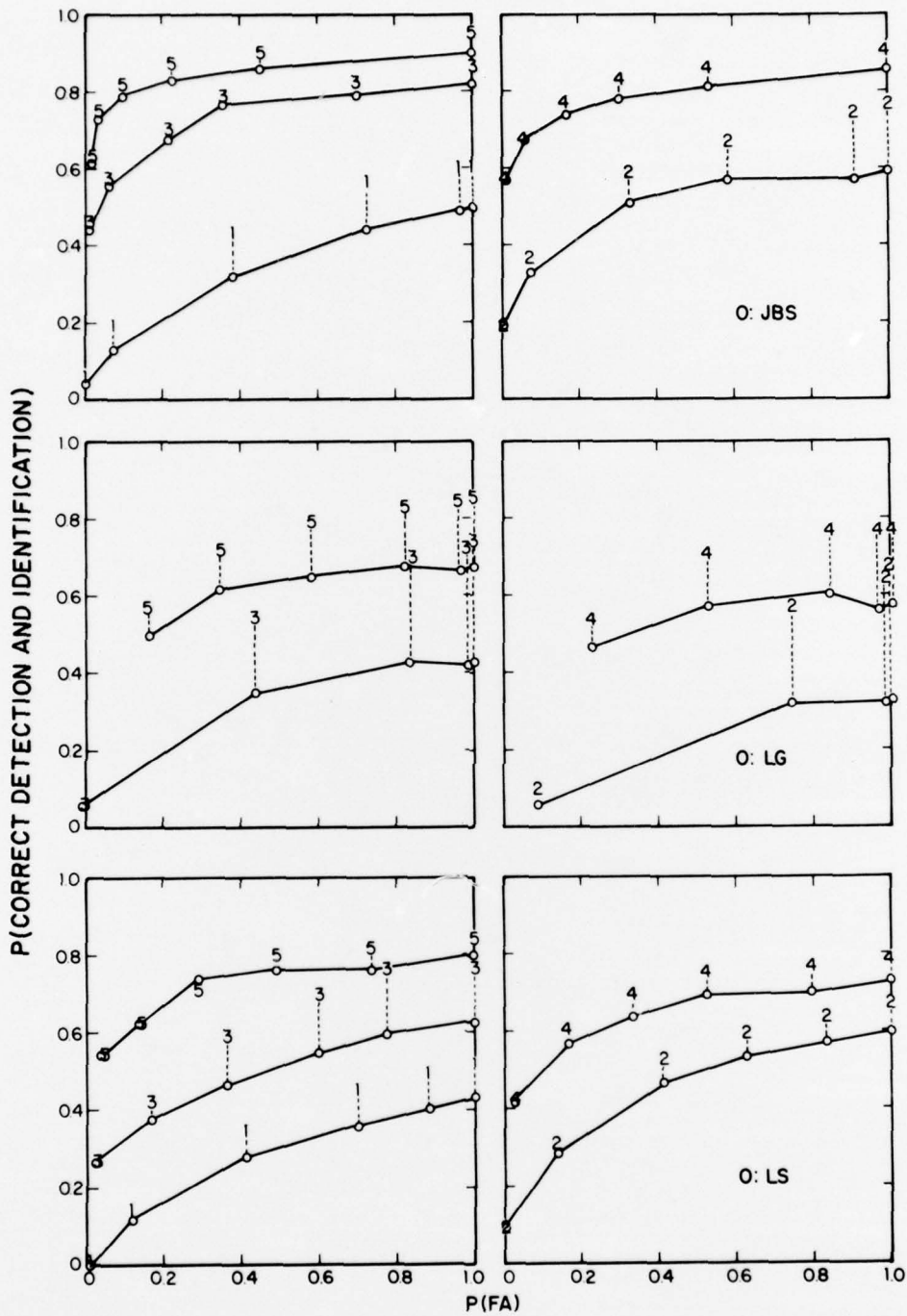


Fig. 15. Experiment II. Joint detection-and-identification ROC curves for three observers for each of five observation stages. Odd and even observation stages are presented in separate panels for clarity. The connected circles show values predicted by the model.

was suggested by the subjective report of one of the observers (JBS).

#### DISCUSSION

Nolte (1967), writing on the design of the "adaptive optimum receiver," suggested that this receiver stores updated probability estimates separately for each signal under consideration, so that detection and identification proceed together in a unitary process that is the basis for responses of either kind. According to this conception, detection does not precede identification, nor vice versa. There is no partial "aha" effect in either direction: the observer does not say "Now that I know a signal is present, I can begin to determine which one," nor "Now that I know which signal I am observing, I can begin to build up detectability." The data presented above, showing detection accuracy and identification accuracy to grow together over time, are consistent with this conception.

Broadbent (1971) has provided the analogy of an array of test tubes, each corresponding to a signal alternative, and each partly full of water. The selection of one tube corresponds to perception of a signal, and the probability of selecting a tube depends on how full it is. The initial level of water in each

tube represents the bias toward recognizing the corresponding signal, and the presentation of a signal causes the level of the water in its tube to rise, to an extent depending on the strength of the signal and the sensitivity of the receiver.

We can imagine the receiver to utilize eight tubes when confronted with eight signals which are lines of different locations, as in our Experiment I. In Experiment II, to extend this conception, the observer might supplement the (five) "signal" tubes with an array of (fifteen) "dimension" tubes, with water levels representing the energy in different locations (or frequency bands). He might then pour the dimension tubes (with replacement) according to the predetermined patterns into the signal tubes. The fact that information is conveyed by second choices, as seen in the foregoing, is another datum supporting the general conception reflected in Nolte's and Broadbent's models: the observer collects and updates data on several signal possibilities, and has access to more than the largest probability estimates, or to more than the fullest test tube.

Nolte's and Broadbent's models apply to the sequential decision task in its complex and realistic form, that is, in which the observer decides when to declare whether or not a signal exists. The observer determines, in effect, how full any



tube must be to be selected, or how empty they must all be to indicate that no signal is present -- perhaps easing both criteria as time passes. Our present experiments bypassed such a speed-accuracy tradeoff, by using trials of fixed length, so that we could focus better on the process of accumulating sensory information. As far as human detection is concerned, treatments of the sequential, or deferred-decision, task have appeared elsewhere (e.g., Swets and Birdsall, 1967).

Nolte's and Broadbent's models also permit the various signals to have different prior probabilities and different utilities, and our present experiments avoided these complications too. We would point out, however, that the decision-theory models permit treating another realistic task -- one in which responses are solicited from the observer at various times during observation, times that are determined by considerations possibly outside of the viewing environment. The varying prior probabilities and utilities may be supplied to the observer at the time that the response is solicited.

Starr, Metz, Lusted and Goodenough (1975) developed the quantitative model that we have applied in our attempt to relate identification and detection at successive stages of observation. They proposed and supported the model for visual localization, or



the identification of a visual signal's location, and we are interested in exploring possible extensions of the model to forms of identification or classification not purely, or not so obviously, locational. The importance of the development by Starr and colleagues, as we see it, is that it is the first apparently successful means of extending the ROC concept in detection theory to treat tasks involving multiple signal alternatives. Early attempts to do so (e.g., by Swets and Birdsall, 1956) achieved rather limited success.

The detection-plus-identification model is seen to fit our data on simple location very well, that is, in Experiment I in which the task was to locate a line signal in one of eight bins or columns. The model also fits reasonably well the data of Experiment II -- in which the signal was one of five combinations of three lines selected (without replacement) from sixteen bins. The task of Experiment II can also be considered one of localization, of course, but the use there of (simulated) spectrographic patterns is suggestive of more general identification tasks -- including, for example, visible speech.

Indeed, the audible correlates of our spectrographic signals should yield data fitted by the model. We have applied the model to Lindner's (1968) data on the detection and identification of

two tones, and found quite close agreement of predicted and obtained data. The prediction was uniformly low, but deviated on the average (of four observers and four criteria) by only 3.0 percentage units. The discrepancies for the four observers individually were 2.1, 4.6, 3.8, and 1.3.

One impact of these results is that time-consuming identification tests need not be conducted in perceptual situations to which the model applies -- the results are predictable from simple detection results. For this practical reason, as well as in the interest of theory, the limits of the model should be determined. We submit that the limits will have to be empirically determined. Though the main assumptions of the model -- orthogonal and equal-energy signals -- are clear and restrictive, we have other evidence that a model based on those assumptions can be rather robust. Specifically, Green and Birdsall (1964) have shown that the so-called one-of-M-orthogonal-signals model (see Nolte and Jaarsma, 1967) accounts for the effect of vocabulary size in tests of speech perception.

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