INFORMATION-PROCESSING RATE AS INFLUENCED

BY THE DEGREE OF RESPONSE DIFFICULTY:

A DISCRETE TRACKING TASK

By Daniel L. Baty

Ames Research Center, NASA
Moffett Field, California

SUMMARY

This study was designed to investigate the dependence of the information-processing rate on the degree of response, or task, difficulty. The degree of task difficulty was quantified for a series of discrete, random-input tracking tasks. Performance on one-dimensional (1-D) and two-dimensional (2-D) tasks was compared at equal values of task difficulty. Fourteen tasks were used, 9 with 4 target alternatives, and 5 with 16 target alternatives. Six subjects performed the self-paced tasks by rapidly touching with a stylus well-defined areas as they were successively illuminated in a random sequence.

Performance in terms of the information-processing rate was primarily determined by the degree of response difficulty and the number of target alternatives. Performance in terms of the average time per response, however, was determined primarily by the degree of response difficulty. For this type of task, higher information-processing rates are possible for 2-D tasks than for 1-D tasks because, for a given number of stimulus alternatives and a constant target size, the 2-D grouping has the lower value of task difficulty.

INTRODUCTION

The extrapolation of theorems from the field of information theory to the human suggests that there may be a human channel capacity which limits the information that can be processed while performing multiple concurrent subtasks. If these theorems can be applied to the human, even with modification, the systems design engineer will have a powerful new tool. In order to verify (or disprove) the applicability of such an approach, the variables that control the human information-processing rate for many different types of operator tasks must be identified and quantified.

The following three categories may help put this study in proper perspective: (a) single channel, continuous input - single continuous control, (b) multiple channel, continuous input - single discrete control, and (c) multiple channel, discrete input - multiple discrete responses.

Continuous control to maintain acceptable vehicle position is of prime concern to mission success. Related to this first type of task is the work of Holding (ref. 1), Elkind and Sprague (ref. 2), and Crossman (ref. 3), who measured human information-processing capacity during simple continuous tracking tasks. It was pointed out by Wempe and Baty (ref. 4) that even for this simple task it was not clear which of the possible information measures is "correct." It may be that the different methods of measurement may prove useful for different purposes. Even so, each method must be related and the overall decrement from the total channel capacity due to involvement with the tracking task must be determined.

In the second type of task the operator repeatedly scans or monitors several instruments that display continuous information and takes corrective action as required. Senders (ref. 5) used information measures as a basis for modeling operator visual-sampling performance for this task. There was no selection of response in these experiments, that is, the response required was the same regardless of which instrument initiated the action. Smallwood (ref. 6) modeled this task further and Carbonell (ref. 7) extended it theoretically to include additional corrective action.

The third type of task consists in monitoring many individual discrete displays, each indicating "go, no-go" status of a vehicle subsystem and requiring a specific response. The composite of these individual displays can be considered as one display and, since the population of possible stimulus choices can be identified, the information transfer rate for this response task can be measured. A task very similar to this was used by Klemmer (ref. 8) for measuring information-processing capacity. His subjects tracked a random, discrete-input display by successively touching lighted areas with a stylus. Fitts and Peterson (ref. 9) did a similar study with a single reaction task rather than a repetitive task.

Figure 1(a) is introduced as an aid in grouping the variables that might influence operator information-transfer rates in any of the tasks mentioned so far and further pinpoints the area of concern for this study. Each block represents the time required for a process from the onset of the stimulus to the completion of the correct response. Variables that will affect the time required, as well as the information transfer rate, can be isolated within each block.

Compare figure 1(a) with the classical block diagram of the communication system (ref. 10) shown in figure 1(b). The transmitter codes the message sent over the communication channel. The receiver then decodes the signal into proper form for the use intended. If this model is applied to the human operator, the light impinging on the eye can be considered the system information source, and the external object on which some pressure is exerted by the operator is the destination. The coding and decoding functions of the transmitter and receiver have both been delegated to the middle block in figure 1(a). Thus, the communication model, when applied to the human operator, must be expanded to include two additional sets of factors, perceptual factors between the information source and the transmitter and response factors between the receiver and the destination. These added factors can greatly limit the operator's ability to process information.

The variables outlined in figure 1(a) are more easily isolated in the discrete tracking task to be described than in continuous tasks. Factors affecting perceptual and coding times, that is, the first two blocks, have been discussed (refs. 8 and 11). This paper reports the results of a discrete tracking experiment designed to explore the importance of a response variable, that is, a variable related to the third block. Specifically, an index of response difficulty is quantified in terms of the geometry of the task, and the information-processing rate is measured as a function of this index, while other relevant variables are held constant.

The basic experiment was similar to one of Klemmer's (1956) experiments. Whereas Klemmer explored the relationship between the information-processing rate and the number of stimulus alternatives for one-dimensional (1-D) and two-dimensional (2-D) tasks, using eight stimulus alternative values, only two stimulus alternative values (4 and 16) were used in this experiment to explore the relationship between information-processing rate and the degree of response difficulty. Two conditions for this experiment were designed to have the same task dimensions as two of Klemmer's conditions so that the two studies could be compared. Pertinent relationships between the two studies will be discussed after the results of this experiment are presented.

The method of measuring the degree of task difficulty for this study was adapted from a study by Fitts and Peterson (ref. 9), who defined an index of task difficulty (ID) for a single reaction motor task as $ID = \log_2(2A/W)$, where A was the distance of hand travel and W, the width of the target to be hit. Since their conditions were two-choice tasks, only one moving distance had to be measured for any one part of the experiment, and the information value ·· esponse (I_V) was always equal to 1. Since they reported average time he onset of the stimulus light to the start of hand movement, and the beginning of hand movement to contact with the target, the average information-processing rate (I_R) could be estimated for each value of ID. This estimate of I_R for each condition showed that I_R was a steadily decreasing function of ID, which suggested that an index of difficulty may also have been an important variable in a study such as Klemmer's. For this experiment, Fitts and Peterson's definition of ID was adapted for tasks with higher values of I_V by substituting average hand-travel distance ($\bar{A}$) during a sequence of responses for the single distance A to obtain $\overline{ID}$, that is, average ID.

METHOD

A 12.5-inch-square tracking surface was divided into a 25 × 25 matrix of 0.5-inch-square cells, each deep enough to hold one small neon bulb below a glass cover. All cells were covered with a sheet of frosted mylar so that each 0.5-inch-square surface could be homogeneously lighted. For each of the 14 experimental conditions, an opaque mask with either 4 or 16 square holes was placed over the mylar and under the glass, making the number and location of the stimulus choices explicit. Six of the patterns were arranged as a one-dimensional (1-D) task and eight as a two-dimensional (2-D) task. Each mask had a different combination of hole size and spacing corresponding to a given value of average index of difficulty ($\overline{ID}$), as shown in figure 2. The resulting hole sizes were 0.5 inch square for conditions 1, 2, 3, 5, 7, 10, 12, 13, and 14; 0.25 inch square for conditions 4, 8, 9, and 11; and 1.50 inch square for condition 6. The term $\overline{ID}$ is defined as $\log_2(2\bar{A}/W)$, where W is the width of the target, and $\bar{A}$, the average movement distance of the stylus tip for each response during the run. For this experiment, the information value of each stimulus presentation (I_V) is $\log_2 N$, where N is the number of stimulus alternatives, each chosen with equal probability; I_R is the average rate of processing the presented information, I_V, in bits/second.

Six male engineers and scientists, 28 to 42 years of age, free from physical defects, volunteered as subjects. Their task was to touch each lighted area with a stylus as quickly as possible after the onset of the light. The test equipment was designed so that the touched light would go out immediately and another randomly chosen (tape controlled) light would come on within 7 msec. Each run continued for 105 stimulus presentations. A timer automatically started after the fifth response so that all times were recorded for 100 responses. The stylus tip contained a photocell. A correct response was registered when there was a combination of photocell response and stylus contact with the board. To prevent a "sliding" strategy while going from one lighted area to another (when not adjacent), an error was counted each time the stylus made contact outside a lighted area. Ten errors were allowed per run before the run was automatically stopped and then restarted.

The experiment was conducted in a dimly lighted room to prevent spurious photocell responses. The subject sat on a high stool so that his line of sight was approximately perpendicular to the tracking surface. No results were given him during the experiment. Each session consisted of one run on each of the 14 conditions, and lasted approximately 40 minutes. First there were three practice sessions and then nine data sessions. Nine different input tapes were used for the data sessions to prevent any chance of the subjects memorizing partial input sequences. The sequence of conditions within a tape was randomly chosen as was the sequence of assigning the tapes to the subjects. Within each run, the stimuli were presented randomly with equal probability with replacement, that is, a given light could repeat one or more times as the stimulus. If a light repeated immediately, contact with the board had to be broken and the light touched again. The primary instruction to the subject was to proceed as rapidly as possible after starting the run until the run automatically terminated after 105 responses.

RESULTS

The primary results of this experiment are shown in figures 3 through 10. The performance of each subject for each condition averaged over the nine experimental sessions is shown in figures 3 through 8, where average I_R

is plotted as a function of $\overline{ID}$. By connecting the points having the same dimension (1-D or 2-D) and the same value of I_V, the important relationships for this experiment can be seen more clearly. Thus, for either value of I_V, the 1-D curve lies consistently above the 2-D curve for all subjects and for both values of I_V; that is, I_R is consistently greater by a small amount for the 1-D task than for the 2-D task when the two are matched for $\overline{ID}$. There were no reversals of this result for any subject. The pattern of performance (figs. 3-8) is remarkably similar for all subjects even though the overall level of performance varied with the individual.

The average performance for all subjects is shown in figure 9. Figure 10 is a plot of the group mean times for each experimental condition (100 responses) plotted against $\overline{ID}$ without regard for the value of I_V or for whether the task was 1-D or 2-D. Figure 10 shows that $\overline{ID}$ is the major controlling variable in the present experiment. The average standard deviation of the run times was 3.42 percent of the total mean time per run for each condition, suggesting that the overall performance was consistent.

DISCUSSION

To further illustrate the importance of $\overline{ID}$ in a discrete tracking task, the results of this experiment will be compared with those of Klemmer's (ref. 8). Whereas only two values of I_V were used for the present experiment, with the prime concern being changes in performance as a function of $\overline{ID}$, Klemmer used eight values of I_V since he was interested in performance as a function of I_V. The equipment and task configurations for the two studies were similar and two of the conditions for this experiment were designed to have exactly the same dimensions as two of Klemmer's tasks. These two conditions (configurations 10 and 12 in fig. 2) were the only two from Klemmer's experiment that had the same value of I_V for both the 1-D and the 2-D tasks. Points K:16 and K:4×4 in figure 9 show the performance for these two conditions.

Klemmer's task was the same as already described for this study. His targets were all 0.5-inch squares, with no spacing between targets. Four stimulus conditions were presented as 1-D tasks (I_V = 2, 3, 4, and 5 bits/presentation) and four conditions as 2-D tasks (I_V = 4, 6, 8, and 10 bits/presentation). Klemmer found that I_R increased asymptotically as I_V increased toward 4.2 bits/sec for 1-D and 6.6 bits/sec for 2-D, as shown in figure 11. Klemmer concluded that these values probably represented the maximum information-processing rate for this type of task.

Since Klemmer's inputs were randomly selected with equal probabilities, and the dimensions for each task were given, it was possible to estimate $\overline{ID}$ for each of his conditions. In figure 12, his values of I_R are plotted against $\overline{ID}$ rather than I_V. The only points in Klemmer's experiment that had equal values of I_V, namely, points K:16 (1-D) and K:4×4 (2-D), each with I_V = 4 bits/presentation, show that the value of I_R was greater for the 2-D task than for the 1-D task. This distance V is 0.6 bit/sec. But it is also shown in figure 12 that $\overline{ID}$ is greater for the 1-D task than for the 2-D task. So it is not clear from Klemmer's data whether I_R is greater for his condition K:4×4 because it was a 2-D task rather than a 1-D task or because of the difference in $\overline{ID}$, which he did not control.

The data from the present experiment (fig. 9) show that the absolute difference in I_R between conditions K:16 and K:4×4 (distance V) is 2.2 bits/sec. A perpendicular line through K:16 intersects the fitted 2-D line of performance at the value of I_R where the interpolated estimate of performance for a 2-D task matches $\overline{ID}$ with condition K:16. The value of I_R at this point is 0.45 bit/sec less than that found for condition K:16, distance X. On the basis of Klemmer's results only this lower performance for 2-D tasks would not be expected. In retrospect, however, the results of the two studies are compatible, since lines drawn through points K:16 and K:4×4 in figure 12 (as shown) with slopes equal to those drawn through K:16 and K:4×4 in figure 9 result in a 1-D line above the 2-D line for Klemmer's data also. Regardless of the direction of the difference, however, this 0.45 bit/sec difference is small when compared with the absolute difference of 2.2 bits/sec between 1-D and 2-D performance for I_V = 4 bits/presentation if $\overline{ID}$ is not considered.

A comparison of figures 9 and 12 shows that the rates obtained for this study were much higher than those obtained by Klemmer for conditions K:16 and K:4×4. Although the equipment was similar for the two studies, there was a primary difference in the determination of when contact had been made with the board. Klemmer's subjects were required to "press down slightly," whereas for this study a slight contact closed the electronic circuit, allowing a quick touch-and-go strategy. The resulting differences in target dwell times would be directly related to a difference in I_R.

It is realized that the method used here to assign values of $\overline{ID}$ to the experimental conditions might not reflect a "true" $\overline{ID}$ since it was based entirely upon the geometry of the task and did not consider perceptual or physiological factors. The small elevation of the 1-D curves could well be an artifact because these factors were ignored. The general uniformity of performance, however, indicates that the $\overline{ID}$ measure accounts for the majority of the differences between performance on the 1-D and 2-D tasks.

CONCLUDING REMARKS

The index of response difficulty ($\overline{ID}$), as defined in this paper, is an important independent variable to consider when operator information-processing rates for a discrete tracking task are being measured. This was illustrated by the results of this experiment and also by a discussion of the results obtained by Klemmer. It was shown that part of the results discussed in a different way by Klemmer could also be explained in terms of $\overline{ID}$ as an independent variable.

For this type of experiment, the main advantage of the 2-D task over the 1-D task, if target sizes are held constant, is that I_V can be made much larger for the 2-D task without increasing the values of $\overline{ID}$. Thus, the higher information-processing rates possible for 2-D tasks are directly attributable to lower values of $\overline{ID}$. Information-processing rates for this kind of task are bound directly by physical response limitations. Because of inertia and energy limitations of the hand-arm response system used in this study, certain irreducible times were required for a correct response. The rest of the information-processing system had to wait while this response was being made. It is probable that the rates would have been higher if $\overline{ID}$ had been lower.

This study points out a practical consideration when measuring human information-processing rates in a control context. The continual exchange of information between the man and his vehicle is not complete until the operator responds. Therefore, any information rate derived for the operator does consider the entire time from stimulus onset to the completion of an appropriate response. The importance of carefully considering the design of controllers and switches, and the way they are combined is thus pointed out, since they have a direct and important influence on achievable information-processing rates in pilot-vehicle tasks.

REFERENCES

1. Holding, D. H.: Rates of Handling Continuous Information. FPRC-1068, Flying Personnel Res. Comm., Air Ministry, 1959.

2. Elkind, J. I.; and Sprague, L. T.: Transmission of Information in Simple Manual Control Systems. IRE Trans. on Human Factors in Electronics, vol. HFE-2, 1961, pp. 58-60.

3. Crossman, E. R. F. W.: The Information-Capacity of the Human Motor System in Pursuit Tracking. Quart. J. Exp. Psychology, vol. 12, 1960, pp. 1-16.

4. Wempe, T.; and Baty, D.: The Usefulness of Transinformation as a Measure of Human Tracking Performance. NASA SP-128, 1966.

5. Senders, J. W.: The Human Operator as a Monitor and Controller of Multidegree of Freedom Systems. IEEE Trans. on Human Factors in Electronics, vol. HFE-5, 1964, pp. 2-5.

6. Smallwood, R. D.: Internal Models and the Human Instrument Monitor. Paper presented at the Seventh IEEE Symposium on Human Factors in Electronics, May 1966.

7. Carbonell, J. R.: A Queuing Model of Many-Instrument Visual Sampling. Paper Presented at the Seventh IEEE Symposium on Human Factors in Electronics, May 1966.

8. Klemmer, E. T.: Discrete Tracking in One and Two Dimensions. Operational Applications Laboratory, Air Force Cambridge Research Center, USAF Rep. AFCRC-TN-56-2, 1956.

9. Fitts, P. M.; and Peterson, J. R.: Information Capacity of Discrete Motor Responses. J. Exp. Psychol., vol. 67, 1964, pp. 103-112.

10. Shannon, E. C.; and Weaver, W.: The Mathematical Theory of Communication. The University of Illinois Press, Urbana, 1949.

11. Deininger, R. L.; and Fitts, P. M.: Stimulus-Response Compatibility, Information Theory, and Perceptual-Motor Performance. Information Theory in Psychology, H. Quastler, ed., The Free Press, Glencoe, Ill., 19[illegible], pp. 316-349.

FIGURE TITLES

Figure 1.- Representation of a human operator and a general communication system.

(a) Time blocks between stimulus and response for a human operator.

(b) Diagram of a general communication system.

Figure 2.- Experimental conditions.

Figure 2.- Continued.

Figure 2.- Continued.

Figure 2.- Concluded.

Figure 3.- The effect of $\overline{ID}$ on I_R; subject 1.

Figure 4.- The effect of $\overline{ID}$ on I_R; subject 2.

Figure 5.- The effect of $\overline{ID}$ on I_R; subject 3.

Figure 6.- The effect of $\overline{ID}$ on I_R; subject 4.

Figure 7.- The effect of $\overline{ID}$ on I_R; subject 5.

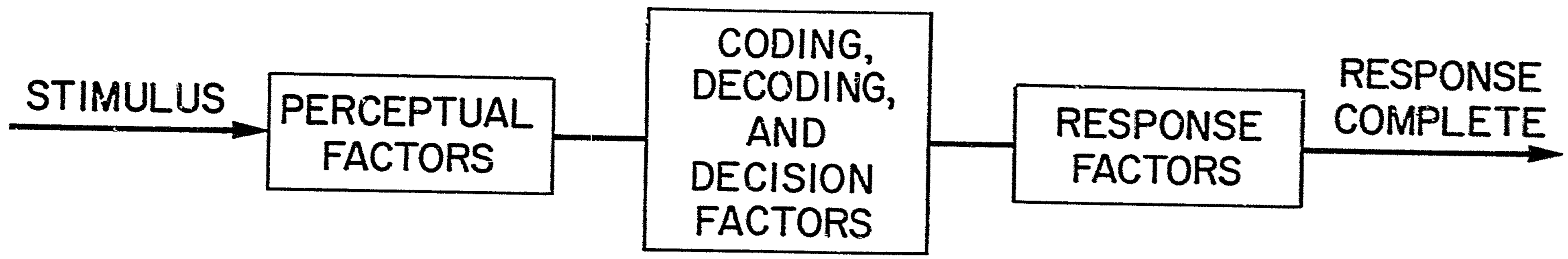
Figure 8.- The effect of $\overline{ID}$ on I_R; subject 6.

Figure 9.- The effect of $\overline{ID}$ on I_R; mean rates from six subjects.

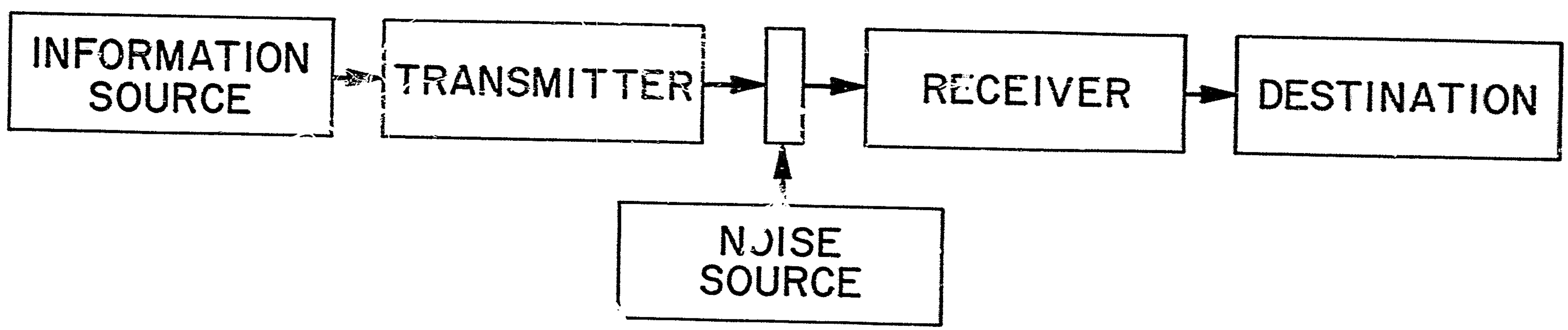
Figure 10.- The effect of $\overline{ID}$ on total response time; mean times from six subjects.

Figure 11.- Rate of information transmission for 1-D and 2-D discrete tracking tasks as a function of target position uncertainty; mean rates from eight subjects (Klemmer, 1956).

Figure 12.- Results of Klemmer's (1956) experiment plotted against $\overline{ID}$.



(a) Time blocks between stimulus and response for a human operator.



(b) Diagram of a general communication system.

Figure 1.- Representation of a human operator and a general communication system.

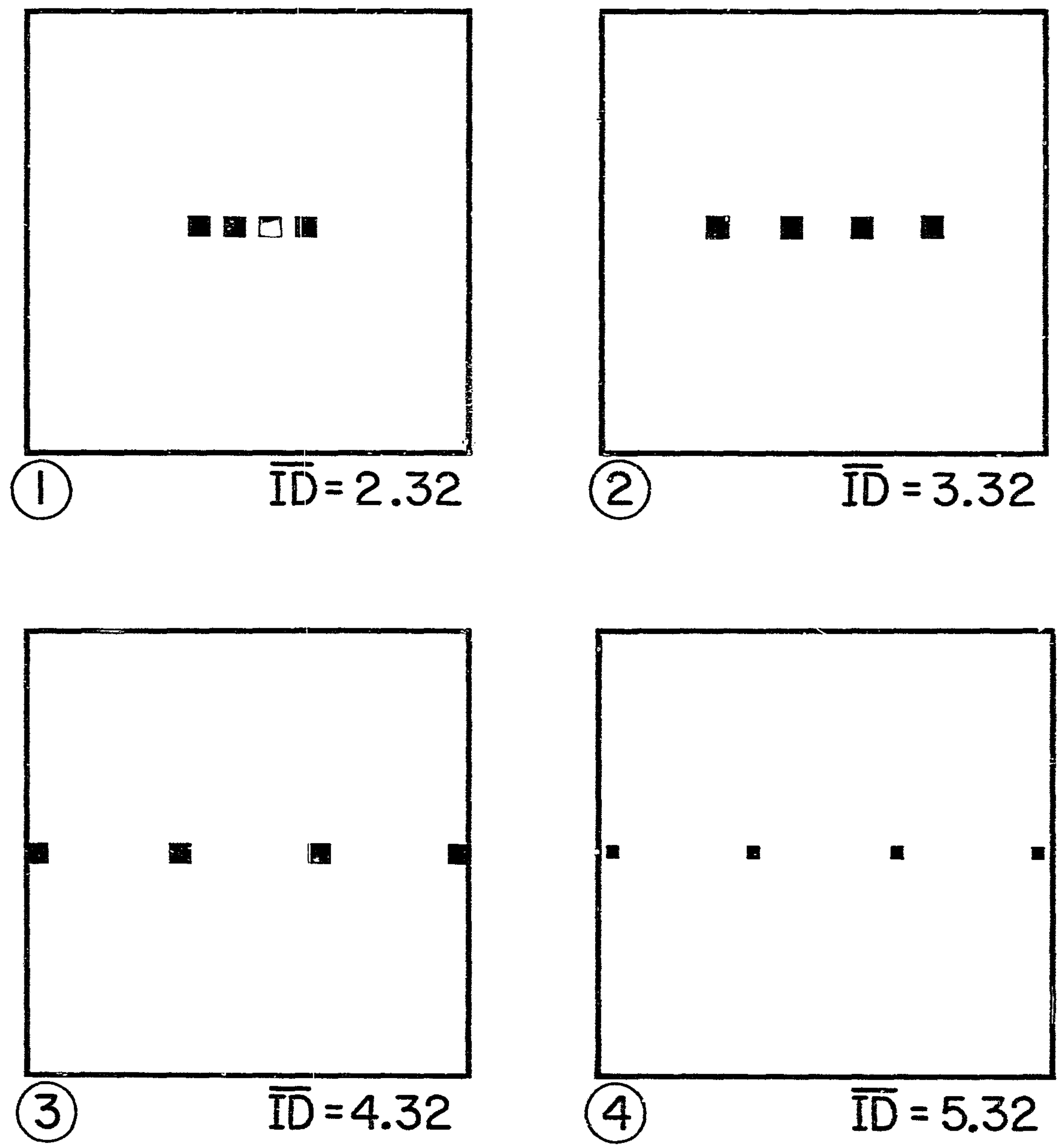


Figure 2.- Experimental conditions.

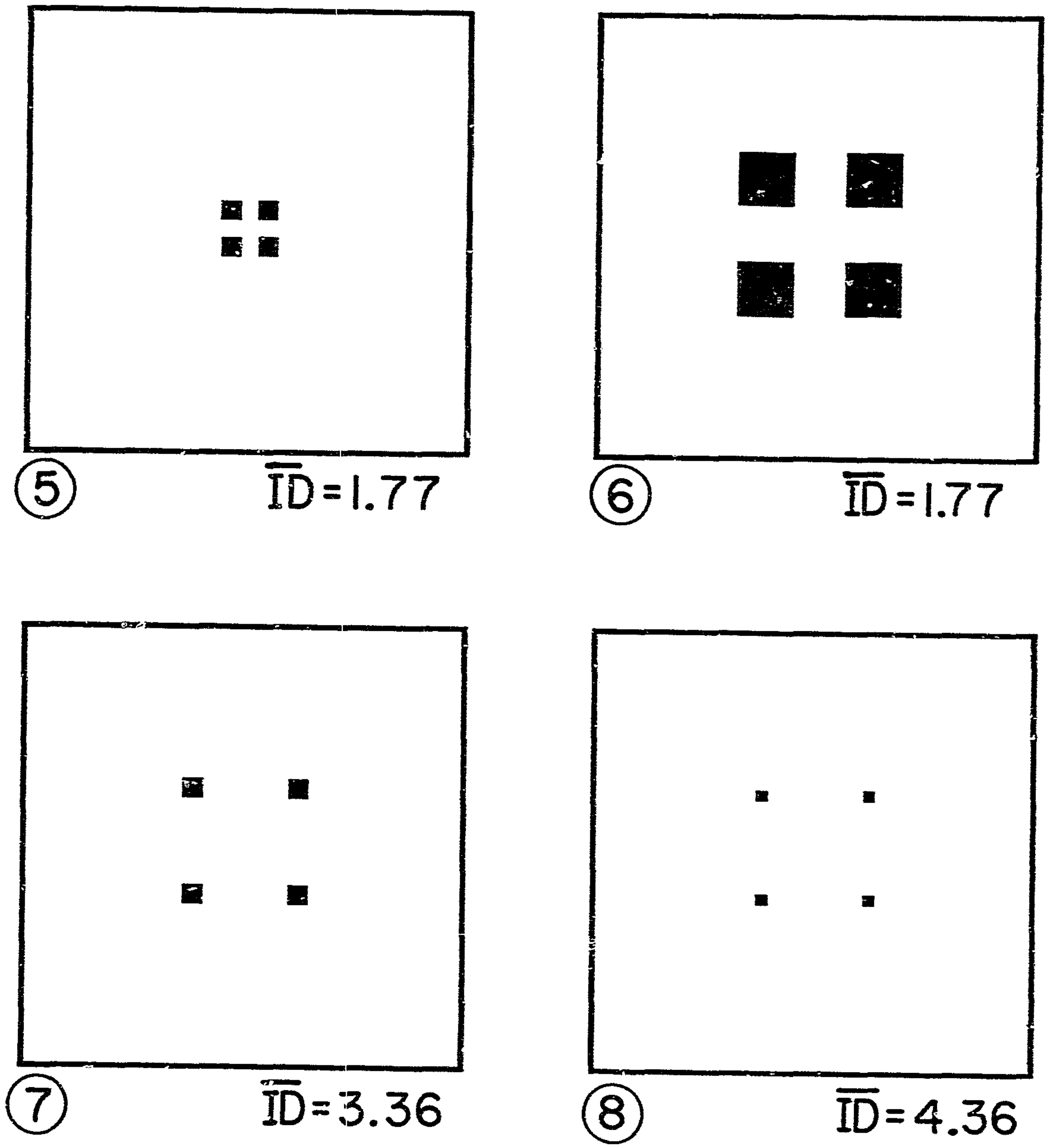


Figure 2.- Continued.

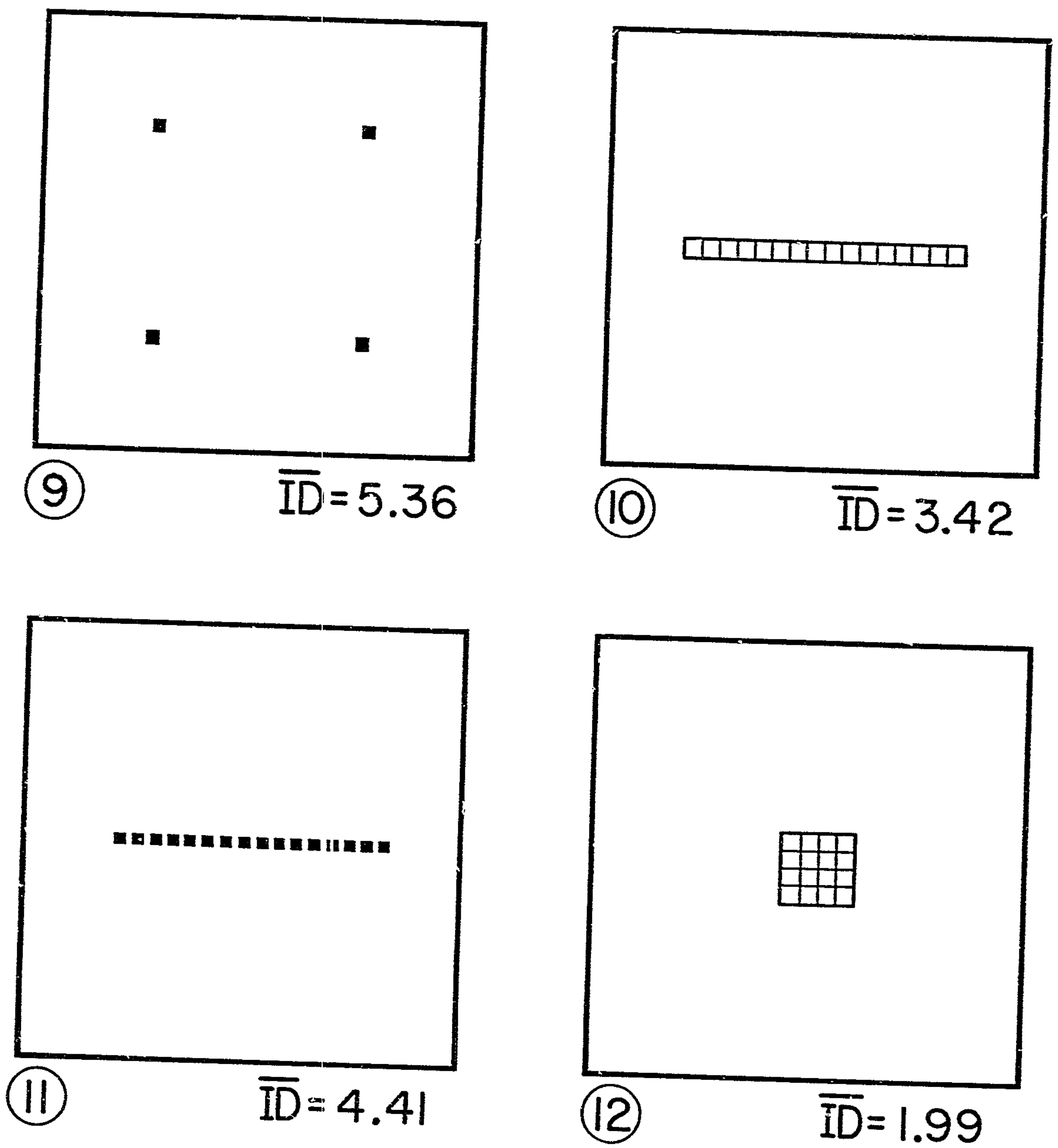


Figure 2.- Continued.

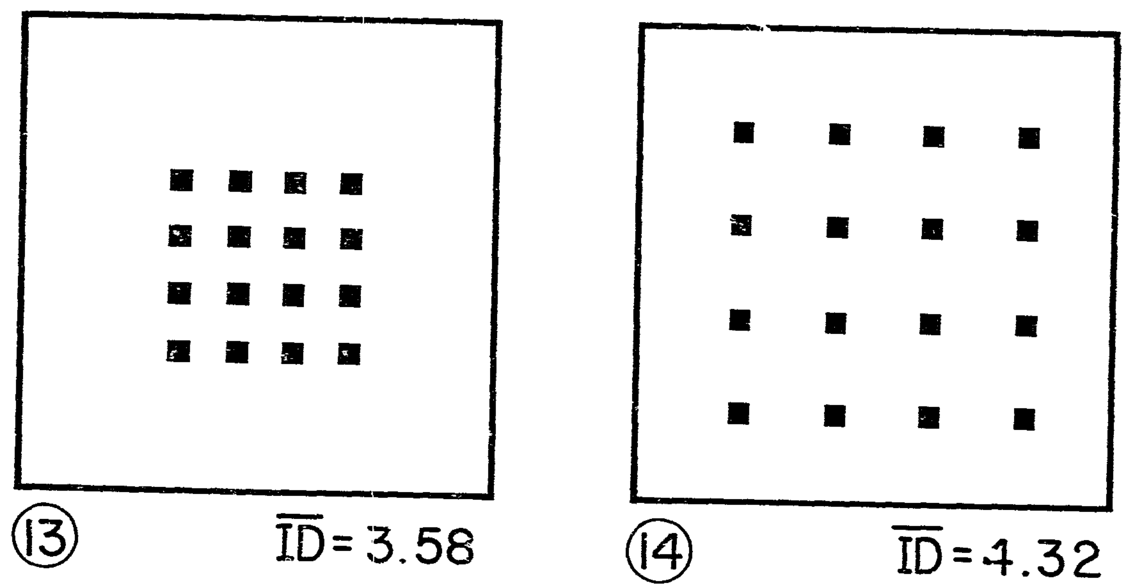


Figure 2.- Concluded.

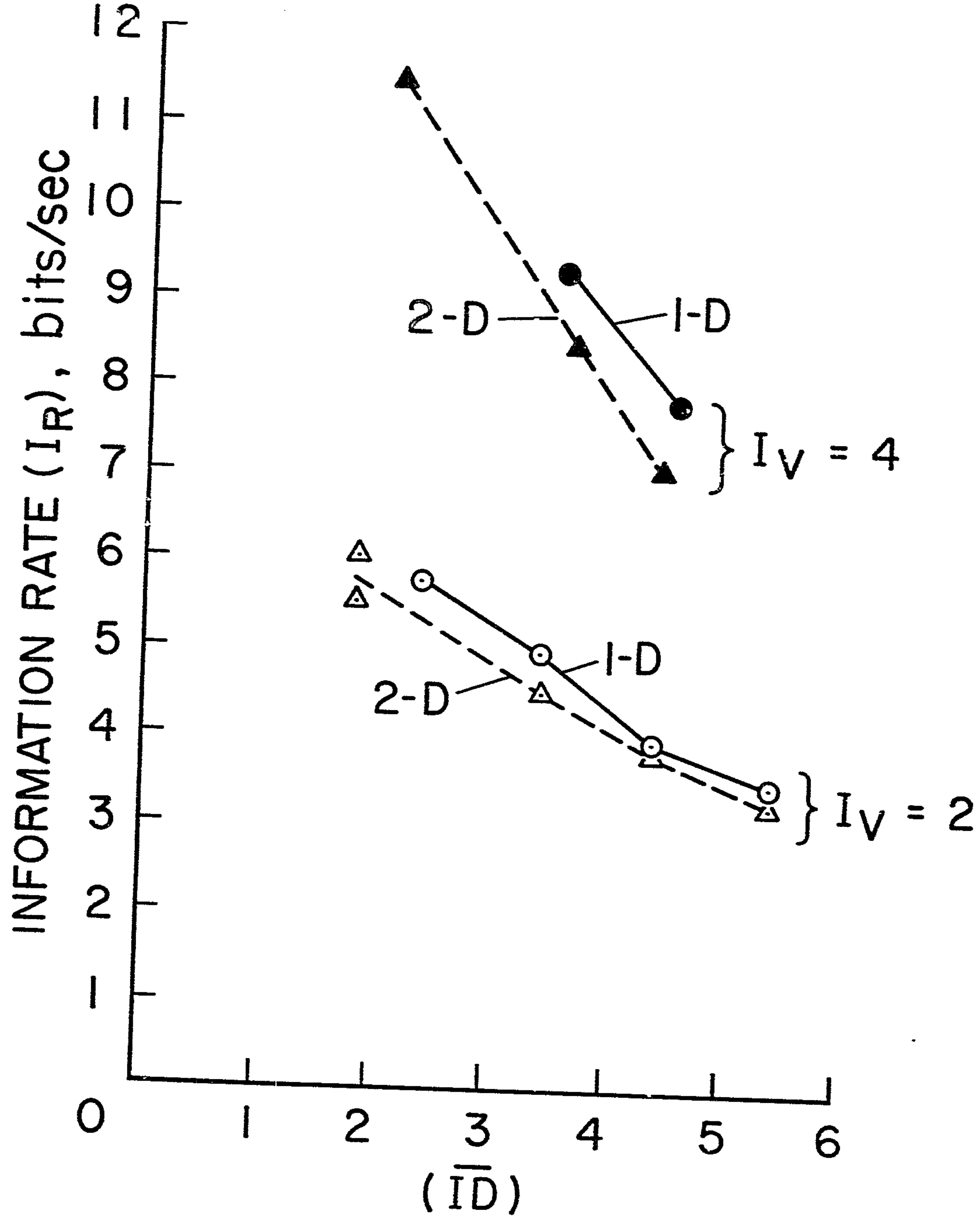


Figure 3.- The effect of $\overline{ID}$ on I_R; subject 1.

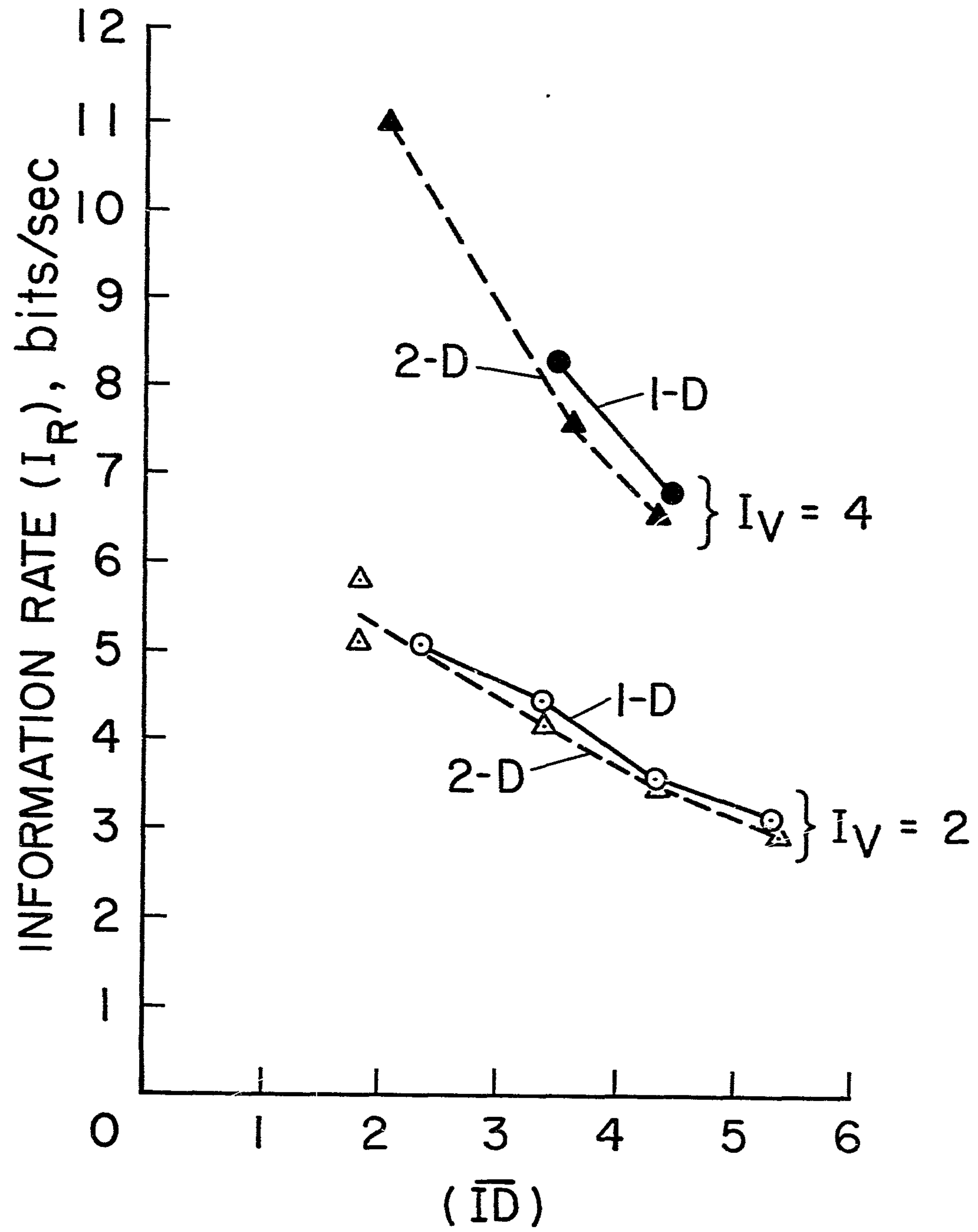


Figure 4.- The effect of $\overline{ID}$ on I_R; subject 2.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

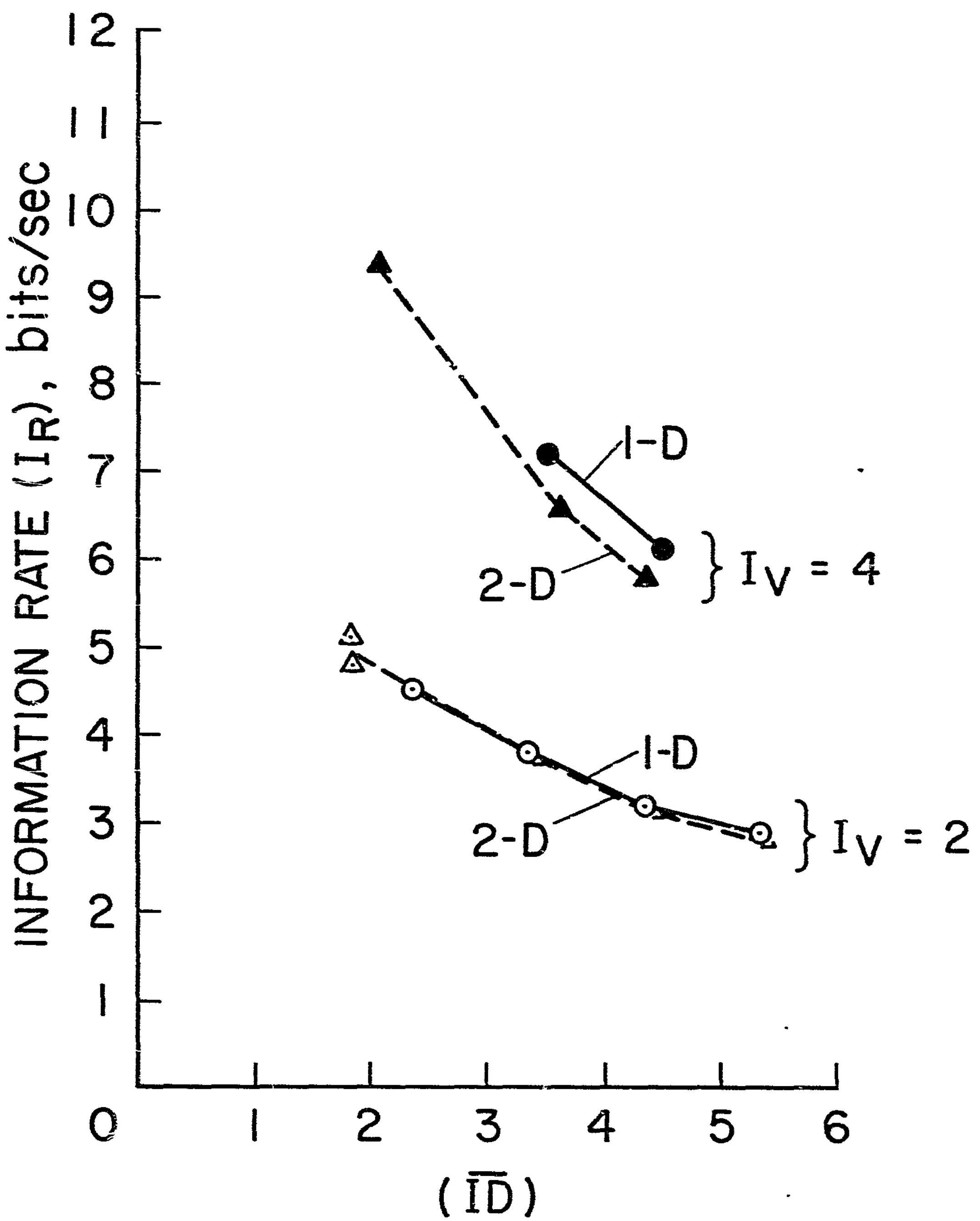


Figure 5.- The effect of $\overline{ID}$ on I_R; subject 3.

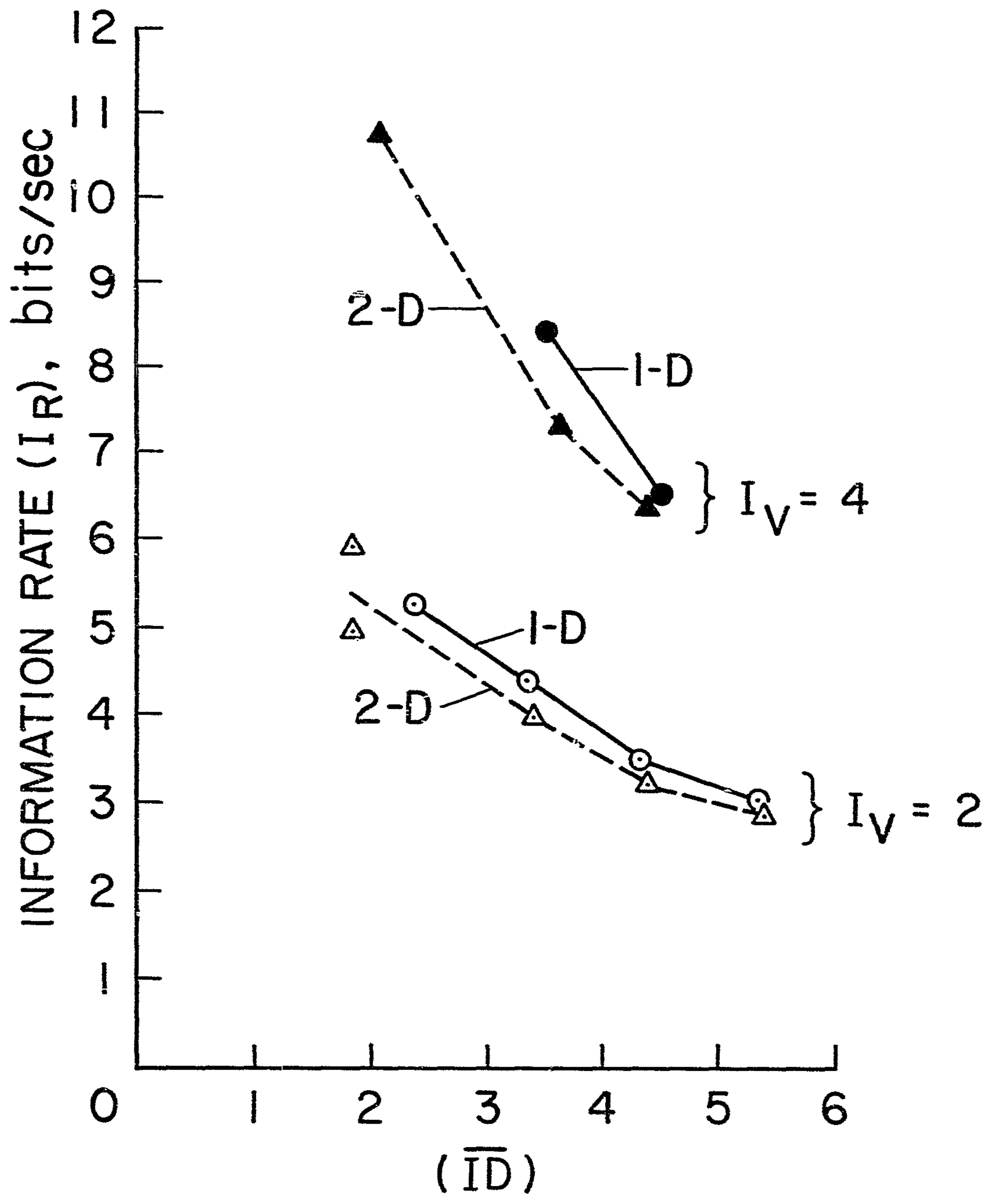


Figure 6.- The effect of $\overline{ID}$ on I_R; subject 4.

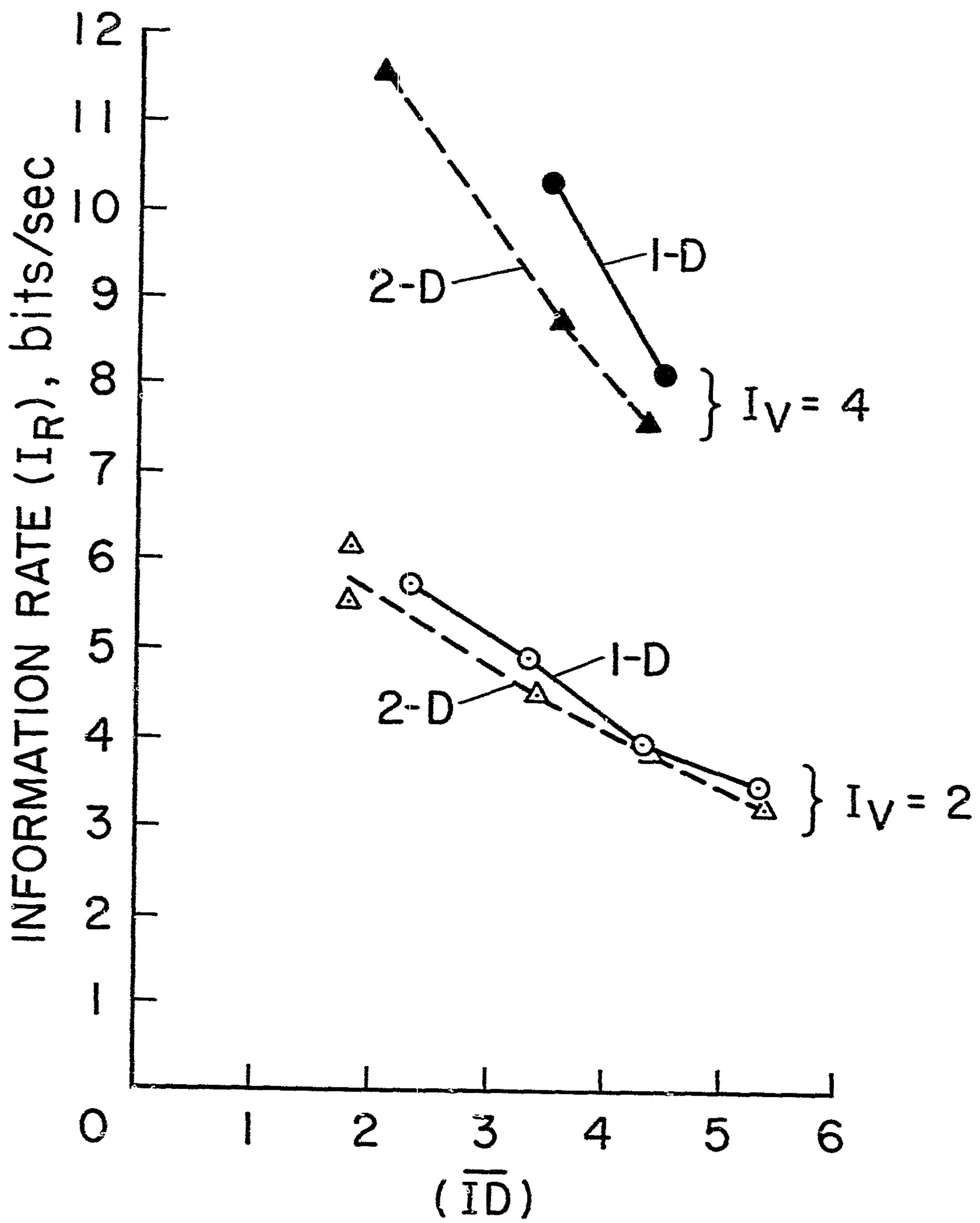


Figure 7.- The effect of $\overline{ID}$ on I_R; subject 5.

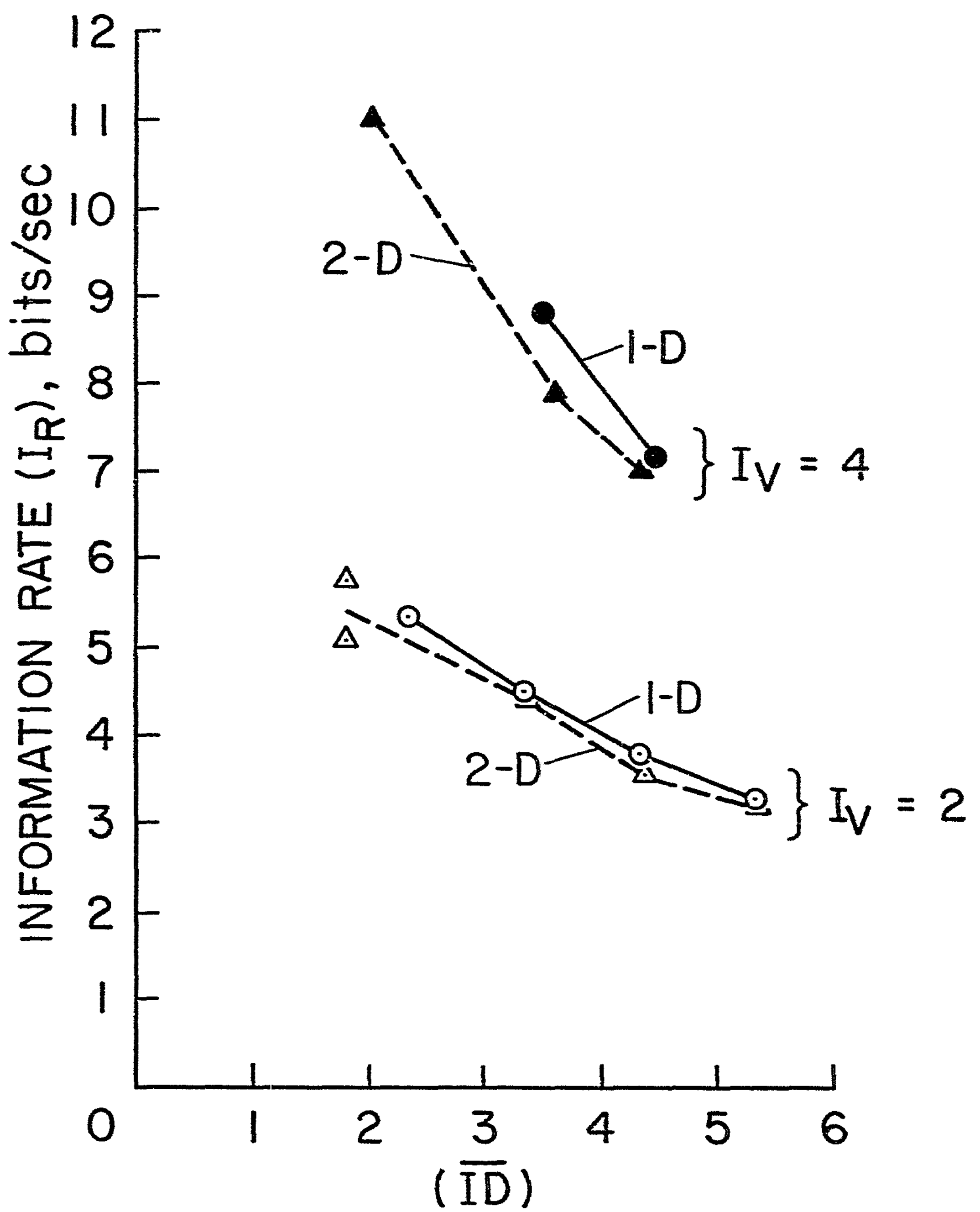


Figure 8.- The effect of $\overline{ID}$ on I_R; subject 6.

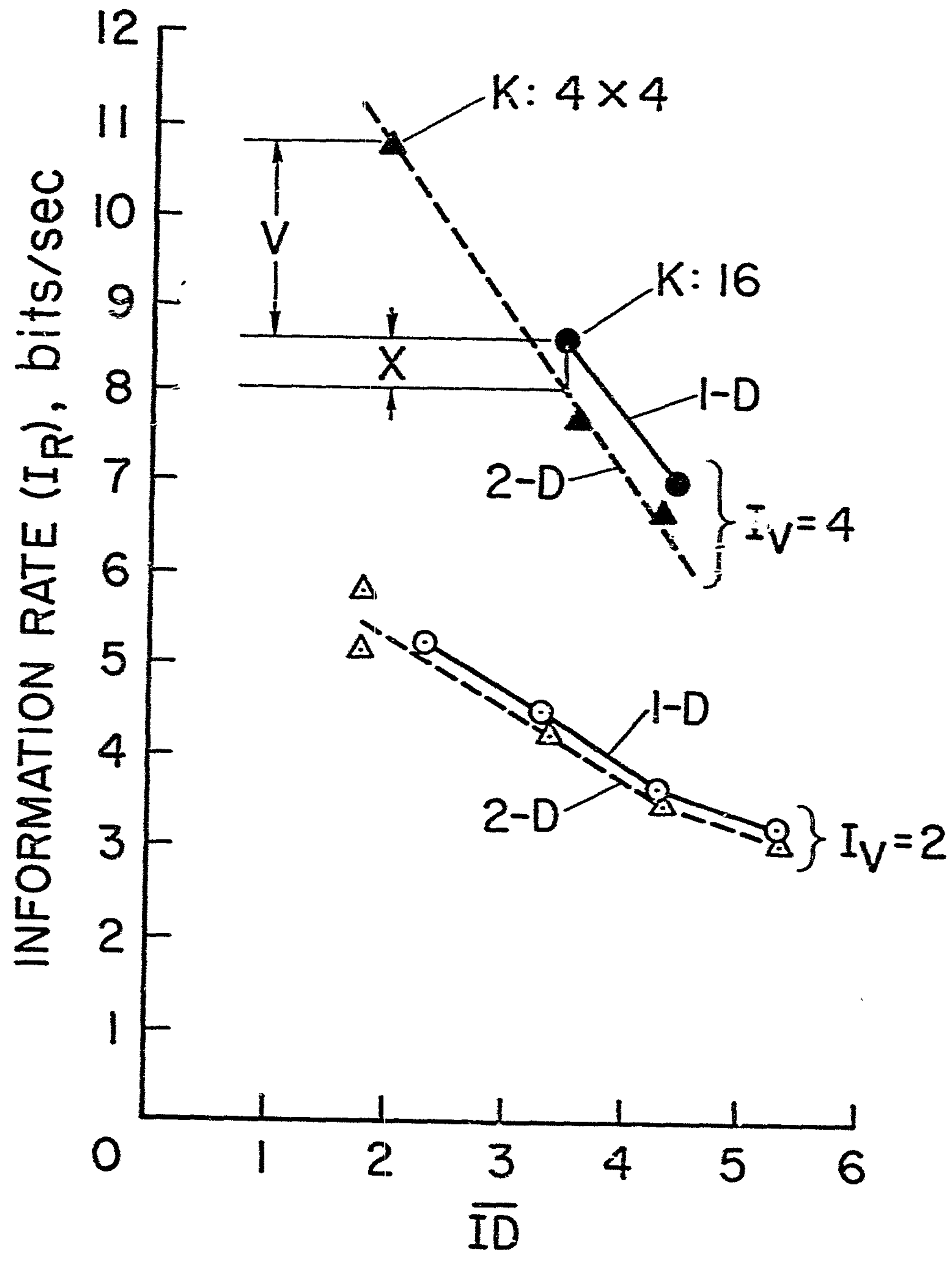


Figure 9.- The effect of $\overline{ID}$ on I_R; mean rates from six subjects.

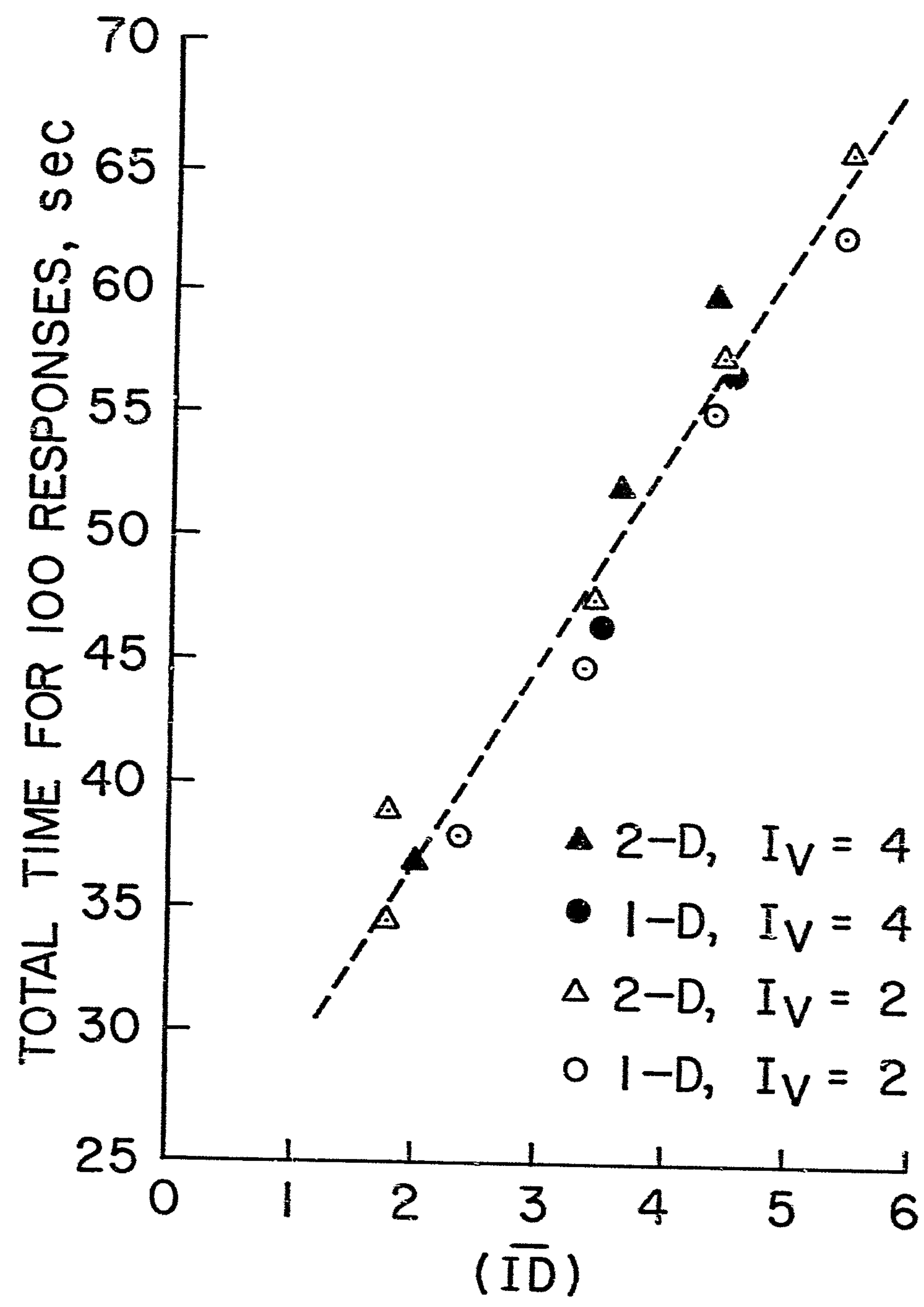


Figure 10.- The effect of $\overline{ID}$ on total response time; mean times from six subjects.

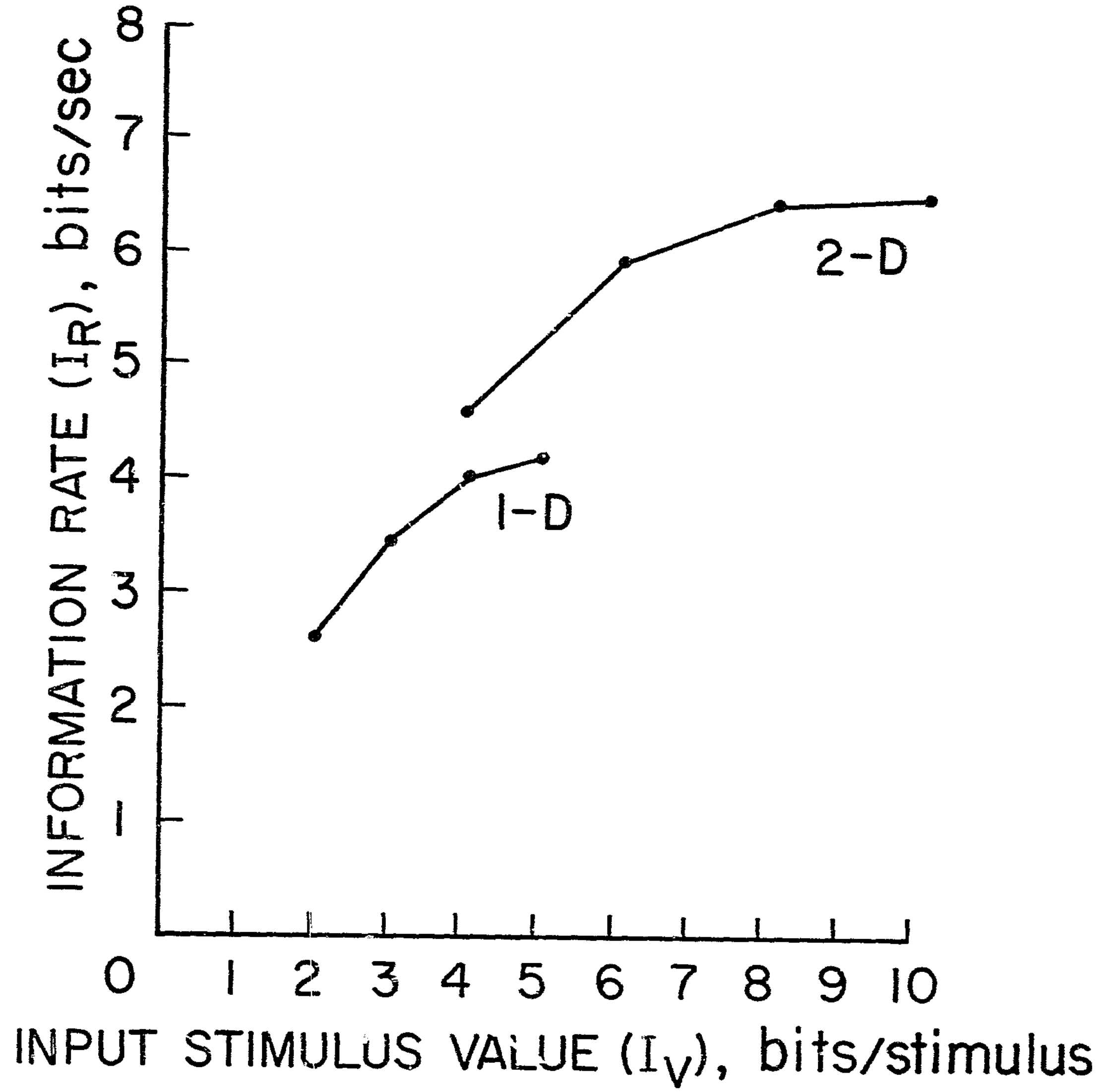


Figure 11.- Rate of information transmission for 1-D and 2-D discrete tracking tasks as a function of target position uncertainty; mean rates from eight subjects (Klemmer, 1956).

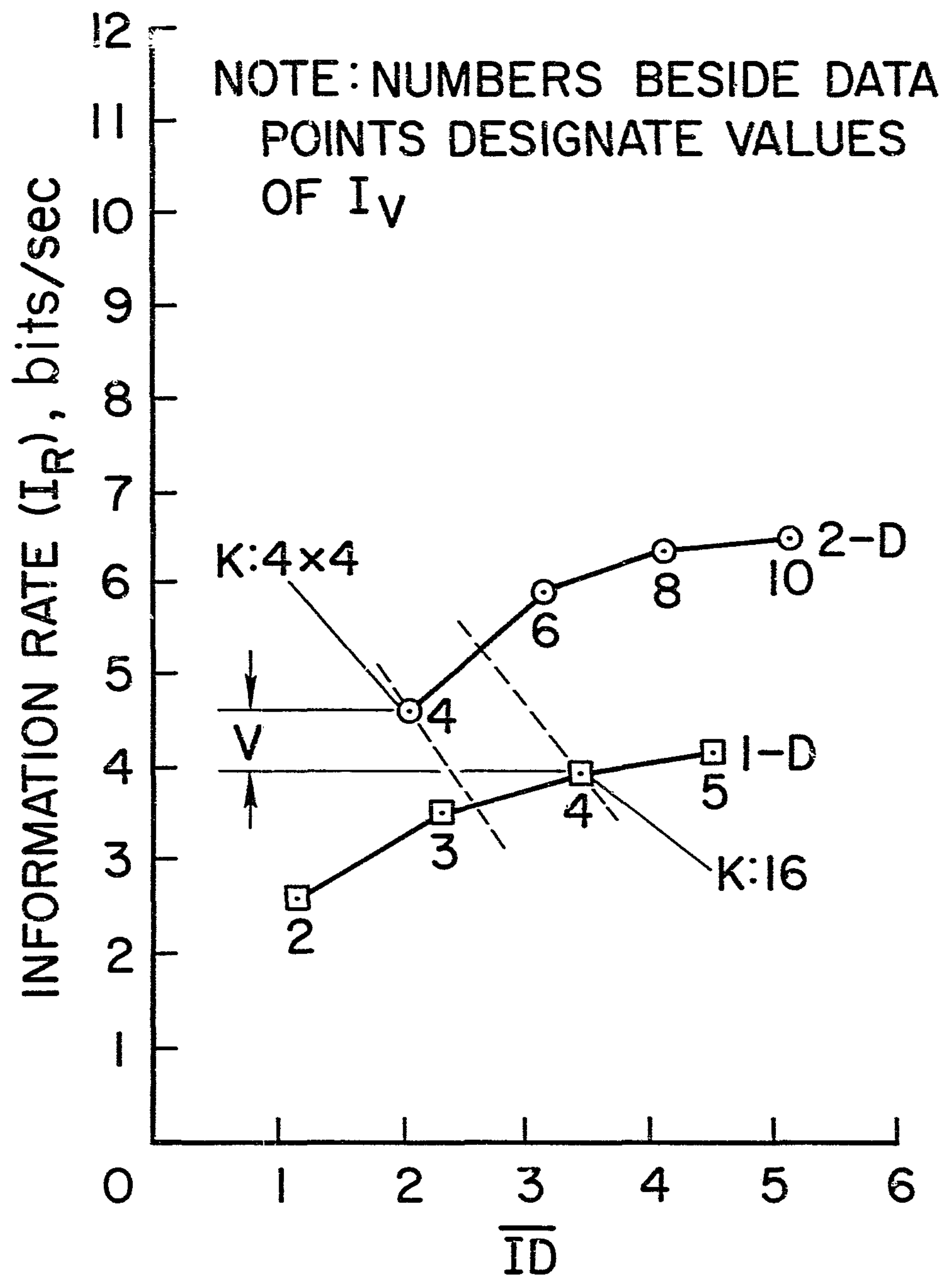


Figure 12.- Results of Klemmer's (1956) experiment plotted against $\overline{ID}$.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA