Perception of sequentially presented tactile point stimuli¹

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Either two or three brief (10 msec) airjet stimuli were sequentially presented to any of the 24 interjoint regions of the fingers (thumbs excluded). The stimulus onset interval (SOI) ranged from zero (simultaneous presentation) through 200 msec. The S's task in one part of the experiment was to report the positions stimulated in the order that the stimuli were presented; in a second part it was to rate the apparent motion produced by the stimulus sequence. While the ability of Ss to spatially localize the stimuli was a constant independent of SOI, their ability to temporally order the stimuli depended strongly on SOI. With two stimuli, these sequential errors decayed exponentially with SOI with a time constant of 26 msec. With three stimuli, however, both the sequential errors and equivalent temporal limen were more than twice as large as with two stimuli, indicating that the three-stimulus task is considerably more difficult than the two, and that the same simple temporal resolution model does not explain both cases. A model with a constant rate of information uptake, however, can explain both of these cases.

In a previous paper (Hill & Bliss, 1968), we made an initial step toward the development of a model for information-handling properties of at least that portion of the tactile channel activated by point stimuli on the fingers. This model was developed by analyzing data from experiments in which from two to 12 simultaneous airjet stimuli were briefly presented on some of the 24 phalanges of both hands. This analysis indicated the existence of a short-term tactile memory, or sensory register, with the following properties: (1) a storage duration of about 1.5 sec, (2) a capacity that varies considerably in size (but not in temporal characteristics) for different Ss, and (3) a capacity limited by localization accuracy, with the most prevalent localization errors being in close proximity to the correct location.

However, many inherent properties of any information-handling model were not investigated in this previous work. For example, left unanswered were such questions as: At what temporal separation can these point stimuli be correctly ordered in time? Does this minimum temporal separation depend on the spatial separation of the point stimuli? Can three stimuli be perceived in their correct temporal sequence at the same minimum temporal separation as two? The experiment reported below considers these questions in order to further develop the previously described model.

Obviously, the transmission of information in the tactile sense is limited by both spatial and temporal interactions. The presentation of a tactile point stimulus either simultaneous with, or in close temporal proximity to, another point stimulus will affect the accuracy of perceiving that stimulus. Hirsh and Sherrick (1961) have compared perceived order in several modalities and found similar limitations in each; that is, two spatially separated stimuli, temporally separated by 20 msec, can be correctly ordered 75% of the time.

METHOD

Apparatus

The experiment was carried out under control of a CDC 8090 computer system, which was used to store stimulus patterns and the sequence in which the patterns were to be presented (Bliss & Crane, 1964). This system was designed for use with up to 96 tactile or visual stimulators. Only 24 tactile stimulators were used in this experiment, one for each of the 24 interjoint regions of the fingers (thumbs excluded). The palmar sides of the fingers were suspended about 1/8 in. above the airjet stimulators in the same apparatus described previously (Bliss, Crane, Mansfield & Townsend, 1966). The Ss' arms were supported from wrist to elbow, permitting the hands to be suspended in this manner for

extended periods without fatigue. Each S had his own set of airjet stimulators, which was initially adjusted to his hands and never reset unless he requested that a particular jet be readjusted. This ensured better constancy in the positioning of the airjets from session to session.

Each jet of air was formed by a 0.031-in. outlet nozzle under control of a high-speed electromagnetic valve. The air-pressure pulse, measured 1/8 in. directly above the airjet outlet, was about 3 psi, with a rise and fall time of about 1 msec and an overall pulse width of about 2.5 msec. A 200 Hz pulse-repetition rate was used throughout the experiments. Thus, all stimulators were simultaneously turned on and off two or three times during the 10-msec stimulus-presentation time. The advantages of airjet stimulation for this investigation were that relatively uniform stimulation was produced over nonuniform cutaneous surfaces and that stimulator spacing could be easily adjusted.

Subjects

Five male Ss were used. The Ss B and L were high school seniors; N was a college freshman; S, a college junior; and G, a graduate student. N had been totally blind from birth; G became blind seven years ago. None of the Ss had previously participated in an experiment of this nature.

Procedure

On any trial, n stimulation points ($n = 2$ or 3) were randomly selected by the computer out of the possible 24 interjoint locations, and the corresponding stimulators then activated, one at a time, for 10 msec. The time interval (stimulus onset interval) between the onset of the first stimulator and the onset of the second stimulator, and, when $n = 3$, between the onset of the second and the onset of the third stimulator, was one of the following: (1) 0 msec (i.e., the 2 or 3 points were simultaneously activated); (2) 12 msec; (3) 60 msec; (4) 110 msec; (5) 210 msec. Except in the simultaneous condition, the same interjoint position could be stimulated repetitively in a single trial. In any one session, the number of points stimulated, n , in each trial was constant and was known by the S, while the stimulus onset interval (SOI) was constant but unknown. All phalanges were stimulated an equal number of times per session.

After each trial the S orally reported the positions stimulated in the order of their occurrence, using the alphabetic labels shown in Fig. 1. Each response was typed into the control computer by the E, and after a fixed delay of 2 sec, the next stimulus sequence was automatically presented. There was no fixed time within which a S was forced to respond. Verbal feedback was given after each response during training only.

Fig. 1. Sketch of the back of the hands showing the alphabetic reporting labels.

Table 1
Summary of Analysis of Variance of Arcsin Content and Sequence Probability

Source of Variation	df	Mean Sq.	F Ratio	Sig.
n = 2				
Between Ss	4	0.04415		
SOI	4	0.87339	> 100	p < .001
SOI x Ss	16	0.00855		
SSP-Linear	1	0.00228	2.96	
SSP x Ss	4	0.00077		
SOI x SSP	4	0.00090	1.32	
SOI x SSP x Ss	16	0.00068		
n = 3				
Between Ss	4	0.11504		
SOI	4	0.98664	60.2	p < .005
SOI x Ss	16	0.01639		
SSP-Linear	1	0.15075	18.8	p < .005
SSP-Quadratic	1	0.12045	15.1	p < .005
SSP x Ss	8	0.00801		
SOI x SSP	8	0.00673	1.44	
SOI x SSP x Ss	32	0.00468		

Each S participated in one 40 to 60 min session a day, five days a week, for four weeks. The first two weeks were devoted to training the Ss, in an attempt to reduce learning effects on performance. The number of trials per training session was selected so that the session would be completed within 40 min. For the test sessions, the number of trials for each value of n (i.e., 2 and 3 at each of the five SOI values) was chosen to allow the variance for the mean number correct per n-value to remain constant. (Specifically, the number of trials per session was set so that the probability that the mean number correct per value of n would exceed the true mean by more than 0.3 stimulus position was < 0.1).

During the actual two week testing period, three tests were run each day. In two of these tests the S was instructed to report the positions perceived, and in the third, the S's task was to rate each stimulus on how much apparent motion was produced by the stimulus. The Ss were instructed to rate the stimuli from 1 to 10, basing their judgments on how smooth the motion appeared and on how much of the area between the stimulated positions appeared to be covered by the "moving" stimulus.

RESULTS

Content and Sequence Accuracies

Subjects in this experiment could make two different types of errors: errors in spatial localization and errors in temporal order.

Table 2
Summary of Analysis of Variance of Arcsin Content Probability

Source of Variation	df	Mean Sq.	F Ratio	Sig.
n = 2				
Between Ss	4	0.17517		
SOI	4	0.01012	1.60	
SOI x Ss	16	0.00634		
SSP-Linear	1	0.03900	17.78	p < .025
SSP x Ss	4	0.00217		
SOI x SSP	4	0.00993	1.88	
SOI x SSP x Ss	16	0.00526		
n = 3				
Between Ss	4	0.30534		
SOI	4	0.00791	1.23	
SOI x Ss	16	0.00615		
SSP-Linear	1	0.06164	9.22	p < .025
SSP-Quadratic	1	0.00046	< 1	
SSP x Ss	8	0.00669		
SOI x SSP	8	0.00646	1.11	
SOI x SSP x Ss	32	0.00580		

These error types cannot be distinguished uniquely in individual stimulus-response pairs, but probability estimates can be made from a collection of data. Thus, to estimate the frequency of each of these error types, and to correct the data for guessing, three measures were defined and calculated from the data as follows:

(1) *Content probability*³—the fraction of positions perceived in the correct location, independent of sequence.

(2) *Content and Sequence probability*⁴—the fraction of positions perceived in the correct sequence and in the correct location.

(3) *Sequence error probability*—the fraction of positions perceived in the correct spatial location but in the wrong temporal sequence (estimated by subtracting 1 from 2).

As an example of the above definitions, consider the case in which the response sequence AEB was given to the stimulus sequence ABC. For easily discriminated stimuli, the most likely perception leading to this response is one *Content and Sequence* position correct (the letter A), two *Content* positions correct (the letters A and B) and one *Sequence* error (the letter B).

An analysis of variance was performed on the *Content* probability and on the *Content and Sequence* probability to evaluate the effects of (1) the five Ss, (2) the five different stimulus onset intervals, and (3) the two or three stimuli sequence positions (SSP). Since these probabilities (essentially ratios of two

Fig. 2. Fraction of positions perceived averaged over all five Ss with n = 2.

numbers) obey the binomial distribution and are often very close to one, the arcsin transformation of these probabilities was used in order to meet the equal variance assumption of the analysis.

The results of the analysis are given in Tables 1 and 2. The salient features of the analysis are as follows:

(1) The *Content and Sequence* probability significantly depends on SOI with both n = 2 and n = 3.

(2) There is not enough evidence to show that the *Content* probability varies with SOI.

(3) The *Content* probability with n = 2 and n = 3 and the *Content and Sequence* probability with n = 3 vary significantly at different positions in the stimulus sequence. Thus, the fraction of positions perceived varies with the position in the Ss' response schedule. This result is in agreement with the results reported by Bliss, Crane, Mansfield and Townsend (1966) for simultaneous point stimuli, and by Bliss, Crane, Link and Townsend (1966) for sequential patterned stimuli.

(4) There was not enough evidence to show that the interaction between SOI and SSP was significant; the data indicate that the probabilities for each S are a linear sum of these two independent terms. This result is in contrast with the results of Bliss, Crane, Link and Townsend (1966), in which a greater percentage of first-response errors was obtained with patterned tactile stimuli for short interstimulus

Fig. 3. Fraction of positions perceived averaged over all five Ss with $n = 3$.

intervals and a greater percentage of second-response errors was obtained for long interstimulus intervals.

The average values of *Content* probability and *Content and Sequence* probability for $n = 2$ and $n = 3$ are given as a function of SOI in Figs. 2 and 3. The graphs were obtained by averaging the data of all five Ss over all stimulus sequence positions. Fig. 4 shows the same data averaged over Ss and SOI. In all cases except for the *Content* probability with $n = 2$, there was a small but significant reduction in accuracy on the later responses. In addition, there is a significant quadratic effect in the *Content and Sequence* probability for $n = 3$. The Ss did not report the second stimulus in the correct sequence position as well as they did the first and third stimulus.

The *Sequence Error* probability was obtained by subtracting the *Content and Sequence* probability from the *Content* probability for each SSP, for each S, and for each value of SOI. The resulting data are given in Fig. 5. A regression analysis of the sequence data

Fig. 5. Sequence Error probability data fitted with exponential regression curves. Time constants are in msec.

Fig. 4. Fraction of positions perceived averaged over all five Ss and over all values of SOI.

was made using different types of models: linear, hyperbolic, and exponential. The best fit was obtained with the exponential curves. The exponential curves shown in Fig. 5 explain a significant portion of the error variation due to the different values of SOI. In fact, the very small amount of residual variance from the curves suggests that an exponential model may be a true model for the data. Summaries of the analysis of variance for the regression lines are given in Table 3. Other curves that were used to fit the data gave not only a significant regression, but also a significant residual; thus, they were not complete models for the data.

The average accuracy for each of the individual Ss is given in Table 4. An interesting feature shown by the table is that the performance of Ss varies considerably more on the content measure than on the sequence measure. The ratios of the variance on these two measures are 7.13 with $n = 2$ and 5.71 with $n = 3$. Since the critical ratio for these variances is 6.39 (5% test) the ratio is significant with $n = 2$. With these large ratios, we may assume that most of the variability between Ss is due to their differing abilities to locate the stimuli in space, not in time.

Table 4 also shows the differences between Ss. On the simplest part of the experiment, locating only two stimuli, it can be seen that almost all of the Ss reach nearly perfect performance (95% correct). On this same task the early blind S (N) located only 85% of the stimuli correctly. This difference between N and the other four Ss was significant (.01 level). Benton (1959, p. 76) found that normal adults perceive two simultaneously presented stimuli on the fingers nearly perfectly. The deficiency in N was attributed to travel fatigue and difficulty in concentrating rather than to his early blind condition. Besides this S, there were no significant differences between the blind and sighted Ss in this experiment.

Temporal Discrimination

Having found that the sequential error is relatively constant for different Ss and, hence, may represent a basic limit in temporal decision-making ability, a more thorough analysis of sequential error was made. To make the analysis as unambiguous as possible and more independent of the spatial localization part of the experiment than the previous sequential error analysis, only the correctly reported patterns were considered. This accuracy restriction eliminated about 30% of the patterns from this sequential analysis. Because of this restriction, however, no guessing correction had to be applied to these patterns. Also, to make the analysis as consistent as possible, only the data of the four similar Ss were used (Ss S, B, G, and L).

The lumped data of these four Ss are given in Table 5. The digits in the report sequence of the table are the order in which the positions of the stimulus pattern were reported by the Ss. For

Table 3
Summary of Analysis of Variance for Regression on Sequential Probability

Source of Variation	df	Mean Sq.	F Ratio	Sig.
n = 2				
Between SOI	4			
due to regression	1	2.2926	653	p < .001
residual	3	0.0052	1.47	
SOI x S	16	0.0035		
n = 3				
Between SOI	4	3.6368		
due to regression	1	3.6368	330	p < .001
residual	3	0.0153	1.39	
SOI x S	16	0.0110		

example, sequence 312 means that the third position stimulated was reported first, and then the first and second positions were reported.

Several probabilities were computed from the data of Table 5. The probabilities are defined as follows:

n = 3

$$\begin{aligned}\text{Pr(Error on 1st Stimulus)} &= (213 + 231 + 312 + 321)/\text{Total} \\ \text{Pr(Error on 2nd Stimulus)} &= (132 + 213 + 231 + 312)/\text{Total} \\ \text{Pr(Error on 3rd Stimulus)} &= (132 + 231 + 312 + 321)/\text{Total}\end{aligned}$$

$$\text{Pr(1 - 2 Reversal)} = (213 + 231 + 321)/\text{Total}$$

$$\text{Pr(2 - 3 Reversal)} = (132 + 312 + 321)/\text{Total}$$

$$\text{Pr(1 - 3 Reversal)} = (231 + 312 + 321)/\text{Total}$$

n = 2

$$\begin{aligned}\text{Pr(Error on First Stimulus)} &= \text{Pr(Error on Second Stimulus)} \\ &= \text{Pr(1 - 2 Reversal)} \\ &= (21)/\text{Total}\end{aligned}$$

where the report sequence (e.g., 123, 132) represents the number of patterns reported in that sequence.

The error probabilities for both $n = 2$ and $n = 3$ are plotted in Fig. 6 together with the average data from a sequential perception experiment by Hirsh and Sherrick (1961) in which temporal resolution was measured using two tactile stimuli on the fingers. The temporal limen predicted by our experiment (26 msec) is substantially longer than that of Hirsh and Sherrick (18 msec); however, in the Hirsh and Sherrick experiment, only two possible positions were stimulated, and, in our experiment, 24 possible positions were stimulated. Since our Ss had a more complex task, in that they had to divide their attention between locating the positions and ordering the positions in time, it is not surprising that our error rates are higher than Hirsh and Sherrick's.

One of the most noticeable features of Fig. 6 is the great increase in sequential error and the extended time course of the sequential error in going from two to three stimuli. With $n = 3$, stimuli must be two to three times farther apart in time to obtain the same error rates as with $n = 2$. Thus, the addition of the third stimulus greatly increases the difficulty of temporally ordering all three stimuli.

While in Fig. 7 the 1-3 reversal curve is practically identical to the reversal curve with $n = 2$, the time interval between the first and third stimuli is twice that between the first and second for any

Table 4
Average Response Probabilities for Each S

Subjects		B	G	L	S	N
Content Probability	n = 2	0.991	0.947	0.977	0.980	0.847
	n = 3	0.929	0.790	0.934	0.904	0.706
Sequential Error Probability	n = 2	0.195	0.183	0.221	0.224	0.175
	n = 3	0.322	0.266	0.353	0.373	0.302

Table 5
Number of Patterns Reported with Each Given Sequence

Report Sequence	0	12	60	110	210
n = 3					
123	97	89	249	311	444
132	93	111	101	56	12
213	80	87	59	33	9
231	69	75	22	7	1
312	86	64	15	6	0
321	93	54	5	3	0
Total	518	480	451	416	466
n = 2					
12	240	251	400	401	438
21	210	188	32	15	2
Total	450	439	432	416	440

SOI value on these curves. Both Fig. 6 and Fig. 7 illustrate the greater number of errors involving the second stimulus when $n = 3$.

The preponderance of 2-3 reversals suggests a model in which the later tactile stimuli of a sequence appear less intense than the earlier stimuli, even though the stimulus strengths are the same (e.g., Rosner, 1959; and Gescheider, 1966). According to this model, the temporal ordering decisions would be based on the relative subjective intensities of decaying "afterimages" of the stimuli. However, more data need to be available with higher values of n before explicit models for temporal discrimination can be constructed.

Apparent Motion

The average apparent motion ratings given by each of the five Ss are shown in Fig. 8. Immediately apparent from these plots is the large amount of variability among Ss, which could either be due to real differences in the amount of motion perceived by each of them, or to differences in their criteria. From Fig. 8 it can be seen that the apparent motion ratings are maximum with stimulus onset intervals from 12 to 110 msec. However, most Ss reported some degree of motion even in the simultaneous test and in the 200 msec test. An analysis of variance showed that changes in the apparent motion ratings did not significantly depend either on stimulus onset intervals or on the number of stimuli.

These results are somewhat in accordance with the results of Kotovsky and Bliss (1963), Sherrick and Rogers (1966), and Sumbly (1965), who found apparent motion most prevalent for stimuli temporally separated by 50 to 150 msec.

DISCUSSION

Temporal Discrimination vs Stimulus Spacing

Hirsh and Sherrick (1961) described a series of perceived order experiments on the tactile as well as on visual and auditory senses. Their data show that all three modalities have equal abilities to differentiate between two temporal stimuli. They hypothesize that there is a central temporal decision-maker common to these three sense modalities. More recent experiments by Babkoff and Sutton (1963) (auditory), and Robinson (1967) (visual), show that the site of stimulation and intensity cues influence the temporal limen. In particular, separate stimuli presented to separate eyes or ears (dichoptic or dichotic) are perceived with greater temporal accuracy than are stimuli presented to only one sense organ or sensory surface. The above authors do not give data to disprove Hirsh and Sherrick's (1961) concept of a constant temporal limen when the two stimuli are presented on the same sensory surface.

Gescheider (1965, 1966) conducted experiments to determine the interstimulus interval where two tactile point stimuli appeared as two successive taps rather than one. He found that this "simultaneous vs successive" limen varied from 1 msec with closely spaced stimuli on a finger to 11 msec for stimuli on separate hands. Gescheider's measure is not the same as the temporal limen, because stimuli that are separated sufficiently in time to be recognized as two rather than one event (were there one or two?) cannot be ordered in time (which came first?) until the time interval is considerably increased.

In order to further investigate human temporal resolution between different body locations, the data of Table 5 with two stimuli ($n=2$) were broken down to make two additional analyses. The first analysis compares temporal resolution when both stimuli were on one hand to that when the stimuli were on separate hands. This analysis tests whether one hand has better temporal resolving power than two. The second analysis compares temporal resolution when both stimuli are on the same hand but occur on the same finger, neighboring fingers, up to and including fingers on the extreme sides of the hand. The analysis tests whether resolution depends on finger spacing.

The data for the one hand vs two-hand analysis are given in Fig. 9. The figure shows little difference between the two conditions. An analysis of variance showed no significant differences between these two *Sequential Error* probabilities.

The data for the finger spacing analysis are given in Fig. 10. The figure shows that there is a decrease in *Sequential Error* with finger spacing at SOI = 12 msec, suggesting that the temporal limen is less for more closely spaced tactile stimuli. An analysis of variance of this data showed no significant differences between the

Fig. 6. Probability of errors at each stimulus sequence position for $n=2$ and $n=3$. Comparable tactile data is redrawn from Hirsh and Sherrick (1961).

Fig. 7. Probability of stimulus reversals between each pair of stimulus sequence positions with $n=2$ and $n=3$.

Fig. 8. Mean apparent motion ratings of the five Ss. The vertical bars represent the standard deviations of the ratings.

Sequential Error probabilities and finger spacing. However, the data of Fig. 10 suggest that the temporal limen may decrease with decreased stimulus spacing; thus, further exploration may be warranted. In the first place, the stimulus onset intervals chosen for the experiment are not the most appropriate for measuring this temporal limen. The data of Figs. 9 and 10 show that the tactile temporal limen is about 26 msec. To most effectively measure this limen, data at additional values of stimulus onset interval between 10 and 40 msec should be obtained. In the second place, this issue has practical importance, since if better temporal resolution results from closer stimulator spacings, smaller tactile displays may be more effective for communicating timing information to human operators.

Transmitted Information

Another important method of evaluating the ability of Ss on tactile tasks is to measure the amount of information they transmit. Like reporting accuracy, the mutual information, $I(S;R)$, in this experiment can be divided into two separate parts:

(1) *Content Information*—information transmitted by the spatial content of the response.

(2) *Sequence Information*—information transmitted by the order or sequence in which the responses are given.

A means of measuring or bounding information in tactile patterns is outlined in the Appendix. *Content Information* can be bounded from below, and *Sequence Information* can be estimated.

Using the method outlined in the Appendix, we determined a lower bound on the content information for each S and for each value of SOI on both the $n=2$ and $n=3$ sessions. Like the *Content* probability, *Content Information* is a constant over different values of SOI. These results, averaged across values of SOI are shown in Table 6.

Fig. 9. Sequence Error probability for two stimuli on the same hand compared with Sequence Error probability for two stimuli on different hands.

Fig. 10. Comparison of Sequence Error probability when two stimuli appear with different stimulus spacings on one hand.

Though Content Information varies greatly from S to S, Sequence Information is relatively constant for all the Ss. The Sequence Information for all five Ss averaged together is given in Fig. 11. The interesting feature of Fig. 11 is that the initial slopes of the information vs SOI are about the same for both $n = 2$ and $n = 3$ conditions, indicating that there may be an intrinsic limit on the rate of tactile information intake. The slopes of the sequence-information rate are about 17 bits/sec, or one bit/60 msec.

APPENDIX

COMPUTATION OF THE INFORMATION TRANSMITTED

To simplify the computation of the information transmitted in this experiment, the total information transmitted was broken down into the content and sequence components. It will be shown that just these two components will adequately account for the information transmitted.

In this experiment, the overall entropy of the stimulus patterns is

$$H(S) = n \log 24.$$

This represents the maximum information that can be transmitted. The maximum information that can be transmitted by the content of the patterns only (considering that the order of responses is immaterial) can also be computed. With $n = 2$ or $n = 3$, the total number of different patterns, considering only the content of the patterns is

$$\left(\frac{24}{n} \right) + 24^n - 1.$$

The additional term, $24^n - 1$ is the number of separate patterns with duplicated locations. The maximum content information is then

$$I_{\text{cont}} = \log \left[\left(\frac{24}{n} \right) + 24^n - 1 \right].$$

The maximum information that can be transmitted by the sequence of the responses alone may also be computed. When $n = 2$, the maximum sequence information is

$$I_{\text{seq}} = \frac{24^2 - 24}{24^2} \log 2 + \frac{24}{24^2} \log 1 = 0.96 \text{ bits.}$$

Table 6
Lower Bounds on Content Information (In Bits)

Subject	S	N	L	G	B	Average
N = 2	7.78	5.92	7.56	7.28	7.98	7.30
N = 3	9.10	5.60	9.60	6.98	9.48	8.14

Fig. 11. The Sequence Information transmitted averaged over all five Ss.

The first and second terms represent the sequence information transmitted respectively when the patterns consist of (1) two different locations (letters) and (2) the same location repeated twice. When $n = 3$, the maximum sequence information is

$$I_{\text{seq}} = \frac{24^3 - 24^2 - 24}{24^3} \log 6 + \frac{24^2 - 24}{24^3} \log 3 + \frac{24}{24^3} \log 1 = 2.53 \text{ bits.}$$

The first, second, and third terms represent the sequence information transmitted by patterns with (1) no location repeated, (2) two locations repeated, and (3) three locations repeated.

The maximum values of the sequence, content, and total information for $n = 2$ and $n = 3$ are given in Table A-1, as is the sum of the content and sequence information. This sum is within 2% of the total information that can be transmitted. The two information components—content and sequence—can thus be computed independently and then summed to get an approximation (within 2%) of the total information transmitted.

The computation of the content information is described by Hill (1967, Chapter 6). One of the greatest lower bounds for low values of n was shown to be the generalized Fano bound. This bound can be used to relate the content information to the number of positions perceived using Model I of Hill and Bliss (1968, Appendix A). This relationship is shown in Fig. A-1. The number of positions perceived in this experiment can be determined by multiplying the average Content Probability by the value of n . This method was used to obtain the data of Table 6.

The computation of the Sequence Information is accomplished by averaging the patterns together to remove the spatial variable. The resulting channel has only $n!$ input and output patterns to consider. All of the conditional transfer probabilities can be computed directly from the data. Given an average stimulus sequence, the $n!$ report sequences are shown in Table 5. The information transmitted by such an average channel is

$$I_{\text{seq}} = \log n! + \sum_{k=1}^{n!} p_k \log p_k.$$

The p_k are the fractions of patterns reported in each of the $n!$ possible report sequences. Note that I_{seq} is an estimate of the sequence information, not a lower bound. This method was used to obtain the data of Fig. 11.

Table A-1
Maximum Information Transmitted (In Bits)

N	I_{seq}	I_{cont}	$I_{\text{seq}} + I_{\text{cont}}$	I_{total}	Discrepancy
2	0.96	8.23	9.19	9.16	0.03
3	2.53	11.46	13.99	13.73	0.26

Fig. A-1. Graph for converting from the number of positions perceived to a lower bound of the content information transmitted.

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NOTES

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3. The number of positions perceived independent of order was obtained using a variant of Model II described in Hill and Bliss (1968, Appendix A). The guessing correction for this particular experiment is determined as follows: We assume that if a stimulus is not perceived, the S guesses from among all 24 possible locations with success at the chance level. Thus, the guessing probability for the i^{th} ($i = 1, 2, \dots, n$) stimulus, (the g_i of Model II) is $1/24$. The net effect of the content guessing correction reduced the S's raw scores by less than 1%.

4. The number of positions perceived in the correct location as well as in the correct order (or sequence position) was obtained by using the modified version of Model II just described. In this case, however, the fraction of correct responses to the i^{th} stimulus, the c_i of Model II, was computed using only the fraction of correct responses to the i^{th} stimulus given on the i^{th} response. This content and sequence correction introduced by Model II was about 3% for $n = 2$ and about 6% for $n = 3$.

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