REACTION TIME: STIMULUS UNCERTAINTY WITH RESPONSE CERTAINTY

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A. INTRODUCTION

The question to which the present study is addressed is as follows: if no choice is required of the subject—i.e., he makes the identical response regardless of which stimulus is presented—will reaction time to a particular stimulus be altered as a function of the probability with which that stimulus follows another stimulus? This question bears on several unsettled problems in the reaction time literature. In order to understand the relevance of the present study, it is necessary to sketch out the current status of these problems.

1. Role of Stimulus Uncertainty

One of the early dramatic applications of information theory to psychology was Hyman's demonstration (11) that stimulus information as defined by information theory was linearly related to choice reaction time (CRT). Merkel (18) had found before the turn of the century that CRT increased as the number of equiprobable alternatives increased. Miller (19) and Hick (10) independently pointed out that a replot of Merkel's data yielded a straight line if CRT was plotted against the log of the number of alternative stimuli, or, equivalently, if CRT was plotted against stimulus information. Hyman's contribution was to demonstrate the generality of the relationship. In addition to manipulating stimulus uncertainty by varying the number of equiprobable alternative stimuli, Hyman (a) varied the relative probability of the stimuli and (b) introduced first order sequential dependencies among stimuli. He

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found that reaction time was identically related to stimulus information in all three conditions. However, in Hyman’s situation there was a one-to-one correspondence between stimuli and responses, and subjects were required to perform without errors. Under such conditions stimulus information, response information, and transmitted information are confounded. In experiments in which stimulus information was held constant, Hick (10) and Bricker (4) obtained data supporting the hypothesis that reaction time is a positive linear function of transmitted information implying that only throughput information is reflected in changes in CRT when stimulus information is varied. Archer (1) and Morin, Forrin, and Archer (20) provided additional experimental support for this position when they found that irrelevant stimulus information had no effect on CRT. Gregg (7) obtained conflicting data which Archer (1) suggests was due to insufficient practice.

One simple way of clarifying the role of stimulus information is to eliminate response information altogether. This can be done by requiring the identical response regardless of stimulus. Any residual alteration of reaction time in such a situation can be attributed only to stimulus information. This is the approach taken in this study. Grice and Hunter (8) recently came to the same conclusions and emphasized the need for a study of stimulus uncertainty under the condition where there is no response uncertainty.

2. "Component" Reaction Time

As noted above, Hyman found average stimulus information to be a predictor of average CRT regardless of the mode of varying information. However, only when information is altered by changing the number of equiprobable alternatives is there an equivalence between the average information of the ensemble and the information in any member of that ensemble. What meaning then is to be attributed to the linear relationship between average CRT and average information when information is manipulated by altering either absolute or sequential probability? For example, consider a particular experimental condition in which there are two choices with different sequential (or absolute) probabilities. Does the average for the condition reflect the fact that the more probable alternative is slower and the less probable alternative is faster? Secondly, is the relationship between the sequential (or absolute) probability of individual stimuli and reaction time a linear one?

Hyman in fact found that “reaction time to a low information component was higher and the reaction time to the high information component was . . . lower” than would be predicted by the “hypothesis that reaction time behaves in a manner analogous to the measure of information” (11, p. 194).
Leont'ev and Krinichik (14) have clarified the issue somewhat by studying the effect of component information in a two-choice RT situation in which relative probability of stimulus occurrence was varied. They found that component reaction time increases with stimulus information though the rate of increase between .09 and 1 bits is much greater than between 1 and 4 bits (in which range the relationship appears to be linear). Additional analyses by the authors indicate their results are consistent with Hyman's as regards latencies generated by "low" and "high" information stimuli. Their study, however, was one in which stimulus and response information were confounded.

In the present experiment, we varied "component" information by manipulating sequential probability but with only one response regardless of stimulus so that stimulus information contributes the only source of variation.

3. Alternation vs. Repetition

Bertelson (2, 3) has found that, for stimuli with the same sequential probability, reaction time to repetitions is more rapid than to alternations. Williams (28) has reported contradictory data. Kornblum (12) has recently utilized Bertelson's findings to suggest that the apparent relationship between information and CRT may reflect the fact that in high information conditions the ratio of nonrepetitions to repetitions is, in general, larger than in low information conditions. Much earlier, Mowrer (22, 23) had noted that, when the stimulus is uncertain but the response required was always the same (as in the present study), "unexpected" stimuli increased reaction time only if the unexpected stimulus was in a different sensory modality than the immediately prior stimulus.

In the present study, we considered the role of alternation vs. repetition in the special case where alternation involves a shift to another sensory modality. Our design, like Mowrer's, permits us to attribute any differences found to stimulus information alone.

4. Role of Practice

Inasmuch as evidence has accumulated that the effect of stimulus uncertainty on CRT diminishes with extensive practice (13, 21), it was of interest to explore the effect of practice on stimulus uncertainty in the condition in which there was no response uncertainty. The present study was designed to permit such an examination.

In summary, we undertook to study the unconfounded role of stimulus uncertainty in influencing reaction time over an extended period of practice. We
used an identical response regardless of stimulus to eliminate response uncertainty. We varied stimulus uncertainty by manipulating sequential dependencies among stimuli. In addition, the design incorporated an examination of the role of alternations vs. repetitions as it affected these relationships.

B. Method

1. Apparatus and Stimuli

The S sat in a dental chair, which was independently adjustable for height and back positions. A chin rest was used to maintain a constant distance (19 inches) both from the visual stimulus and from the loudspeaker. When the S was in position, his eyes were level with the center of the visual stimulus, which filled a circular cutout in a black vertical board. The S's elbow was supported by a foam rubber rest at the same height as the wooden plate containing the reaction key. He was instructed to lift his finger as rapidly as possible at the occurrence of each stimulus and then to return it to the key. The stimulus presentation simultaneously activated a clock of local design which was accurate to ±1 millisecond.

The visual stimulus was a 2.0 millilambert flash superimposed on a circular field (7° visual angle) diffusely illuminated by white incandescent light; the flash was of similar composition. The background illumination was 1.0 millilambert. The auditory stimulus, which emanated from a loudspeaker, was a 1200 cps tone 30 db above threshold when presented against a background noise of 69-72 db (re: .0002 dynes/cm²) produced by an air conditioning unit. Both stimuli were response terminated.

Stimuli were always presented in pairs. They were preprogrammed at the beginning of a session and presented automatically. Each run consisted of 36 pairs of stimuli presented at 10-second intervals. The second stimulus of a pair was presented automatically one second after the S had responded to the first stimulus. The timer, of local design, was accurate to ±2 per cent.

2. Subjects and Procedure

Since there were two possible stimuli, a sound and a light, and stimuli were presented in pairs, four type of pairs are generated. A sound followed by a sound (SS), a sound followed by a light (SL), a light followed by a light (LL), and a light followed by a sound (LS). Although the S reacted to all stimuli, in order to simplify the design we considered only the reaction time to the second member of a pair and only if it was a sound. In one set of experimental conditions (Set A), we presented in quasi-random order only
three of the four possible pairs, SS, LS, and SL. This limitation to these three pairs results in the fact that if light is the first member of the pair, the second must be a sound. For this type of pair, sound in the second position is certain and, since it is in a different sensory modality than the first member of the pair, it is called crossmodal. However, if sound is the first member of the pair then the second member of the pair may be either a sound or a light. Here, sound in the second position is uncertain and, since it is in the same sensory modality as the first member of the pair, it is called ipsimodal. By varying the proportion of the three types of pairs various probabilities of occurrence are generated for sound as the second member of the pair. The following table summarizes the different Set A conditions:

Set A Ipsimodal uncertain, crossmodal certain

\[ A_1 \rightarrow SS, LS, SL \text{ in the ratio } 1:1:1 \quad P(S/S) = .50 \quad P(S/L) = 1 \]
\[ A_2 \rightarrow SS, LS, SL \text{ in the ratio } 1:1:2 \quad P(S/S) = .33 \quad P(S/L) = 1 \]
\[ A_3 \rightarrow SS, LS, SL \text{ in the ratio } 1:1:4 \quad P(S/S) = .20 \quad P(S/L) = 1 \]

In the second set of experimental conditions (Set B), everything is the same except that the LL pair is substituted for the SL pair. Again sequential dependency is varied by altering the relative probability of the three pairs. With respect to sound in the second position, this substitution generates a situation in which the uncertain sound has been preceded by a light (crossmodal uncertain), while the certain sound has been preceded by another sound (ipsimodal certain). The following table summarizes these conditions:

Set B Crossmodal uncertain, ipsimodal certain

\[ B_1 \rightarrow SS, LS, LL \text{ in the ratio } 1:1:1 \quad P(S/L) = .50 \quad P(S/S) = 1 \]
\[ B_2 \rightarrow SS, LS, LL \text{ in the ratio } 1:1:2 \quad P(S/L) = .33 \quad P(S/S) = 1 \]
\[ B_3 \rightarrow SS, LS, LL \text{ in the ratio } 1:1:4 \quad P(S/L) = .20 \quad P(S/S) = 1 \]

There are thus three levels of uncertainty for the sound stimulus in the second position, \( \rho = .50, \rho = .33, \rho = .20 \). However, in the first set of conditions, Set A, the uncertain sound is a repetition, whereas in the second set of conditions, Set B, the uncertain sound is an alternation.

Two Ss were chosen randomly from a group of 11 male Ss, attending college, in the age range 18-22, and available to serve as Ss over an extended period of time. The Ss were paid.

Subject L. K. was randomly assigned to Set A conditions—one condition per session for 18 sessions, the order of conditions within a set being quasi-random, as explained below. Following this, he was assigned to Set B condi-
tions for the last 18 sessions. Subject J. M. was assigned to the two sets of conditions in reverse order; that is, to Set B conditions for the first 18 sessions and to Set A conditions for the last 18 sessions.

The intraset sequence of sessions was as follows:

Set A conditions—A2 A3 A1 A1 A3 A2 A2 A1 A3 A2 A3 A3 A1 A2

The above order was random subject to the restrictions that every condition was represented in consecutive sixths of the set and that the six sixths contain every possible permutation.

Since both Ss were exposed to both sets of conditions, there was a need to reduce the influence of any carryover of effects from one set to the next. This was done by intercalating sessions using all four pairs between Set A and Set B conditions. The four pairs were presented in random order in equal proportions. This condition was maintained until the difference between the mean crossmodal reaction times and the mean ipsimodal reaction times was five milliseconds or less. One S achieved this in one session, the other required two sessions.

There were six blocks per session and 36 pairs within each block presented in random order but subject to the restriction that each third of a block conformed to the ratio for the total condition. This was done to prevent the occurrence of unusual runs which might lead the S to speculate that the E was altering the ratio. S was not informed of this restriction. He was told that the overall program for the session was such that the whole day's run would conform to the ratio for the condition and he was told what this ratio was. The sequential probabilities were clearly spelled out. Thus, for example, for condition B2 he was told, "Today you will get the following pairs, sound-sound, light-sound, and light-light in the ratio 1:1:2. This means if you get a sound first, sound will always follow; if you get a light first, sound will follow 1/3 of the time and light will follow 2/3 of the time." In addition the S was told: "You will have a rest period of two to three minutes between blocks. During this time I will add up all your scores and tell you whether you have met your criterion which you can best meet by reacting as fast as possible to every single stimulus without anticipating." The S was not told that the criterion was the sum of all the reaction times to the second signal, whether light or sound, as compared to the same sum for the previous run.
If it was lower or equal, he was told he had met his criterion. If it was higher, he was told he did not meet his criterion. The S was always told he had met his criterion for the initial run. The S was informed immediately of any anticipations. The criterion for an anticipation was a reaction time below 90 milliseconds for sound and below 130 milliseconds for light. During the terminal 18 sessions these were lowered to 85 and 125 milliseconds, respectively. This procedure kept anticipations at a low level (under 3 per cent).

C. Results and Discussion

The distributions of reaction times (Figures 1 through 4) to the sequentially certain and uncertain sound stimuli presented separately by subject are displayed as the log proportion of responses shorter than a given reaction time. Such plotting and analysis is described by McGill (16, 17). As he notes, this

**Figure 1**
Cumulative Distributions of Reaction Times to Sequentially Certain and Uncertain Sound Stimuli for Each Session in Set A for J. M.
procedure "tends to stabilize the frequency distributions containing relatively few observations" (16, p. 197). In the present experiments the number of observations per experimental category varied from as few as 36 per session (for the 1:1:4 condition) to 72 (for the 1:1:1 condition).

**FIGURE 2**
*Cumulative Distributions of Reaction Times to Sequentially Certain and Uncertain Sound Stimuli for Each Session in Set A for L. K.*

1. *The Effect of Stimulus Uncertainty*

For almost all sessions the distribution of latencies to the uncertain stimulus is displaced to the right of the distribution of latencies to the certain stimulus, thus indicating reaction times are longer to the uncertain stimulus, whether ipsimodal or crossmodal. This in general is true for both Ss under all conditions. In fact the median RT elicited by the uncertain stimulus was higher than for the certain stimulus in 35 out of 36 sessions for J. M. and in 34 out of 36 sessions for L. K.
The implication is clear—stimulus uncertainty *per se* does affect performance, even when there is no response information and therefore no transmitted information. The present data, generated by sequentially dependent stimuli, are consonant with data obtained by Griew (9) in a similar single

![Diagram](image)

**FIGURE 3**

*Cumulative Distributions of Reaction Times to Sequentially Certain and Uncertain Sound Stimuli for Each Session in Set B for J. M.*

response situation which, however, differed in that information was varied by changing the number of equiprobable alternatives. The present data are also consonant with CRT data obtained by Schlesinger and Melkman (25) in a situation in which stimulus information was varied while transmitted information and response information were held constant. The latter authors suggest in part that the failure of previous investigators to obtain such a result may have been due to a confounding of stimulus information with stimulus discriminability. Collectively, these studies support Schlesinger and Melk-
man's contention that Bricker's hypothesis (5)—that CRT is a function of transmitted information and is not affected by stimulus or response information unless these alter the information transmitted—is no longer tenable. It is becoming apparent that any complete formulation involving human information processing will have to take into account stimulus information and response information. In fact, a number of recent studies have concerned themselves with obtaining data designed to clarify the relative roles of stimulus and response information (6, 15, 24). Although, at present, no satisfactory comprehensive model can be formulated to encompass all the known data, a recent attempt is noteworthy. Welford (27) proposed the existence of an independent perceptual mechanism within the central processes concerned with stimulus identification. The present finding, that stimulus uncertainty affects reaction time even though there is no response uncertainty or information being transmitted, certainly is consonant with this proposal.
2. The Effect of the Degree of Stimulus Uncertainty on Component Reaction Time

The cumulative plots (Figures 1 through 4) are suggestive, but by no means conclusive, regarding the effect of the degree of uncertainty. Thus it

CUMULATIVE DECADE AVERAGE

![Graph showing cumulative decile average for J.M., Sets A and B](image)

appears that, for each S on Set B, the spread between the certain and uncertain distributions is greater for the 1:1:4 condition than for the 1:1:1 condition. This does not appear to hold true for either S in Set A. To facilitate comparisons, cumulative decile average plots were prepared (Figures 5 and 6). Each point was determined by averaging the six session values (Figures 1 through 4) corresponding to a given decile level for a given S on a given condition. The upper quadrants summarize data generated by the sequentially uncertain sound stimuli in the different conditions (the 1:1:1, 1:1:2, and 1:1:4 designations refer to the conditions in which the uncertain stimulus had a probability of .50, .33, and .20, respectively). The lower quadrants
summarize data generated by the sequentially certain sound stimuli, the legends indicating the conditions in which the respective distributions were obtained.

It is apparent that for both Ss the probability parameter exerts its greatest effect on the distributions generated by the crossmodal uncertain stimulus (upper right hand quadrant). The important implication is that performance on this task is sensitive to the degree of uncertainty only if the uncertain stimulus is crossmodal. By inspection, the effects are not quantitatively symmetrical for the two Ss. For L. K. \( p = .5 \) and \( p = .33 \) yield distributions which are relatively close compared to \( p = .20 \), which gives longer reaction times. For J. M. \( p = .5 \) gives shorter reaction times, while the other two probability conditions yield essentially similar reaction times. However, it is of interest that, if one averages the data across both Ss, the average reaction time generated by the uncertain crossmodal stimulus appears linearly related to the information it delivers (Figure 7). In contrast, the reaction time behavior generated by the ipsimodal uncertain stimulus is independent of the amount of information it delivers. This finding, nonlinearity when Ss are
plotted separately but linearity when Ss are averaged, may mean that despite our attempt to wash out order effects (intercalating sessions using all four pairs), order effects remain. These seem to counterbalance in the average across the two Ss. However, further experimentation is required to support this inference, and the linearity obtained when both Ss are averaged may be a chance result.

![Graph](image)

**COMPONENT INFORMATION IN BITS**

**FIGURE 7**

Reaction Time Averaged Across Both Ss as a Function of Component Information

While the question of linearity of the relationship between component reaction time and stimulus information cannot be resolved, the findings taken together with those of Leont'ev and Krinchik (14) obtained for CRT are promising enough to suggest that further study of component reaction time would be desirable.

3. *Alternation vs. Repetition and the Role of Modality*

As stated above, the quantitative effects of stimulus uncertainty were limited to the case where the sequence involved a shift of sensory modality. Mowrer
et al. (22, 23) also obtained evidence in a situation in which there was no response uncertainty that change in modality was critical. They reported that an “unexpected” stimulus in the same sensory modality as the preceding stimulus resulted in little if any increase in reaction time, while an “unexpected” stimulus in a different sensory modality from the preceding stimulus resulted in a large increase in reaction time.

The more complicated issue which cannot be resolved by the present study relates to the fact that a stimulus in the same modality may or may not be identical with the preceding stimulus. In the present study the ipsimodal sequence always involved two identical stimuli. Mower did not obtain a lengthening of reaction time when unexpected stimuli were different but in the same modality. Sutton and Zubin (26), also utilizing a situation with no response uncertainty, report conflicting data. They found that ipsimodal non-identical sequences (e.g., high tone following low tone) gave longer reaction times than ipsimodal identical sequences (e.g., high tone following high tone).

There is an extensive literature on the intramodality aspect of the question which is generally referred to as the effect of alternation versus the effect of repetition. Hyman (11) reported three instances where his data ran counter to his hypothesis that stimulus information was a determinant of reaction time and each instance involved stimulus repetitions. First, Hyman’s third experiment (sequential dependencies varied) contained conditions in which stimulus repetition occurred and conditions in which they did not occur. In those conditions in which they did not occur, stimulus information was lower so that CRT should have been shorter—in fact it was longer than in the conditions in which repetitions did occur. Second, although all of Hyman’s three procedures for delivering stimulus information supported his hypothesis, increasing the number of equiprobable alternatives yielded data which deviated least from the linear relationship between stimulus information and reaction time. In this procedure repetitions occurred least often. Third, Hyman found that in conditions with four and eight alternative stimuli a repeated stimulus produced the shortest reaction time even though all the stimuli within a condition were equiprobable. However, the fact that the reaction time for a repetition in the lower information (2-bit) condition is so much lower than for the higher information (4-bit) condition suggests the effect of stimulus repetition on reaction time depends on the program within which repetitions are embedded. A similar result was observed in the present study. Thus latencies to the ipsimodal certain stimulus in the program in which the cross-modal uncertain stimulus had a probability of occurrence of .2 appear to be slightly longer than to the ipsimodal certain stimulus occurring in the program
in which the uncertain crossmodal stimulus had a probability of occurrence of .5 (see Figures 5 and 6). A similar finding is apparent in data reported by Kornblum (12) obtained in a CRT design. Williams (28) reported that alternations in a two-alternative equiprobable CRT procedure resulted in shorter latencies than did repetitions. Bertelson (2), however, for a comparable condition reported no difference.

4. The Effect of Practice

Figures 1 through 4 do not disclose any apparent decrease in the effect of uncertainty as a result of practice. In fact, the spread between the certain and uncertain distributions seems to increase slightly with practice. The only exception is for L. K. in Set A where the spread for the first three sessions in a condition does not appear to be noticeably different from that for the terminal three sessions.

As has been noted, CRT may become independent of stimulus information if practice is prolonged. In the present study, practice did not diminish the effect of stimulus information on performance. One possibility is that our Ss were insufficiently practiced. The S in the Mowbray and Rhodes (21) experiment had 45,000 trials, 15,000 of which involved the same stimulus and the same response. It was these latter trials which entered into the analysis. Each S in our experiment made a minimum of 15,552 identical responses, half of which involved the same stimulus. Another possibility is that practice does not affect behavior similarly in the two reaction time procedures. Although no convincing support for this position can be offered at present, a recent proposal by Welford (27) leads to one possibility. Welford postulates the existence of a translational mechanism (in the central processes) involved in transforming the neural correlates of a perceived stimulus into the neural impulses which order the response. He suggests that this mechanism can be preset with sufficient practice which explains the effect of practice on CRT. This is tantamount to suggesting a kind of stimulus-response reflex in the sense that a response may be effected without a central process decision. One possible relevant difference between CRT in which practice reduces the effect of stimulus uncertainty and the procedure in the present experiment where practice does not reduce the effect of stimulus uncertainty is the fact that there is a one-to-one correspondence between stimulus and response in the former procedures, whereas there was a two-to-one correspondence in the present procedure. Perhaps "presetting" cannot occur, if it does at all, in this situation.
D. Summary

Reaction time to one of two alternative stimuli (sound) is considered as a function of varying sequential dependency in a situation in which response information and transmitted information are zero; i.e., the S makes the identical response regardless of stimulus. It was found that (a) despite the fact that only stimulus information is varied, reaction time to sequentially uncertain stimuli is longer than reaction time to sequentially certain stimuli; (b) reaction time is sensitive to the degree of stimulus uncertainty if the sequence involves a shift in sensory modality (crossmodal), but not if the sequence involves no shift in sensory modality; (c) when averaging across two Ss, the relationship between reaction time and stimulus information is linear if the sequence is crossmodal; and (d) practice does not appear to alter these relations.

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