Processing demands of sequential information*

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Three experiments examined the processing capacity required to use sequential information in a serial reaction time task with partially predictable sequences. The first two experiments varied the response stimulus interval (RSI) between 0 and 500 msec and found the relative advantage of the high-probability stimulus to be independent of the length of the RSI. The third experiment compared utilization of sequential information either with or without a secondary task. The secondary task did not affect the high-probability stimulus but did increase the amount of time required to respond to the low-probability events. The results are discussed in terms of the attentional demands of memory access.

In most skilled tasks, events occurring at one point in time can be used to predict what is likely to occur later. When this information is used, performance is facilitated. Hershman and Hillix (1965) and Shaffer and Hardwick (1968), for example, showed that people type words, which are highly redundant, faster than random letters, even when only one letter of a word is exposed at a time. One letter in a word helps people predict what letter will occur next, reducing typing time if the anticipated letter does occur. More formally, Hyman (1953), Hyman and Umiltà (1969), and Umiltà and Trombini (1968) found that the time to process and respond to successive events depends on the information content of the events. When information is reduced by making some events more likely to occur following other events, reaction time (RT) decreases.

The present study asks if processing capacity is required to use this type of sequential information. In the first two experiments, the time available for using sequential information is controlled by manipulating the time between the response to one stimulus and the onset of the next stimulus in a partially predictable sequence of stimuli. If processing capacity is required for predicting what stimulus is most likely to occur next, then reducing the time available for prediction should impair one's ability to use the sequential information. On the other hand, if utilizing sequential information requires little or no capacity, overlap should occur between processing the current stimulus and anticipating

the next. In a third experiment, the time for processing sequential information is reduced not only by a short interval between the response and stimulus, but also by adding a secondary task to further compete for processing capacity.

These experiments have general implications for theories of attention. Posner and Keele (1970) and Keele (1973) suggest that attention can be assessed by the degree of interference between tasks. Processes that do not interfere with other processes are said to require no attention. Thus, the overlap between anticipating a subsequent stimulus and processing the current stimulus will tell us whether or not anticipation requires attention. Posner and Boies (1971) used the interference technique to infer that nonspecific preparation generated by a warning signal is nonattentive. Here we ask whether or not anticipation of a specific event, which requires access to memory in order to determine what event is likely to occur next, requires attention. More generally, therefore, the present studies relate to the question of whether or not access to information stored in memory is an attention-demanding process.

EXPERIMENT I

The basic task was a serial RT task with four lights horizontally arranged and a finger-operated key beneath each light. Three different conditions of sequential dependency were: (1) *Equiprobable*. There were no sequential constraints between successive lights. (2) *High-Probability Sequential*. Sequential lights tended to follow each other in a partially predictable left-to-right order. (3) *High-Probability Repetition*. This condition was similar to the sequential case, except that there was a high probability of a light repeating rather than changing to another light. It was included because of suggestions (e.g., Kornblum, 1969) that repeated events are processed more efficiently than are other types of sequential events. Consequently, less capacity might be required to prepare for repeated events than for other event types.

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Fig. 1. Mean RT to correct responses as a function of the response stimulus interval (RSI), event type, and condition of sequential predictability (Experiment I).

The time available for using sequential information was manipulated by allowing 0, 125, 250, or 500 msec to elapse between the offset of a response to a light and the onset of the next light.

Method

Subjects

Thirty-six Ss recruited from the University of Oregon Student Employment Service were paid \$4.50 each for serving in three sessions on successive days.

Apparatus

The stimuli were four incandescent lamps each covered with a white lens cap and mounted on a horizontal straight line on a vertical display board. Adjacent lights were mounted with centers 1 in. apart. Beneath the lights were four Plexiglas keys that closed microswitches when depressed and that were operated by the middle and index fingers of the two hands. A correction procedure was used so that a light remained on until the correct key was depressed and released. The interval between the release of the key and the onset of the next stimulus was 0, 125, 250, or 500 msec. After a block of 75 stimuli, all with the same response stimulus interval (RSI), the mean RT and number of errors for the last 65 stimuli were presented to the S on an oscilloscope. Stimulus presentation, feedback, timing, and data collection were controlled by a PDP-9 computer.

Tasks

Twelve Ss were assigned randomly to each of three conditions. In the equiprobable condition, each light had a probability of .25 of following any other light. For the high-probability repetition group, there was a probability of .61 that a stimulus would repeat on the succeeding trial. The other three stimuli occurred with probabilities of .13 each. Over a long series of stimuli, therefore, each stimulus occurred about equally often, but the stimuli tended to occur in runs of the same light. If the lights were designated 1, 2, 3, and 4, from left to right, then in the high-probability sequential condition, there was a .61 probability that Light 2 would succeed Light 1. The other three lights had probabilities of .13. In a similar manner, Light 3 tended to follow 2, 4 tended to follow 3, and 1 tended to follow 4. Again, over a long sequence of lights, each stimulus occurred approximately the same number of times.

Each S performed on two sequences of 75 lights at each of the four RSIs on each of the 3 days. The order of the RSI conditions was balanced within Ss by means of an ABCD DCBA design in

each day and between Ss with 4 by 4 Latin squares. Following the eight blocks of 75 stimuli, blocks where more than five errors occurred were rerun.

Results and Discussion

Figure 1 presents the mean RTs for correct responses averaged over all Ss and over Days 2 and 3. Day 1 was considered practice and was excluded from the analysis. Although RT improved from Day 2 to Day 3, there were no interactions that would alter any conclusions. The only important interaction was a slight flattening of functions relating RT to RSI in the high-probability sequential condition, whereas the slope of the functions in the other two conditions remained about the same over days. This Day by Condition by RSI interaction is significant at the .05 level of confidence [$F(6,99) = 2.24$].

The events in each of the three conditions of sequential predictability are of three types. Some of the events are repetitions of the preceding event. Repetitions occurred with probabilities of .25, .61, and .13 in the equiprobable, high-probability repetition, and high-probability sequential conditions, respectively. A second event type is called sequential to denote cases where Light 2 followed 1, 3 followed 2, 4 followed 3, or 1 followed 4. Sequential events occurred with probabilities of .25, .13, and .61 in the respective conditions. Finally, the two possible events other than repeated or sequential events each occurred with probabilities of .25, .13, and .13 in the respective conditions.

The first point to notice is that one of the event types is responded to faster than the others in each condition of sequential predictability. Repeated events are responded to faster than other event types in both the equiprobable condition and the high-probability repetition condition, but in the high-probability sequential condition, sequential events are responded to fastest. This Condition by Event Type interaction is highly significant [$F(4,66) = 100.91, p < .001$].

The more important observation is this: The relative

advantage of the high-probability event over the other events in both the high-probability repetition and the high-probability sequential conditions is quite independent of the RSI. Even when no time elapses between the response to one light and the onset of the next, the high-probability event is responded to much faster than low-probability events. This lack of interaction is reflected in the statistically nonsignificant interaction between condition of sequential predictability, event type, and RSI [$F(12,198) = 1.042$]. The Event Type by RSI interaction is significant, however, reflecting the differently shaped function relating RSI and RT for repetitions than for the other event types [$F(6,198) = 2.98, p < .01$].

These results imply that anticipation for the most likely succeeding event occurs either at the same time as processing the current stimulus or during the response to the current stimulus. This is particularly clear when the high-probability event is a repetition. One problem with this interpretation for the high-probability sequential condition, however, is that RTs to all event types in that condition are relatively high at the 0-msec RSI.¹ Nevertheless, even at the shortest RSI, the RT to the high-probability sequential event is shorter than RTs in the equiprobable condition, supporting the contention that anticipation for the succeeding event did occur while processing and responding to the current event. Furthermore, this problem of high RTs at the shortest RSI in the high-probability sequential condition was not found in the next experiment.

A final observation in this experiment deals with the repetition effect. When repetitions occur with high probability, they are responded to faster than high-probability sequential events. This result confirms similar results of Umiltà, Snyder, and Snyder (1972), though those authors found the advantage of repetitions to disappear at an RSI exceeding 3 sec. However, when some event other than a repetition has a high probability, the RT to repetitions is little different than other low-probability events. This result supports other data (Keele, 1969; Schvaneveldt & Chase, 1969), indicating that the repetition effect is primarily an anticipatory phenomenon; when Ss have reason to anticipate some event other than a repetition, repetitions lose most or all of their advantage.

EXPERIMENT II

The first experiment presented evidence that sequential constraints improve performance as much when there is no delay between one response and the next stimulus as when there is a delay of as much as $\frac{1}{2}$ sec. In both of the sequential conditions, however, the sequencing was very simple, being either repetitive in nature or a simple left-to-right order. The second experiment was an exact replication of the high-probability sequential condition of the first experiment, except that it involved a more complex

Fig. 2. Mean RT to correct responses as a function of the response stimulus interval (RSI) and event type (Experiment II).

sequencing of events. This change was made to determine whether more difficult sequencing would be processed less well at very short RSIs.

Method

Subjects

A new group of 8 Ss was obtained from the University of Oregon Student Employment Service and paid \$4.50 for participating in three sessions.

Task

Exactly the same apparatus and procedure was used as in the high-probability sequential condition of the previous experiment, with one exception: The sequencing was changed. Designating the lights 1, 2, 3, and 4 from left to right, given that Light 1 had occurred, Light 3 had a .61 probability of occurring next. The other three lights, including a repetition of the preceding stimulus, each had probabilities of .13 of occurring next. Similarly, Light 2 followed 3 about 61% of the time, 4 tended to follow 2, and 1 tended to follow 4. It was expected that the sequencing 1 3 2 4 1 would be more difficult to process than the earlier sequencing 1 2 3 4 1.

Results and Discussion

Mean RTs for correct responses averaged over Days 2 and 3 are shown in Fig. 2. At all RSIs, the RT to the high-probability sequential events was faster than RTs to low-probability events. Low-probability repeated events were responded to only about 5-10 msec faster than other low-probability events. Although there was a slight tendency for RT to increase with decreasing RSI, the change was approximately the same for both high- and low-probability events so that the difference between the two conditions was maintained.

An analysis of variance confirmed these general observations. The effect of event types was significant at the .001 level [$F(2,14) = 20.96$], and RSI was significant at the .001 level [$F(3,21) = 10.94$]. However, the interaction of these two variables was nonsignificant ($F < 1$).

The results of the second experiment confirm those of the first experiment. Even though the sequencing is presumably more difficult in the present case, the sequential predictability is taken advantage of even when the succeeding signal occurred with no delay following termination of the preceding response. Apparently, the anticipation of a particular succeeding event can occur while the current signal is being processed. This experiment also confirms that repetitions are responded to little faster than low-probability nonrepetitions when there is reason to anticipate some other event.

EXPERIMENT III

In the first two experiments, the RSI was timed from the release of the response key to onset of the next stimulus. Thus, it may be argued that anticipation for a succeeding event occurred during the response phase and not during the preceding decision phase. Indeed, Ellis (in press) and Posner and Keele (1969) have shown that movements requiring no accuracy, as in the present case where the fingers rest on the keys, do not require attention. The movement phase is free for other processing activities. This experiment attempted to eliminate that explanation by two methods. First, the RSI was timed from the onset of the keypress to the current stimulus rather than from the offset of the keypress. The effect was to reduce further the time available for preparation. Second, a secondary task was added as a method for controlling spare processing capacity. If anticipating the high-probability events indeed requires processing capacity, then the addition of a secondary task should interfere with the anticipation, and consequently RT to highly predictable events should increase more than the less likely events. Earlier studies by Bahrick and Shelly (1958) and by Crowder (1967) found that a secondary task resulted in less interference rather than more interference with performance on predictable sequences than performance on random sequences. Crowder, however, compared random sequences of events with *perfectly* predictable sequences. It may be that with high degrees of learning, perfectly predictable sequences are responded to with unmonitored chains of responses. With only partial predictability, as in the present experiments, unmonitored responding would result in high error rates. Therefore, the results with partial predictability might differ from Crowder's results. In the Bahrick and Shelly study, successive signals occurred at *fixed* time intervals. To the extent that sequential dependencies reduced total processing time, residual time would be available for processing the secondary task. With the present procedure, when sequential dependencies reduce the time to respond, the next signal also occurs earlier, leaving no additional time for the secondary task.

Method

Subjects

Thirty Ss were obtained from the University of Oregon Student Employment Service and paid \$1.50 for each of two sessions. Fifteen of the Ss were assigned randomly to the high-probability sequential group and the others to the equiprobable group.

Apparatus and Tasks

The RT task was similar to that used in Experiments I and II, except that plus (+) marks which could appear at four different horizontal positions on an oscilloscope screen were used instead of incandescent lights. This change was made so that under memory load conditions, Ss would not have to shift their gaze from the place where letters for the memory task occurred to the place where the RT signals occurred.

The two RT conditions were identical to the equiprobable and high-probability sequential conditions of Experiment I. In the equiprobable condition, the probability of any stimulus following any other was .25. In the high-probability sequential condition, the signals tended to come on in left-to-right order with Signal 2 following Signal 1 with a probability of .61, 3 tending to follow 2, and so on. At the start of a sequence of signals, all four plus marks were illuminated. When S was ready, he pressed a start key, the four signals went off, and, when no memory load was presented, the first plus mark in the sequence came on. After the onset of a response, the signal went off and another signal appeared 50 msec later. The S continued pressing to the lights for a period of 20 sec.

For sequences involving a memory load, the four plus marks again signaled the start of a trial. Upon pressing the start key, the plus marks terminated and five letters were presented one at a time for 1 sec each. The letters were drawn randomly from the consonants of the alphabet with the restriction that no letter appear twice in a sequence of five letters. Immediately following offset of the fifth letter, the first RT signal appeared and the S then responded to the signals for 20 sec. The S then attempted to recall the five letters. Ss were instructed to rehearse the letters while responding on the keypressing task.

During the first session, each S was given 10 20-sec trials of practice on the RT task alone. He was then given 2 practice trials with both the letters to be recalled and the keypressing task. Finally, he was given 6 20-sec experimental trials under memory load conditions and 6 20-sec trials with no memory load. On Day 2, 2 warm-up trials without memory load and 2 warm-up trials with memory load were given. That was followed by 12 memory load trials and 12 no-memory load trials. On each day, memory load and no-memory load conditions were alternated from trial to trial. Half the Ss started on the memory load condition and half on the no-memory load condition.

Results and Discussion

Since Ss were instructed to rehearse the letters while keypressing, little difference would be expected between the equiprobable and high-probability sequential conditions on the memory task. Fifty-nine percent of the five-letter sequences were correctly recalled in the equiprobable condition and 72% in the high-probability sequential condition, a nonsignificant difference [$F(1,28) = 2.55$]. Using a more lenient scoring method of granting 1 point for each of the five letters recalled and 1 point for recalling a letter in the correct position,

Table 1
Mean Correct Reaction Time (Milliseconds) and Percent Errors

		Random			High Probability Sequential		
		Repetition p = .25	Sequential p = .25	Other p = .25	Repetition p = .13	Sequential p = .61	Other p = .13
No Memory Load	RT	286	329	359	356	270	360
	Errors	.7	4.1	5.8	3.5	1.1	10.4
Memory Load	RT	298	353	383	394	286	386
	Errors	.8	4.8	7.0	4.6	1.5	10.0

the mean recall was 8.7 points for the equiprobable case and 9.2 points for the high-probability sequential case. Again, the difference was nonsignificant [$F(1,28) = 2.12$].

Of greater interest is the effect of the secondary memory task on primary task performance. Table 1 shows the mean RT to correct responses, excluding the first response in a sequence, and the percentage of responses in error for repetitions, sequential events, and other events in the equiprobable and high-probability sequential condition.² The addition of the memory task caused a significant decrement in performance as measured by RT [$F(1,26) = 24.26$, $p < .001$]. Furthermore, the Condition by Event Type by Memory Load interaction was significant [$F(2,52) = 6.53$, $p < .005$], reflecting the fact that memory load was least detrimental to repetitions in the equiprobable condition and to sequential events in the high-probability sequential condition. A subsequent analysis only on the high-probability sequential condition confirmed the significant Memory Load by Event Type interaction [$F(2,26) = 3.52$, $p < .05$], indicating that memory load was less detrimental to the high-probability event.

Separate analyses of the proportions of key responses in error showed significant effects of event type, but neither the memory load variable nor the Memory Load by Event Type interaction reached significance at the .05 level.

Overall, the results of the third experiment support the conclusion from the first two experiments that using sequential information requires little or no processing capacity. The high-probability events in the sequential condition are still responded to faster and with fewer errors than less probable events, even when the subsequent event occurs only 50 msec after the onset of the preceding response. Furthermore, the addition of a memory load, while decreasing RT to all event types, has a smaller detrimental effect on high-probability events than on low-probability events.

IMPLICATIONS FOR THEORIES OF ATTENTION

A useful conception for the analysis of attention distinguishes the processing components that underlie task performance. In particular, Posner and Keele (1970) and Keele (1973) have suggested two components,

memory retrieval and subsequent operations. Memory retrieval involves the access of information stored in memory regarding a stimulus. The information may include the name of the stimulus, an appropriate response, or some other meaning. Once the information is elicited in memory, some operation can be made such as rehearsal of the name, initiation of the response, or some other operation. A number of sources of evidence (see Posner & Keele, 1970; Keele, 1973) suggest that the interference between two or more tasks arises not from the stage of memory retrieval, but rather in a subsequent stage of operation. For example, two stimuli that are redundant and yield the same response facilitate rapid responding, suggesting that the stimuli access memory in parallel (Biederman & Checkosky, 1970; Morton, 1969). When one of the stimuli is irrelevant to a response, it may not interfere unless its representation in memory leads to a conflicting response (Hintzman et al, 1972; Keele, 1972). The degree of interference in processing two nearly simultaneous and nonredundant signals depends more on the requirement for two responses than on the retrieval time for the information itself (Karlín & Kestenbaum, 1968; Keele, 1970; Schvaneveldt, 1969). Thus, memory retrieval is said to be a nonattentive process, while subsequent operations demand attention.

The present three studies provide further support for the idea that memory retrieval is nonattentive. When sequential dependencies are present, information stored in memory about a stimulus includes not only the response appropriate to that stimulus, but also information about what stimulus will most likely occur next. Apparently, information about the current response and information about the next stimulus can be retrieved from memory simultaneously and without apparent interference. Furthermore, such noninterference occurred in the present study in a highly speeded task where a subsequent stimulus followed immediately after the preceding response. Parallel access to memory appears not to require a discrete trial procedure with ample time between successive events to mobilize processing capacity.

REFERENCES

- Baehrick, H. P., & Shelly, C. Time sharing as an index of automatization. *Journal of Experimental Psychology*, 1958, 56, 288-293.
- Biederman, I., & Checkosky, S. F. Processing redundant

- information. *Journal of Experimental Psychology*, 1970, 83, 486-490.
- Crowder, R. G. Short-term memory for words with perceptual-motor interpolated activity. *Journal of Verbal Learning & Verbal Behavior*, 1967, 6, 753-761.
- Ells, J. G. An analysis of temporal and attentional aspects of movement control. *Journal of Experimental Psychology*, in press.
- Hershman, R. L., & Hillix, W. A. Data processing in typing: Typing rate as a function of kind of material and amount exposed. *Human Factors*, 1965, 7, 483-492.
- Hintzman, D. W., Carre, F. A., Eskridge, V. L., Owens, A. M., Shaff, S. S., & Sparks, M. E. "Stroop" effect: Input or output phenomenon? *Journal of Experimental Psychology*, 1972, 95, 458-459.
- Hyman, R. Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology*, 1953, 45, 188-196.
- Hyman, R., & Umiltà, C. The information hypothesis and non-repetitions. *Attention & Performance II*. *Acta Psychologica*, 1969, 30, 37-53.
- Karlin, L., & Kestenbaum, R. Effects of number of alternatives on the psychological refractory period. *Quarterly Journal of Experimental Psychology*, 1968, 20, 167-178.
- Keele, S. W. Repetition effect: A memory-dependent process. *Journal of Experimental Psychology*, 1969, 80, 243-248.
- Keele, S. W. Effects of input and output modes on decision time. *Journal of Experimental Psychology*, 1970, 85, 157-164.
- Keele, S. W. Attention demands of memory retrieval. *Journal of Experimental Psychology*, 1972, 93, 245-248.
- Keele, S. W. *Attention and human performance*. Pacific Palisades, Calif: Goodyear, 1973.
- Kornblum, S. Sequential determinants of information processing in serial and discrete choice reaction time. *Psychological Review*, 1969, 76, 113-131.
- Morton, J. The use of correlated stimulus information in card sorting. *Perception & Psychophysics*, 1964, 5, 374-376.
- Posner, M. I., & Boies, S. J. Components of attention. *Psychological Review*, 1971, 78, 391-408.
- Posner, M. I., & Keele, S. W. Attention demands of movements. *Proceedings of the XVIIth Congress of Applied Psychology*. Amsterdam: Zeitlinger, 1969.
- Posner, M. I., & Keele, S. W. Time and space as measures of mental operations. Paper presented at the 78th Annual Convention of the American Psychological Association, Miami, September 1970.
- Shaffer, L. H., & Hardwick, J. Typing performance as a function of text. *Quarterly Journal of Experimental Psychology*, 1968, 20, 360-369.
- Schvaneveldt, R. W. Effects of complexity in simultaneous reaction time tasks. *Journal of Experimental Psychology*, 1969, 81, 289-296.
- Schvaneveldt, R. W., & Chase, W. G. Sequential effects in choice reaction time. *Journal of Experimental Psychology*, 1969, 80, 1-8.
- Umiltà, C., Snyder, C., & Snyder, M. Repetition effect as a function of event uncertainty, response-stimulus interval, and rank order of the event. *Journal of Experimental Psychology*, 1972, 93, 320-326.
- Umiltà, C., & Trombini, G. La distribuzione delle probabilità degli stimoli come fattore determinante nei tempi di reazione a scelta multipla. *Rivista Di Psicologia*, 1968, Fascicola Speciale, 91-98.

NOTES

1. The Sequential Predictability by RSI interaction is significant at the .001 level of confidence [$F(6.99) = 7.79$].
2. Fourteen Ss from each condition rather than 15 were used in the analysis due to an error resulting in the loss of data from one of the Ss.

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