

The effect of first response complexity on the psychological refractory period: A reanalysis*

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The effect of first signal complexity on the delay of the second response within the paradigm of PRP has been the subject of several recent papers. The results show that, for the same interstimulus interval, the more complex the first reaction, the more the second response is delayed. This paper reports a reanalysis of the data presented by these investigators in terms of comparable response-stimulus intervals. The implications for theories of limited attention are discussed.

Man's limitations as an information transmitter are demonstrated by his inability to process two closely successive signals without delaying his response to the second one. This phenomenon, which is usually called the psychological refractory period (PRP), occasioned a great deal of experimentation and theorizing. Recently, interest has focused on one particular aspect of the phenomenon, namely, on the effect of the complexity of the first response on the delay of the second one. A number of papers have appeared (Bertelson, 1967; Broadbent & Gregory, 1967; Smith, 1967, 1969; Karlin & Kestenbaum, 1968) which reported that, for the same interstimulus interval (ISI) between the two stimuli, the more complex the first reaction, the more the second response is delayed. This mode of analysis of response times on the basis of comparable ISIs has recently been criticized as dissatisfactory, and alternative modes have been suggested (Kahneman, 1973; Tolkmitt, 1973).

This paper reports another such attempt of reinterpretation. The data reported by the above mentioned five papers will be reanalyzed, and the results examined for their implications to theories of limited attention.

Among the various interpretations of the PRP effect are three different theories which postulate a limit on the capacity of the central information processing mechanisms. The oldest one is the "single channel" theory of Welford (1952) and Davis (1956). According to this theory, the locus of the limitation is in the response selection mechanism, which is unable to process a second signal while still concerned with the current response. This theory predicts that, when two signals come in close succession, the second reaction time is lengthened at least by the amount of time which separates the presentation of the second signal from the completion of the first response (RSI: response-stimulus interval).

According to the theory, the "single channel" is completely occupied by whatever signal passes it. Consequently, the crucial variable for the amount of delay of the second reaction is not the complexity of

either task but the length of the "waiting interval" (RSI). The theory predicts, therefore, equal delay of the second response whatever the complexity of the first response, if the delay of RT_2 is plotted as a function of the interval between the second signal and the first response (RSI). The possible equality of delays is obscured if RT_2 is plotted as the function of interstimulus interval. For first responses of different length, a given ISI represents "waiting intervals" of different length: The longer the first reaction, the longer the waiting interval. Therefore, the delays in RT_2 are expected (and found) to be a monotonic function of first task difficulty for any given ISI. The equality hypothesis can be tested only if the delays are plotted as a function of RSI ("waiting time") for the different first reactions. This analysis has not been carried out in any of the papers reporting effects of first response complexity on RT_2 .

A different theory of limited capacity is advocated by Moray (1967) and by Kahneman (1973). According to this view, the sharing of attention between different signals is possible if the attention demands of both do not overload the capacity of the system. The more capacity is invested in one of the responses, the less is available for the preparation of the other one. Both authors claim that most, if not all, processing is performed by limited capacity mechanisms; therefore, one can increase the attentional demands of a response in a number of ways: by making stimulus encoding more difficult, by increasing the complexity of response selection, and by making response organization more difficult.

Within the framework of Kahneman's (1973) effort theory, the claim that one task demands more attention than another may have two different meanings. The theory postulates that the amount of capacity invested in a response varies continuously with momentary changes in the demands of the task. Therefore, it is meaningful to differentiate between the total capacity demand of a task that is necessary for its successful completion and the momentary rate of expenditure of effort in various stages of that task. Effort theory would predict that, apart from an unquestionable increase in

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total demands, tasks of increasing complexity increase also in the rate of expenditure of effort, at least in the relevant substages affected by the manipulation of complexity. This prediction is difficult to test by most paradigms of simultaneous performance, because the measures used are sensitive only to the total demands of the measured tasks, not to the momentary rate of expenditure. As expected, total capacity demand increases with complexity in a great variety of tasks (Mowbray, 1953; Michon, 1964; Posner & Rossman, 1965; Keele, 1967; Baddeley, 1966; Shulman & Greenberg, 1971), but this result leaves open the question of whether or not the momentary rate increases.

Within the PRP paradigm, this question can be answered. Once again the critical variable is the length of the interval between the second signal and the first response. During this interval, the two successive tasks have to compete for the limited capacity of the system. If tasks differ on the rate of expenditure of effort, then the more complex task should demand more capacity than the other during equal intervals of any given length. Therefore, for a given interval between second signal and first response, the second response should be more delayed if the first task is a more complex one.

A variation capacity-sharing theory is held by Posner and colleagues (Posner & Keele, 1970; Posner & Boies, 1971; Posner & Klein, 1971) and by Keele (1970, 1973). In this view, stimulus encoding, memory retrieval, stimulus categorization, and even response selection do not require access to the limited capacity mechanisms, while rehearsal, complex transformations of the stimulus, and response initiation do require attention. Thus, it should be possible to manipulate the difficulty of a task (as measured by its latency) without increasing its attentional requirements, if the increase in complexity occurs in one of the earlier stages of processing.

Although Posner and Keele agree on which task components demand attention, Keele's position is more radical on the question of capacity sharing. While Posner maintains that the possibility of time sharing is a matter of degree, rather than all-or-none, Keele claims that only one attention-demanding operation can be performed at the same time (Keele, 1973). In addition, Keele claims that within the paradigm of PRP the locus of interference between the two successive responses is in the response initiation stage, so that "the delay in responding to the second of two signals depends on the amount of time that has elapsed since the first response. Apparently, some minimum time must pass after the initiation of one response and before another mental operation can occur [Keele, 1973, p. 138]." This view entails not only the nonoverlap of response initiation processes but also the existence of a sort of refractory phase for the duration of the minimal interresponse interval (about 200 msec) found in some experiments.

By both of these claims, Keele's theory is a new version of single-channel theory rather than a capacity-sharing theory.

There is a fundamental difference between single-channel and capacity-sharing theories regarding the slope they predict for the PRP function (RT_2 as a function of ISI). The single-channel theories (those of Welford and Keele) predict slopes of either -45 or 0 deg, depending on whether or not the first response occupies the single channel. On the other hand, the capacity-sharing theories of Kahneman and Posner predict slopes between -45 and 0 deg, depending on the amount of time sharing during the processing of the first signal.

The evidence generally favors the capacity-sharing theories: In most PRP experiments, including those reviewed here, the slopes were markedly less steep than -45 deg at small ISIs and more than 0 deg at large ISIs (Burns & Moskovitch, 1971; Borger, 1963; Nickerson, 1967; Bernstein, Blake, & Hughes, 1968; Bertelson, 1967; Broadbent & Gregory, 1967). The best fitting curve usually has a negative exponential function. Because of this evidence, capacity sharing is considered possible in the present paper. The main point on which evidence is sought is whether all manipulations increasing the latency of a task also increase the momentary demand of effort of the task.

REANALYSIS OF DATA FROM SIX EXPERIMENTS

Karlin and Kestenbaum, 1968

In this study, the complexity of the first response (R_1) was manipulated by varying the number of alternatives from one to two to five. The number of

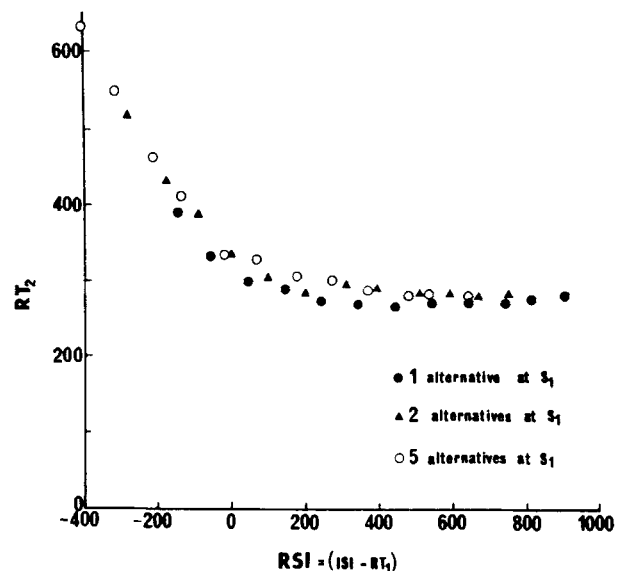


Fig. 1. Two-choice RT_2 as a function of RSI and the number of alternatives at R_1 . (Based on Karlin and Kestenbaum, 1968, Table 1.)

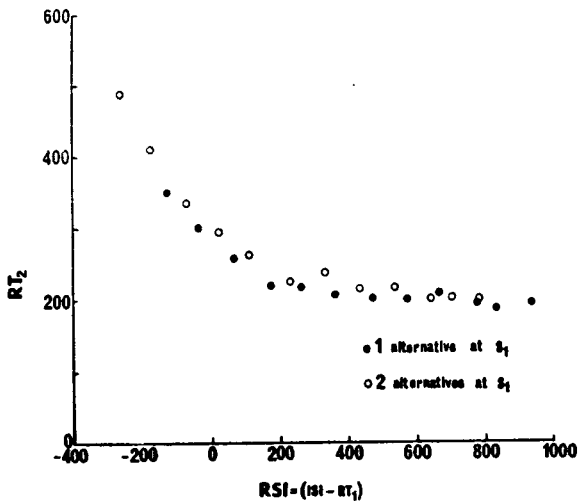


Fig. 2. Simple RT_2 as a function of RSI and the number of alternatives at R_1 . (Based on Karlin and Kestenbaum, 1968, Table 4.)

alternatives in the second response (R_2) was kept constant at two. All conditions appear in Fig. 1, in which RT_2 is plotted as the function of RSI (the interval between the first response and the second stimulus).

As can be seen from Fig. 1, the delay of R_2 is invariant in respect to the number of alternatives in R_1 .

In two additional conditions in the same study, the second reaction was kept at a constant of one alternative and the number of alternatives at R_1 was varied from one to two. The two conditions appear in Fig. 2.

When RT_2 is a single reaction, there is a slight difference of about 20 msec between the two conditions for values of RSI smaller than zero. As the difference between the two first reactions is about 140 msec, a difference in R_2 of 20 msec seems negligible.

The data allow asking an additional question: How

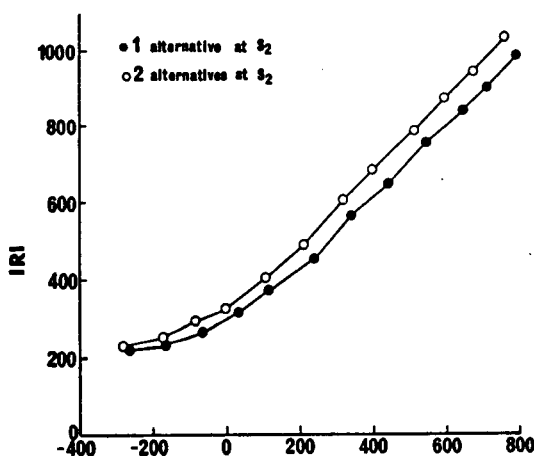


Fig. 4. The interval between first and second response (IRI) as a function of RSI and the number of alternatives at R_2 . (Based on Karlin and Kestenbaum, 1968, Tables 1 and 4.)

does the complexity of R_2 affect the delays in R_2 for the same first reaction? It is possible to plot the delay¹ in RT_2 as a function of number of alternatives in R_2 and RSI. The two conditions compared are one or two alternatives in R_2 with two alternatives in R_1 in both cases. Figure 3 presents this data.

The prediction for this comparison is the same by all three theories as to the effect of manipulation of R_1 on R_2 . According to the single-channel theories, neither the complexity of the first response nor that of the second response should affect the delay in R_2 for a given waiting interval. According to Kahneman's effort theory, any increase in the complexity of either task should make time sharing more difficult and, therefore, cause a larger delay in R_2 . Lastly, memory retrieval is attention free, according to Posner, and, therefore, the manipulation of the number of alternative signals (either in S_1 or in S_2) should not affect the delay in R_2 .

Figure 3 shows that there is a substantial difference

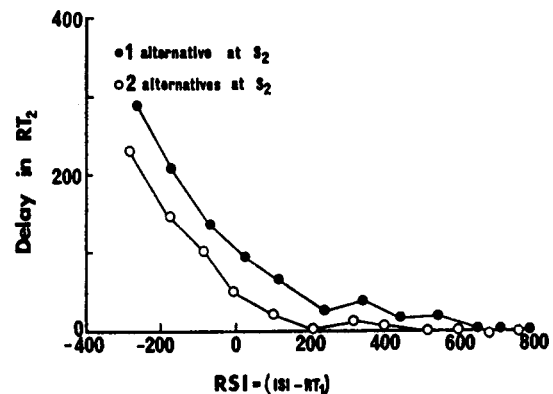


Fig. 3. The delay in RT_2 as a function of RSI and the number of alternatives at R_2 . (Based on Karlin and Kestenbaum, 1968, Tables 1 and 4.)

between the delays in the two conditions: The easier condition is more delayed by about 50 msec for the first part of the curve. It seems that, while the number of alternatives at R_1 has no effect or only a very small one on the delay of R_2 , the same is not true of the effect of the number of alternatives in R_2 , where an increase in the number of alternatives brings about an apparent facilitation in the PRP effect.

An alternative way of presenting the data of Fig. 3 is to plot the interval between the first and second response (IRI) as a function of RSI. This is presented in Fig. 4.

For a given RSI, the interresponse interval should be greater for the longer second response. In fact, the two functions have the same value for RSI of about -300 msec, and they become more and more differentiated only as the overlap between R_1 and R_2 decreases. The equality of the minimal IRI for the two conditions in R_2 is considered by Keele (1973) a piece

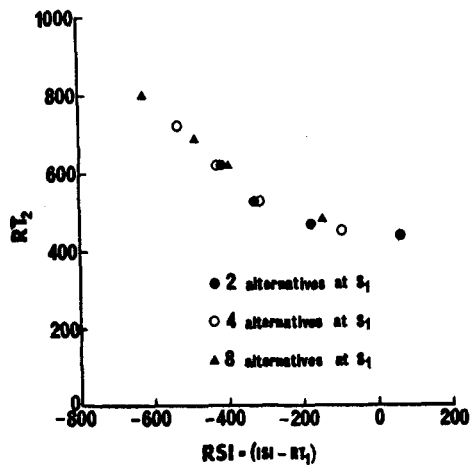


Fig. 5. RT_2 as a function of RSI and the number of alternatives at R_1 . (Based on Smith, 1969, Figs. 1 and 2.)

of conclusive evidence for the existence of a refractory phase following response initiation, independent of stimulus complexity. However, two features of the data seem to contradict such an explanation. In the first place, the slope of the PRP functions is less than -45° even at the steepest part of the curves: This implies that some capacity is shared by the two reactions for the whole length of the latency of R_1 . By a refractoriness theory, time sharing should not be possible. Although, according to Keele, some early stages of processing are effortless and therefore can be performed concurrently with a second task, this sort of time sharing involves no capacity sharing and, thus, cannot be manifested in an intermediate slope. In any case, the existence of a refractory phase following the initiation of R_1 should in theory cause the emergence of a slope of -45° for any R_2 that should have been initiated during the refractory phase. In this study, a slope of -45° is expected for RSIs between -300 and 0 msec, but in fact the slope for this interval is between -35 and 3° .

In the second place, inspection of Fig. 3 and Fig. 4 reveals that the relatively greater interference with the simple second reaction still appears at RSI of about 200 msec, that is, when S_2 appears 200 msec after the initiation of R_1 . To explain this effect by a refractory phase following R_1 , one should postulate such a phase to last 400 msec or more, while the minimal interresponse interval in this experiment (and others) is only about 200 msec. Nevertheless, even at $RSI = 200$ msec, the simple R_2 is more delayed than a two-choice response. Although this finding must be considered deviant by a capacity-sharing theory, the data do not support Keele's contention that response selection is effortless and only response initiation demands processing capacity.

In conclusion, the Karlin and Kestenbaum (1968) study showed that the number of alternatives at R_1 has

no effect or only a very small one on the delay of R_2 . On the other hand, increasing the number of alternatives at R_2 decreases the delay of that response.

Smith, 1969

This study may be considered a replication of a part of the Karlin and Kestenbaum (1968) study. In this paper the complexity of R_1 was varied by varying the number of alternatives from two to four to eight. The second reaction was always a two-alternative choice. Figure 5 presents RT_2 as the function of RSI (interval between S_2 and R_1) and first response complexity.

As can be seen from Fig. 5, there is no difference between the delay of RT_2 in the three conditions of R_1 , replicating the findings of the Karlin and Kestenbaum (1968) study.

Broadbent and Gregory, 1967

Two different experimental variations in R_1 are reported in this paper. In the first one, the stimulus-response compatibility was varied at the same time both at R_1 and R_2 . In the compatible condition, Ss responded to each signal by depressing a key immediately below an illuminated lamp. In the incompatible condition, Ss responded by depressing, not the key immediately below the signal light, but the key below the other, unlighted lamp. There were two stimulus alternatives both at S_1 and S_2 . Figure 6 presents the delay in RT_2 as a function of RSI for the two conditions.

The two curves in Fig. 6 diverge for values of RSI smaller than 150 msec. At RSIs greater than 150 msec, no difference is observed between the curves. This finding implies that (a) the compatibility of the stimulus-response arrangement affects the delay in RT_2 and (b) the effect is not restricted to any particular substage in processing but is more or less uniform across the whole latency of the response.

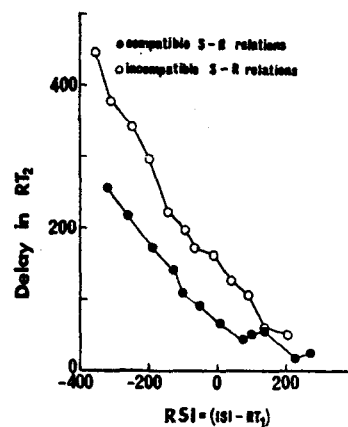


Fig. 6. The delay in RT_2 as a function of RSI and the stimulus-response compatibility in R_1 . (Based on Broadbent and Gregory, 1968, Figs. 1 and 3.)

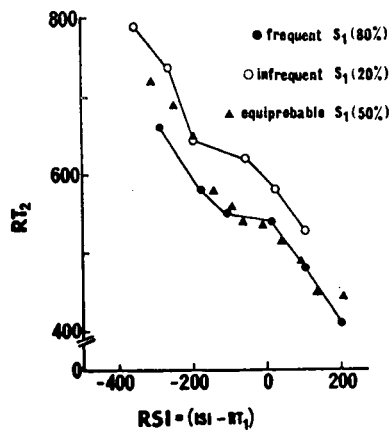


Fig. 7. RT_2 as a function of RSI and first signal probability. (Based on Broadbent and Gregory, 1968, Figs. 3 and 4.)

In the second experiment relevant to this paper, the difficulty of the first reaction was varied by unequal signal probabilities: One of the signals appeared 80% of the time. The alternative signals at S_2 had equal probabilities. This manipulation usually shortens the latency of the more probable signal and lengthens the latency of the other one. Figure 7 depicts the effect of this manipulation on RT_2 . In this experiment an incompatible arrangement was used.

First signal probability is found to affect the delay in RT_2 for all values of RSI studied. At RSI of 100 msec there is still a greater delay for the less frequent first signal. Figure 7 also shows the data from the incompatible condition of the previous arrangement. In that case, the two alternative signals were equiprobable both at S_1 and S_2 . The rather interesting finding is that for values of RSI of -200 msec or less the equiprobable first signal causes about the same delay in RT_2 as an infrequent (20%) first signal. For values of RSI of 150 msec or more, the delays are equal to that caused by a frequent (80%) first signal. This finding is difficult to explain; the answer lies somewhere in the different mechanisms that are affected by the bias in the first signal probability. Welford (1960), for example, suggested that during the stimulus categorization stage the S first makes those tests for which positive answers are consistent with the most probable stimulus. In another version of this view, Bertelson (1963) made the assumption that the first test made on a stimulus determines whether it is identical to the preceding one. If it is identical, it can be categorized with one test. A new stimulus would have to be categorized with a greater number of tests required for its complete classification. A similar view is held by Tversky (1968) and by Lindsay and Lindsay (1966). Thus, with low values of RSI, presumably the overlap between the first and second reaction includes also the stimulus categorization stage of the *first* reaction, in which a frequent stimulus should demand less effort than either

an equiprobable or an infrequent one. On the other hand, reaction-time theories cannot explain why, in the last 150 msec of processing, it is as easy to process an equiprobable stimulus as a frequent one, while an infrequent stimulus demands more effort than either. This finding implies that stimulus frequency affects not only the stimulus categorization stage but also response selection and organization.² It remains still unexplained why equiprobable signals have a privileged position at the latter but not at the former stage.

Bertelson, 1967

The relevant data from Bertelson's study concerns the effect of the finger used in the first reaction on the delay of the second one. Responses made with the index finger are faster by about 25 msec than responses made by the middle finger. Figure 8 presents RT_2 as a function of RSI and the finger with which the first reaction was made.

No effect of first response difficulty on RT_2 is found by this analysis. It seems that organizing the more difficult response does not demand more effort than organizing the simpler response, although it takes more time.

Smith, 1967

In this paper the difficulty of R_1 was manipulated by varying the intensity of S_1 in a simple reaction task. R_1 to a dim light was slower by about 35 msec than reaction to a bright light. The second stimulus was in both conditions a bright light. Figure 9 presents RT_2 as a function of RSI and the intensity of S_1 .

The intensity of S_1 did not affect the delay of RT_2 .

DISCUSSION

One thing that emerges clearly from the preceding discussion is that the PRP effect is sensitive to the differing attentional demands of the different tasks if the data are presented as a function of the overlap between the two successive tasks.

Different manipulations of first (and second) task complexity, which all influence the latency of the

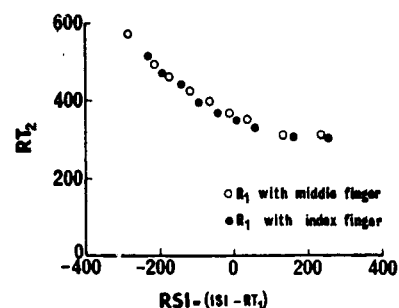


Fig. 8. RT_2 as a function of RSI and the finger used for R_1 . (Based on Bertelson, 1967, Fig. 5.)

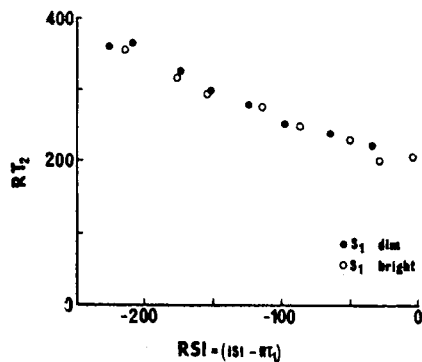


Fig. 9. RT_2 as a function of RSI and the intensity of S_1 . (Based on Smith, 1967, Table 2.)

response, have different effects on the attentional demands of the tasks. Increasing the number of alternative signals or responses does not seem to increase the momentary attentional demands of the task as well; neither do stimulus intensity and the difficulty of the motor task have any effect on the attentional demands. On the other hand, stimulus-response compatibility and signal probability do influence the capacity demands of the task, and the data imply that the mechanisms which demand this additional capacity are probably quite different in the different conditions.

The single-channel theory of Welford (1952) does not fare well in view of the findings discussed here. Evidence against strictly serial processing emerges from all of the experiments discussed here. In addition, this theory cannot be reconciled with the finding that, for the same waiting interval, different delays can be observed as a function of stimulus-response compatibility or signal probability.

The fact that increasing the number of alternative signals or responses at R_1 does not increase the momentary capacity demands of the task does not necessarily imply that stimulus encoding and response selection are completely effortless, as suggested by Posner (Posner & Klein, 1971) and by Keele (1973). In the first place, it is possible to manipulate the difficulty of the processes by other means, such as varying the relative frequency of a signal or the S-R compatibility, and these manipulations do influence the capacity demands as well. In the second place, it may be possible for a mental act to require a constant rate of effort within a considerable range of difficulty. The fact that the investment of effort does not change with manipulation of difficulty does not logically imply that the process does not demand attention at all.

Nevertheless, some of the findings discussed here pose difficulties to Kahneman's (1973) general effort theory. The fact that the difficulty of either signal categorization or motor response may not influence momentary effort cannot be reconciled with the theory as it is presently formulated. A modified theory should

be able to state in which cases it is expected that the increasing difficulty of a task merely increases total effort but not the momentary rate of expenditure. A possible characteristic of these cases may be that the increase in complexity is dealt with by the insertion of additional substages into the stream of processing, without changing the previously active ones. This explanation of the diverging results is necessarily of an ad hoc character, but none of the theories discussed here can, without some such addition, predict or explain all the findings.

REFERENCES

- Baddeley, A. D. The capacity for generating information by randomization. *Quarterly Journal of Experimental Psychology*, 1966, 18, 119-129.
- Bernstein, I. H., Blake, R. R., & Hughes, M. H. Effects of time and event uncertainty upon the psychological refractory period. *Perception & Psychophysics*, 1968, 3, 177-184.
- Bertelson, P. S-R relationships and reaction times to new versus repeated signals in a serial task. *Journal of Experimental Psychology*, 1963, 65, 478-484.
- Bertelson, P. The refractory period of choice reactions with regular and irregular interstimuli intervals. *Acta Psychologica*, 1967, 27, 45-56.
- Borger, R. The refractory period and serial choice reactions. *Quarterly Journal of Experimental Psychology*, 1963, 15, 1-12.
- Broadbent, D. E., & Gregory, M. Psychological refractory period and the length of time to make a decision. *Proceedings of the Royal Society*, 1967, 168, 181-193.
- Burns, M. M., & Moskovich, H. Response time to a first signal as a function of time relationship to a second signal and mode of presentation. *Perceptual & Motor Skills*, 1971, 32, 811-816.
- Davis, R. The limits of "psychological refractory" period. *Quarterly Journal of Experimental Psychology*, 1956, 8, 24-38.
- Kahneman, D. *Attention and effort*. London: Prentice-Hall, 1973.
- 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. Compatibility and time-sharing in serial reaction-time. *Journal of Experimental Psychology*, 1967, 75, 529-539.
- Keele, S. W. Effects of input and output modes on decision time. *Journal of Experimental Psychology*, 1970, 85, 157-164.
- Keele, S. W. *Attention and human performance*. New York: Goodyear, 1973.
- Lindsay, R. K., & Lindsay, J. M. Reaction time and serial vs parallel information processing. *Journal of Experimental Psychology*, 1966, 71, 294-303.
- Michon, J. A. A note on the measurement of perceptual motor load. *Ergonomics*, 1964, 7, 461-463.
- Moray, N. Where is capacity limited? A survey and a model. *Acta Psychologica*, 1967, 27, 84-92.
- Mowbray, G. H. Simultaneous vision and audition: The comprehension of prose passages with varying levels of difficulty. *Journal of Experimental Psychology*, 1953, 46, 365-372.
- Nickerson, R. S. Psychological refractory phase and the functional significance of signals. *Journal of Experimental Psychology*, 1967, 73, 303-312.
- Posner, M. I., & Boies, S. J. Components of attention. *Psychological Review*, 1971, 78, 391-408.
- Posner, M. I., & Keele, S. W. Time and space as measures of mental operations. Invited address, Division 3, American Psychological Association, September 1970.
- Posner, M. I., & Klein, R. On the functions of consciousness. In S. Kornblum (Ed.), *Attention and performance IV*. New York: Academic Press, 1972.
- Posner, M. I., & Rossman, E. Effect of size and location of informational transforms upon short-term retention. *Journal of Experimental Psychology*, 1965, 70, 496-505.
- Sanders, A. F. Some variables affecting the relation between relative stimulus frequency and choice reaction time. In A. F. Sanders (Ed.), *Attention and performance III*. Amsterdam: North Holland, 1970.
- Shulman, H. G., & Greenberg, S. N. Perceptual deficit due to division of attention between memory and perception. *Journal of Experimental Psychology*, 1971, 88, 171-176.

- Smith, M. C. Reaction time to a second stimulus as a function of intensity of the first stimulus. *Quarterly Journal of Experimental Psychology*, 1967, 19, 125-132.
- Smith, M. C. The effect of varying information on the psychological refractory period. In W. G. Koster (Ed.), *Attention and performance II*. Amsterdam: North Holland, 1969. Pp. 220-231.
- Tolkmitt, F. J. A revision of the psychological refractory period. *Acta Psychologica*, 1973, 37, 139-154.
- Tversky, B. G. *Pictorial and verbal encoding in short-term memory*. Technical Report No. 10. Ann Arbor: Human Performance Center, University of Michigan, 1968.
- Welford, A. T. The "psychological refractory period" and the timing of high speed performance: A review and a theory. *British Journal of Psychology*, 1952, 43, 2-19.
- Welford, A. T. The measurement of sensory-motor performance:

Survey and reappraisal of twelve years' progress. *Ergonomics*, 1960, 3, 189-230.

NOTES

1. The delay in RT_2 was calculated as the deviation from the mean asymptotic value for the two conditions. These were 195 msec for a simple R_2 and 270 msec for a two-choice R_2 .
2. A similar conclusion is drawn by Sanders (1970) from the fact that stimulus probability and S-R compatibility interact on their effect on RT.

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