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# RELATION BETWEEN THE IMMEDIATE MEMORY SPAN AND THE MEMORY SEARCH RATE[1]

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A comparison of memory span and item recognition data across several classes of stimuli shows that the time to search through a full memory (i.e., the number of items stored equals the memory span) in the item recognition task is a constant one-quarter of a second, regardless of material.

It has long been known that the span of immediate memory depends on the type of material tested (Jacobs, 1887); similarly, Sternberg (1969) has shown that the rate at which items are processed in memory in the item recognition task varies with the type of stimulus. To date, no comparison has been made between these two paradigms, perhaps because of their differences—the former is a recall task involving an error criterion and the latter a recognition task involving latency data.

Freund, Brelsford, and Atkinson (1969), however, have recently given evidence that differences in retrieval processes are sufficient to account for the differences between recall and recognition error performance. Furthermore, reaction time experiments comparing context recall and context recognition (Sternberg, 1969) indicate that the memory search processes in both tasks are identical. Thus, both error and latency measurements have supported the hypothesis that recall and recognition may use a common memory and store equivalent information. If this is the case, span and processing rate are both measures of the same memory system, and a comparison of the two across stimulus classes should point to important properties of the system.

Memory span has been measured by a great variety of methods (cf. Blankenship, 1938); generally, the task involves the presentation of increasingly longer lists of items, with the longest to achieve a certain error criterion in ordered recall being reported as the span. The span therefore can be considered a measure of the storage capacity of short-term memory for the class of material being tested.

The measurement of the memory processing rate has followed a more consistent procedure: subspan lists of varying length are memorized; a test item is then presented and classified as positive (a member of the memorized set) or negative (not a member). The dependent variable is the response latency from the presentation of the test item to the execution of the classification response; the independent variable is the length of the memorized list. In general, a linear relation has been found between these two variables (Sternberg, 1969). The slope of this relation thus estimates the processing rate (in milliseconds per item) for the class of stimuli being tested. No differentiation will be made between the two common variations in procedure (fixed vs. varied set) as both have been shown to give equivalent results and so presumably involve a common memory (i.e., short-term memory; Sternberg, 1969). Only a few of the studies reported here demonstrate significantly nonlinear relations (Egeth & Smith, 1967; Nickerson, 1966; Smith, 1967). In these cases, linear regressions estimate average processing rates, none of which differ markedly from others in the same stimulus class.

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TABLE 1

Processing Rate and Memory Span and Corresponding Studies for Various Stimulus Classes

| Stimulus class | Processing rate[a] | Memory span[b] |
|---|---|---|
| Digits | 35 (Bracey, 1969) | 8.0 (Brener, 1940) |
| | 27 (Burrows & Okada, 1971) | 8.2 (Gates, 1916) |
| | 30 (Cruse & Clifton, 1971) | 7.3 (Kinsbourne & Cohen, 1971) |
| | 38 (Sternberg, 1966) | 7.7 (Olsson & Furth, 1966) |
| | 39 (Sternberg, 1967) | 7.3 (Watkins, 1914)[c] |
| | 36 (Sternberg, 1969) | |
| | 28 (Theios, Smith, Haviland, & Traupmann, 1971) | |
| | 34 (Yio & Santa, 1970) | |
| *M* | 33.4 | 7.70 |
| Colors | 38 (Checkosky, 1971)[d] | 7.1 (Brener, 1940) |
| *M* | 38.0 | 7.10 |
| Letters | 29 (Cavanagh & Chase, 1971) | 7.3 (Brener, 1950) |
| | 44 (Chase & Calfee, 1969) | 5.4 (Kinsbourne & Cohen, 1971) |
| | 53 (Chase & Posner, 1965) | |
| | 43 (Cruse & Clifton, 1971) | |
| | 41 (Ellis & Chase, 1971) | |
| | 24 (Egeth & Smith, 1967) | |
| | 42 (Forrin & Morin, 1969) | |
| | 33 (Klatzky & Atkinson, 1971) | |
| | 44 (Klatzky, Juola, & Atkinson, 1971) | |
| | 65 (Nickerson, 1966) | |
| | 26 (Williams, 1971) | |
| | 38 (Wimberly, 1968) | |
| | 39 (Yio & Santa, 1970) | |
| *M* | 40.2 | 6.35 |
| Words | 52 (Burrows & Okada, 1972) | 5.5 (Brener, 1940) |
| | 50 (Goldring, 1968) | |
| | 36 (Juola & Atkinson, 1971) | |
| | 50 (Smith, 1967) | |
| *M* | 47.0 | 5.50 |
| Geometrical shapes | 50 (Checkosky, 1970) | 5.3 (Brener, 1940) |
| *M* | 50.0 | 5.30 |
| Random forms | 92 (Bashark, 1968) | 3.8 (Olsson & Furth, 1966) |
| | 42 (Briggs & Blaha, 1969) | |
| | 45 (Sternberg, 1969) | |
| | 93 (Swanson, Johnsen, & Briggs 1972) | |
| *M* | 68.0 | 3.80 |
| Nonsense syllables | 73 (Checkosky & Checkosky, 1972) | 2.5 (Brener, 1940) |
| | | 4.3 (Watkins, 1914)[c] |
| *M* | 73.0 | 3.40 |

[a] Milliseconds per item.
[b] Items.
[c] Based on 50% correct recall; values reported in study are based on 60% correct recall.
[d] Practice effect is reversed in color condition (shape filtering) of Checkosky's (1970) study; processing rates in Session 3 are greater than in Session 2. For this reason, Sessions 2 and 3 are averaged to obtain better reliability.

To compare the measures of the two tasks, a search of the memory span and memory search literature was conducted according to criteria that are described shortly. Seven classes of stimuli were found for which both measures were available: the digits 0 through 9; colors; the letters of the alphabet; familiar words; geometrical shapes such as

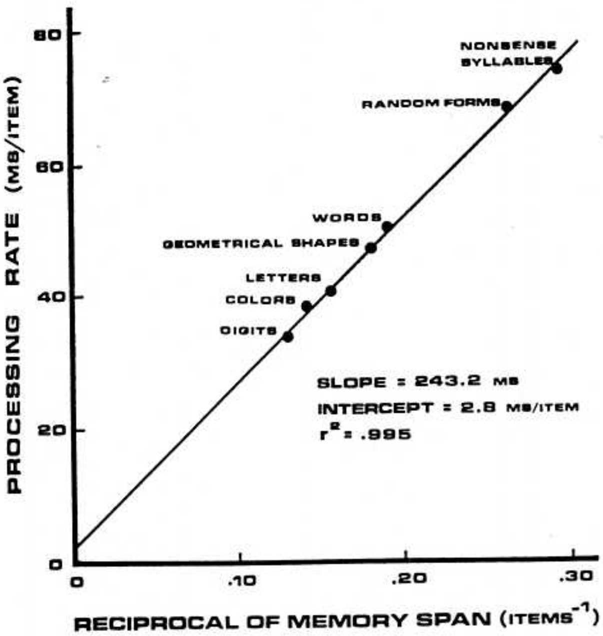

FIG. 1. The relation between short-term memory-processing rate and the reciprocal of the memory span for seven classes of stimuli (ms = millisecond).

squares, circles, and triangles; random forms—polygons of low associational value; and nonsense syllables (consonant-vowel-consonant).

The results are shown in Table 1. An inverse relationship is evident in the average values for the stimulus classes—the greater the memory span, the faster the processing rate. To determine the exact form of this relation, the mean values of processing rates are plotted, in Figure 1, against the reciprocals of the mean memory spans. The least squares linear fit accounts for 99.5% of the variance with a root mean standard deviation of 1.02 milliseconds/item ($df = 5$); the slope of the regression line is 243.2 milliseconds, and the intercept does not differ significantly from zero.

The data thus show a reciprocal relation between processing rate and memory span. The procedure for collecting the data attempted to rule out any confounding effects that might have arisen. In both paradigms, only results for adults were included. Since insufficient data on auditory item recognition are available, both memory span and item recognition studies were limited to visual modality. The items to be memorized could be presented either successively or simultaneously. The average exposure time per item in the studies selected was of the same magnitude (1–2 seconds) for both tasks. Reported memory span was the length of the longest list recalled correctly 50% of the time; although the method of scoring and the mode of recall—verbal, written, ordered selection from a large pool—varied between studies, the memory span values are not greatly affected by such variations (cf. Guilford & Dallenbach, 1925). Memory processing rates were estimated from the slope of the least squares linear relation between reaction time (averaged over positive and negative responses) and the length of the memorized list. Since the amount of practice given in memory span tasks is generally small, processing rate data were limited to the first two sessions of each study, where possible. Finally, since Klatzky, Juola, and Atkinson (1971) have shown that mixed presentation of test stimulus conditions results in processing that is markedly different from that found when a test stimulus type remains constant over a long series of trials, recognition studies were not accepted if any factors (modality, size, upper vs. lower case, etc.) other than list length or response type (positive or negative) varied within experimental blocks.

Although the criteria restrict the number of studies that can be drawn upon, the equating of experimental conditions and modality for the two tasks ensures an accurate determination of the memory span–processing rate relation. Since only group data are available in the literature, it is not possible at present to ascertain the degree to which the reciprocal relation holds for individual subjects. An appropriate within-subjects design might not only extend the results demonstrated here but might also indicate that the between-subjects variance in the two measures within stimulus classes is substantially accounted for by their reciprocal relation.

There are a number of theories that may predict this reciprocal relationship given suitable assumptions. The simplest of these might be termed the "size" hypothesis. According to this approach, the representation of a stimulus in memory is composed of a list of features. Short-term memory, with a constant, limited amount of available "space," can hold only a fixed number of features—$T$. The number of lists of features, that is, stimuli, of a particular class, $c$, that can be stored—$N(c)$—therefore depends on the number of features per list or the "size" of the representation—$s(c)$. The memory span, $N(c)$, is thus a measure of this size—the greater the mean number of features per stimulus, the fewer stimuli will fit in memory:

$$N(c) \cdot s(c) = T. \qquad [1]$$

Stimulus size is therefore inversely related to memory capacity as estimated by memory span:

$$s(c) = \frac{T}{N(c)}. \qquad [2]$$

If recognition involves serial testing of features (i.e., the test stimulus is compared feature by feature against each stored stimulus) and the time per feature test—$t$—is a constant, then the processing time per item for stimulus class $c$—$b(c)$—will be directly proportional to the number of features per item:

$$b(c) = s(c) \cdot t \qquad [3]$$

$$b(c) = \frac{T \cdot t}{N(c)}. \qquad [4]$$

The processing rate is thus inversely related to the memory span. Notice that an exhaustive search procedure similar to that described by Sternberg (1966) is necessary if this memory system is to be compatible with the data of the item recognition task.

A second hypothesis is based on the decay of memory traces. Mackworth (1963) has shown that the duration of report from a brief visual display is a constant 1 to 2 seconds, regardless of material. She concluded that this duration reflects the decay of the visual image and, therefore, that the number of items reported depends on the rate at which they can be identified. In a similar manner, this second hypothesis assumes that the duration of report from immediate memory when recalling a list of length equal to the memory span is also a constant—$d$—representing the decay time of items in short-term memory. The memory span for stimulus class $c$ thus depends on the rate of report—$r(c)$—from immediate memory:

$$N(c) = \frac{d}{r(c)}. \qquad [5]$$

Since rehearsal is, in effect, self-report from immediate memory, the rate of rehearsal in the item recognition task will be assumed to be the same as the rate of report in the memory span task. The time to rehearse a list whose length equals the memory span is therefore also a constant, $d$, as given in Equation 5. If memory processing time for a test item is related by some function $g$ to the time since its last rehearsal, then the average processing time when the memorized list length equals $N(c)$ is constant (the mean rehearsal-test delay will be one-half $d$, independent of stimulus class). Since processing time can be estimated (Sternberg, 1966) by the product of the processing rate, $b(c)$, and the number of items in memory, $N(c)$, the following expression results:

$$b(c) \cdot N(c) = g(d/2) \qquad [6]$$

$$b(c) = \frac{g(d/2)}{N(c)}. \qquad [7]$$

Since $g(d/2)$ is independent of $c$, a reciprocal relation between processing rate and memory span is again obtained. Note that ($a$) for reaction times to vary linearly with memory set size within stimulus classes, $g$ itself must be a linear function; ($b$) additional assumptions are necessary to predict reaction times for negative test items—for example, negative reaction time could be proportional to the mean delay (averaged across memory items) between rehearsal of a memory item and presentation of the negative test; ($c$) memory span in this hypothesis is not viewed as storage capacity but only as the number of items that can be reported before the memory trace fades.

Finally, a third hypothesis, whose prediction of the inverse memory, span–processing rate relation led to this study, is based on a neural holographic model of short-term memory (Cavanagh, 1972). There is insufficient space here for a description of the model, but its prediction is based on the assumption that in dynamic activity, such as language or problem solving, the brain attempts to optimize its processing capacity. This implies, among other things, use of full memory capacity and minimization of recognition reaction times. The model allows reaction times in the item recognition task to be expressed as a function of a number of parameters involved in the representation and storage of information; minimized reaction times can therefore be determined by solving the total differentials of these equations when the number of items stored equals the memory span. The resulting minimized reaction times demonstrate an inverse memory span–processing rate relation.

These three hypotheses have involved assumptions that cannot be tested with the data surveyed, and they have been presented only to demonstrate possible explanations of the data. The reciprocal relation of memory span and processing rate does not, therefore, offer a critical test of the hypotheses but does provide a necessary boundary condition that must be met by any theory of the structure of memory. The corollary of this reciprocity condition is that the time required to process a full memory load is a constant, independent of the type of material stored, with a value in the order of one-quarter of a second, the slope of the regression line in Figure 1.

## REFERENCES

BASHARK, L. T. High-speed scanning of random figures in human memory. Unpublished master's thesis, Ohio State University, 1968.

BLANKENSHIP, A. B. Memory span: A review of the literature. *Psychological Bulletin,* 1938, **35**, 1–25.

BRACEY, G. W. Two operations in character recognition: A partial replication. *Perception & Psychophysics,* 1969, **6**, 357–360.

BRENER, R. An experimental investigation of memory span. *Journal of Experimental Psychology,* 1940, **26**, 467–482.

BRIGGS, G. E., & BLAHA, J. Memory retrieval and central comparison times in information processing. *Journal of Experimental Psychology,* 1969, **79**, 395–402.

BURROWS, D., & OKADA, R. Serial position effects in high-speed memory search. *Perception & Psychophysics,* 1971, **10**, 305–308.

BURROWS, D., & OKADA, R. Parallel retrieval of physical and semantic information. Paper presented at the meeting of the Midwestern Psychological Association, Detroit, May 1972.

CAVANAGH, J. P. Holographic processes realizable in the neural realm: Prediction of short term memory performance. Unpublished doctoral dissertation, Carnegie-Mellon University, 1972.

CAVANAGH, J. P., & CHASE, W. G. The equivalence of target and nontarget processing in visual search. *Perception & Psychophysics,* 1971, **9**, 493–495.

CHASE, W. G., & CALFEE, R. C. Modality and similarity effects in short-term recognition memory. *Journal of Experimental Psychology,* 1969, **81**, 510–514.

CHASE, W. G., & POSNER, M. I. The effects of auditory and visual confusability on visual and memory search tasks. Paper presented at the meeting of the Midwestern Psychological Association, Chicago, May 1965.

CHECKOSKY, S. F. Speeded classification of multidimensional stimuli. Unpublished doctoral dissertation, State University of New York at Buffalo, 1970.

CHECKOSKY, S. F., & CHECKOSKY, N. B. Memory search for CVC and CCC trigrams. Unpublished manuscript, Lake Forest College, Lake Forest, Illinois, 1972.

CRUSE, D., & CLIFTON, C., JR. Recoding strategies and the retrieval of information from memory. (Cognitive Processes Laboratory Rep. No. 71–1) Amherst: University of Massachusetts, 1971.

EGETH, H., & SMITH, E. E. On the nature of errors in a choice reaction task. *Psychonomic Science,* 1967, **8**, 345–346.

ELLIS, S. H., & CHASE, W. G. Parallel processing in item recognition. *Perception & Psychophysics,* 1971, **10**, 379–384.

FORRIN, B., & MORIN, R. E. Reaction times for items in short- and long-term memory. *Acta Psychologica,* 1969, **30**, 126–141.

FREUND, R. D., BRELSFORD, J. W., JR., & ATKINSON, R. C. Recognition vs. recall: Storage or retrieval differences? *Quarterly Journal of Experimental Psychology,* 1969, **21**, 214–224.

GATES, A. I. The mnemonic span for visual and auditory digits. *Journal of Experimental Psychology,* 1916, **1**, 393–403.

GOLDRING, S. L. The effect of presentation and test mode on short term retention of words. Unpublished master's thesis, University of Wisconsin, Madison, Wisconsin, 1968.

GUILFORD, J. P., & DALLENBACH, K. M. The determination of memory span by the method of constant stimuli. *American Journal of Psychology,* 1925, **36**, 621–628.

JACOBS, J. Experiments on "prehension." *Mind,* 1887, **12**, 75–79.

JUOLA, J. F., & ATKINSON, R. C. Memory scanning for words versus categories. *Journal of Verbal Learning and Verbal Behavior,* 1971, **10**, 522–527.

KINSBOURNE, M., & COHEN, V. English and Hebrew consonant memory span related to the structure of the written language. *Acta Psychologica,* 1971, **35**, 347–351.

KLATZKY, R. L., & ATKINSON, R. C. Specialization of the cerebral hemispheres in scanning for information in short-term memory. *Perception & Psychophysics,* 1971, **10**, 335–338.

KLATZKY, R. L., JUOLA, J. F., & ATKINSON, R. C. Test stimulus representation and experimental context effects in memory scanning. *Journal of Experimental Psychology,* 1971, **87**, 281–288.

MACWORTH, J. F. The duration of the visual image. *Canadian Journal of Psychology,* 1963, **17**, 62–81.

NICKERSON, R. S. Response times with a memory-dependent decision task. *Journal of Experimental Psychology,* 1966, **72**, 761–769.

OLSSON, J. E., & FURTH, H. G. Visual memory span in the deaf. *American Journal of Psychology,* 1966, **79**, 480–484.

SMITH, E. E. Effects of familiarity on stimulus recognition and categorization. *Journal of Experimental Psychology,* 1967, **74**, 324–332.

STERNBERG, S. High-speed scanning in human memory. *Science,* 1966, **153**, 652–654.

STERNBERG, S. Two operations in character recognition: Some evidence from reaction-time measurements. *Perception & Psychophysics,* 1967, **2**, 45–53.

STERNBERG, S. Memory scanning: Mental processes revealed by reaction-time experiments. *American Scientist,* 1969, **57**, 421–457.

SWANSON, J. M., JOHNSEN, A. M., & BRIGGS, G. E. Recording in a memory search task. *Journal of Experimental Psychology,* 1972, **93**, 1–9.

THEIOS, J., SMITH, P. G., HAVILAND, S., & TRAUPMANN, J. Memory scanning is a serial self-terminating process. (Wisconsin Mathematical Psychology Program Rep. No. 71–1) Madison, Wis.: University of Wisconsin, 1971.

WATKINS, S. H. Immediate memory and its evaluation. *British Journal of Psychology,* 1914, **7**, 319–348.

WILLIAMS, J. D. Memory ensemble selection in human information processing. *Journal of Experimental Psychology,* 1971, **88**, 231–238.

WIMBERLY, F. C. A generalization of some results of Sternberg. (Complex Information Processing Working Paper No. 135) Pittsburgh, Pa.: Carnegie-Mellon University, 1968.

YIO, J. H., & SANTA, J. L. Reaction time in short-term recognition with digits and letters. *Psychonomic Science,* 1970, **20**, 121–122.

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