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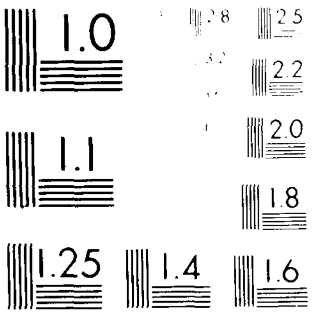

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TECHNICAL REPORT #23

A PUPILLOMETRIC INDEX OF OPERATOR WORKLOAD

JACKSON BEATTY
DEPARTMENT OF PSYCHOLOGY
UNIVERSITY OF CALIFORNIA AT LOS ANGELES

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A PUPILLOMETRIC INDEX OF OPERATOR WORKLOAD

Jackson Beatty
Department of Psychology
University of California at Los Angeles

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A PUPILLOMETRIC INDEX OF OPERATOR WORKLOAD

By Jackson Beatty

Department of Psychology
University of California at Los Angeles

SUMMARY

The momentary workload that is imposed by a cognitive task upon the limited capacity human information-processing system appears to be accurately reflected in the momentary level of central nervous system activation. The utility of pupillometric methods of workload assessment is evaluated and several lines of experimental evidence relating activation and cognitive function are reviewed.

INTRODUCTION

Information processing tasks differ in the extent and duration of the demands that they place upon the limited capacity of the human nervous system to handle information. For most tasks, processing demands are not constant, but vary from moment to moment in response to changes in the functional organization of the task. These demands may be thought to represent the cognitive workload associated with the task, a time-varying function of the demand for limited resources.

Given the assumption that cognitive capacity is fixed (Broadbent, 1958), the momentary demands of any single processing function for capacity may be estimated by determining the amount of residual capacity that may be allocated to another processing task that is assigned a secondary priority (Kerr, 1973). Secondary-task measurement of cognitive workload is of major importance in the study of both cognitive capacity and the resource demands of particular processes, but both technical (Kerr, 1973) and theoretical (Norman & Bobrow, 1975) difficulties preclude the utilization of secondary-task procedures in many situations. For this reason the more convenient method of subjective estima-

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tion of cognitive workload is still commonly employed (McCormick, 1970) despite serious questions as to both the reliability and validity of such rating procedures.

A third approach to the problem of measuring momentary cognitive workload stems from the observation that momentary workload is directly reflected in the momentary level of central nervous system (CNS) activation (Kahneman, 1973; Pribram & McGuiness, 1975). Of the various indicators of activation, pupillometric measurement techniques (Loewenfeld, 1958; Hess & Polt, 1964; Goldwater, 1972) appear to be most sensitive and reliable (Kahneman, Tursky, Shapiro, & Crider, 1969).

The present paper examines several lines of evidence suggesting that pupillometric measures of activation serve as a reliable indicator of cognitive workload in perception, memory, decision and complex problem solving. An extension of this experimental method to the study of problems of workload optimization in complex man/machine systems is then considered.

PHYSIOLOGICAL BASIS

As early as 1920, Lowenstein recognized that the pupil of the eye dilates during cognitive activity (Goldwater, 1972). These dilations may be observed under conditions of constant illumination and are quite independent of the well-known light reflex, which constricts the pupil as illumination increases. Pupillary movements are produced by changes in the relative activation of two muscle groups in the iris. One set of iris musculature, the dilator pupillae, are radially oriented smooth muscle fibers that are innervated by fibers from the sympathetic branch of the autonomic nervous system. Sympathetic activation, therefore, acts to dilate the pupils. Functionally and structurally opposed to the dilator pupillae are the parasympathetically-innervated muscles called the sphincter pupillae, which constrict the pupil as they contract. Thus momentary pupillary diameter reflects the activation of both sympathetic and parasympathetic musculature. In terms of gross autonomic function, pupillary dilation may be interpreted as a sign of autonomic activation.

Activation in the autonomic nervous system appears to be closely coupled to central activation. For example, the reticular activating system of the brainstem has been shown to respond to changes in the activity of the cerebral cortex, giving rise to the idea that reticular system activity is controlled by patterns of cerebral activity during waking (Lindsley, 1960). Changes in reticular activity are also clearly visible in autonomic systems such as the pupil. Electrical stimulation of the reticular activating system results in pupillary dilation, mediated by increased sympathetic and decreased parasympathetic output to the iris musculature (Moruzzi, 1972). Thus pupillary movements may be used to provide a physiological index of brainstem activity during complex cognitive processing in man, and for that reason may provide a true physiological indicator of mental workload.

PERCEPTUAL PROCESSES

Perceptual processes appear to proceed quite effortlessly and place rather little demand upon the limited capacity of the human information-processing system (Kahneman, 1973). Thus Wickens 1974) was unable to observe a secondary task decrement when a sensory signal-detection task was imposed as the primary task in an experiment investigating the distribution of processing capacity. The workload involved in the detection of weak signals is quite small.

In this context, it is of interest to note that small but reliable pupillary dilations accompany the detection of both visual and acoustic signals at near-threshold intensities. Hakerem and Sutton (1966) examined the pupillary movements that accompany the perception of weak visual stimuli and were able to show a dilation for signals that were detected which was absent for signals that were missed. More recently Beatty and Wagoner (1975) provided a pupillometric analysis of activation in the detection of weak acoustic signals using a rating-scale response procedure (see Green & Swets, 1966). Using unmarked observation intervals, no pupillary dilations were observed in the absence of a signal regardless of the outcome of the observer's decision. In the presence of a signal, a dilation of the pupil appeared in the interval between signal delivery and response cue onset. The magnitude of this dilation varied monotonically with the observer's rated probability that a signal had been presented.

These data raise the interesting possibility that pupillometric methods may provide a more sensitive measure of cognitive load than do conventional secondary-task measurement techniques. Thus the small pupillary dilations observed during perceptual processing may be indexing brain workload levels that are not of sufficient magnitude to be detected by secondary task interference methods.

DECISION PROCESSES

Even simple decision processes appear to impose some workload on the cognitive system as indicated by pupillometric measures of activation. For example, Simpson and Hale (1969) measured pupillary diameter in two groups of subjects who were required to move a lever to one of four positions. In the decision group, subjects were told at the beginning of each trial that either of two directions was permissible (e.g., front or left). Seven seconds later a response cue was presented and the subject initiated one of the two movements. In the no-decision control group, subjects were instructed exactly as to the desired movement on each trial (e.g., front). Pupillary dilation in the post-instruction pre-response period was larger and more prolonged for those subjects who had to choose between two movements before responding.

Substantially larger pupillary dilations are observed to accompany more difficult decision processes. In an experiment reported by Kahneman and Beatty (1967), listeners were required to determine whether a comparison tone was of higher or lower pitch than the standard. Clear pupillary dilation occurred in the 4-second decision period between presentation of the comparison tone and the response cue. The amplitude of this dilation varied as a direct function of decision difficulty, the difference in frequency between the standard (850 Hz) and comparison tones. This relation is shown in Figure 1, which presents both the amplitude of dilation in the decision period and the percent decision errors as a function of the frequency of the comparison tone. These dilations were highly reliable and did not habituate over the experimental session. Pupillary dilations during decision appear to vary as a function of cognitive workload, as inferred from task parameters and performance data.

MEMORY PROCESSES

The idea that human information-processing capacity is limited arose directly from the study of the limitations of human short-term or working memory (Miller, 1956). Our capacity for unrelated items is on the order of seven or eight, with some adjustment being made for the difficulty of the to-be-remembered units. If pupillary movements reflect CNS activation shifts as a function of cognitive workload, then these relations should be clearly revealed in the pupillometric investigation of memory processes.

Kahneman and Beatty (1966) provided a demonstration that the momentary load placed upon the cognitive system by a memory task is reflected in pupillary diameter. In a series of experiments on short-term serial memory using placed recall, students were required to listen to strings of from one to seven items and, after a 2 second pause, repeat the string at the rate of one item per second. For strings of digits, pupillary diameter increased as each item of the input string was heard and decreased as each item of the output string was spoken. Thus pupillary diameter at the pause between input and output varied as a monotonic function of the number of items held in memory. These pupillary functions are shown in Figure 2A.

Workload in a memory task depends not only upon the number of items to be remembered, but also upon the difficulty of each of the items themselves. Thus, as fewer unrelated words may be reliably recalled than unrelated digits, the load imposed by each word upon the cognitive system is presumed to be greater. Figure 2B presents the results of a serial memory experiment involving strings of four digits or four words. For the simple recall conditions, it is apparent that the slope of the pupillary function is greater for the more difficult word strings than for the easier digit strings. That these pupillary response functions are sensitive to processing parameters is evident from the large dilations observed under the condition labelled "transformation," in which the subject was required to respond to the string of 4 digits with another string obtained by adding 1 to each digit of the input string. This transformation task is the most difficult of all memory tasks studied, as indicated by the error data, and it consistently was accompanied by larger pupillary movements indicating CNS activation.

Behavioral data supporting the contention that the demands upon limited information-processing capacity increase during the rising phase of the pupillary response function as items are entered into working memory and decrease during the falling phase of that function as items are successively recalled from memory, is provided by an experiment in which residual capacity was measured using secondary-task measurement. Kahneman, Beatty, and Pollack (1967) reported that the pattern of interference with a secondary perceptual-detection task exactly paralleled the pupillary-activation curve obtained for the serial memory transformation task alone. For serial memory tasks, changes in cognitive workload appear to be reflected in the momentary level of CNS activation, as indexed by pupillometric measurement.

COMPLEX PROBLEM SOLVING

Pupillary dilations accompanying complex problem solving appear to be related directly to the difficulty of such processing, although behavioral assessments of workload have not yet appeared for these types of cognitive tasks. For example, in a pupillometric study of individual differences in cognitive processing, Ahern presented undergraduates with multiplication problems at three levels of difficulty (Ahern, 1978; Ahern & Beatty, in preparation). Figure 3 presents these data. An initial dilation is observed as the multiplicand is encoded and stored. A second, larger dilation follows the presentation of the multiplier and persists during the solution of the problem. The magnitude of the response is a direct function of problem difficulty.

Similar effects may be seen in sentence processing and comprehension. As a quantitative paradigm to study sentence processing, Ahern used Baddeley's grammatical reasoning task, in which a sentence such as "A precedes B" or "B is not followed by A" is presented along with a letter pair (Ahern, 1978; Ahern & Beatty, in preparation). The task is to determine if the sentence accurately describes the ordering of the pair. Figure 4 presents the task-evoked pupillary responses as a function of sentence complexity. Although in general the amplitudes of these responses are similar, significantly larger dilations accompany the processing of grammatically more complex sentences.

Other types of complex problem solving tasks show similar relationships between pupillary dilation and problem difficulty. For example, Bradshaw (1968) has reported that larger pupillary dilations accompany the solving of more difficult anagrams, and that these dilations are maintained until solution is reached.

IMPLICATIONS FOR WORKLOAD EVALUATION IN MAN/MACHINE SYSTEMS

Traditional interference and subjective-rating methods of workload evaluation have been employed in the design of complex man/machine interfaces, but neither is without its own particular limitations. Pupillometric methods of workload estimation provide a third alternative that in certain situations might be preferable to either of the more traditional measurements.

The most intriguing possibility is that the measurement of central nervous system activation associated with cognitive function might provide a common metric for the comparison of workload in tasks that differ substantially in their functional characteristics. Underlying this possibility is the idea that CNS activation is the limited general resource that is allocated among cognitive processes demanding capacity. If this is the case, then it may be possible to directly compare perceptual, memory, symbol manipulation and response processes in terms of activation requirements.

This possibility is strengthened by the finding that the magnitude of task-evoked pupillary responses during cognitive processing is independent of baseline pupillary diameter over a physiologically reasonable range of values (Bradshaw, 1969, 1970). It is therefore possible to compare the absolute values of task-evoked dilations that have been reported in a variety of cognitive tasks from different laboratories. Figure 5 presents such a comparison. On the left is the average amplitude of the pupillary dilation that occurs in the short-term memory task. These data are taken from Peavler (1974) but are similar to those previously reported by Kahneman and Beatty (1966). It can be seen that the magnitude of the response increases up to about seven digits, the limit of error-free performance in the short-term memory task. On the right are the peak dilations obtained from other, quite different cognitive tasks. The three values for mental multiplication are from Ahern (Ahern, 1978; Ahern & Beatty, in preparation), as are the data for complex sentence comprehension. The sensory discrimination data are from Kahneman and Beatty (1967). The smallest dilation presented in Figure 5 is for a letter matching task (Beatty & Wagoner, 1978) in which subjects viewed a pair of letters and determined whether thay differed in name or category (vowels or consonants). It can be seen that this physiological measure of mental workload gives a plausable ordering of qualitatively different tasks, with the more complex and demanding tasks eliciting larger task-evoked pupillary responses.

These data suggest that a physiological measure of operator workload may be feasible. The next step in this program of research is to use such data to predict performance in operators of complex man/machine systems.

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FIGURE CAPTIONS

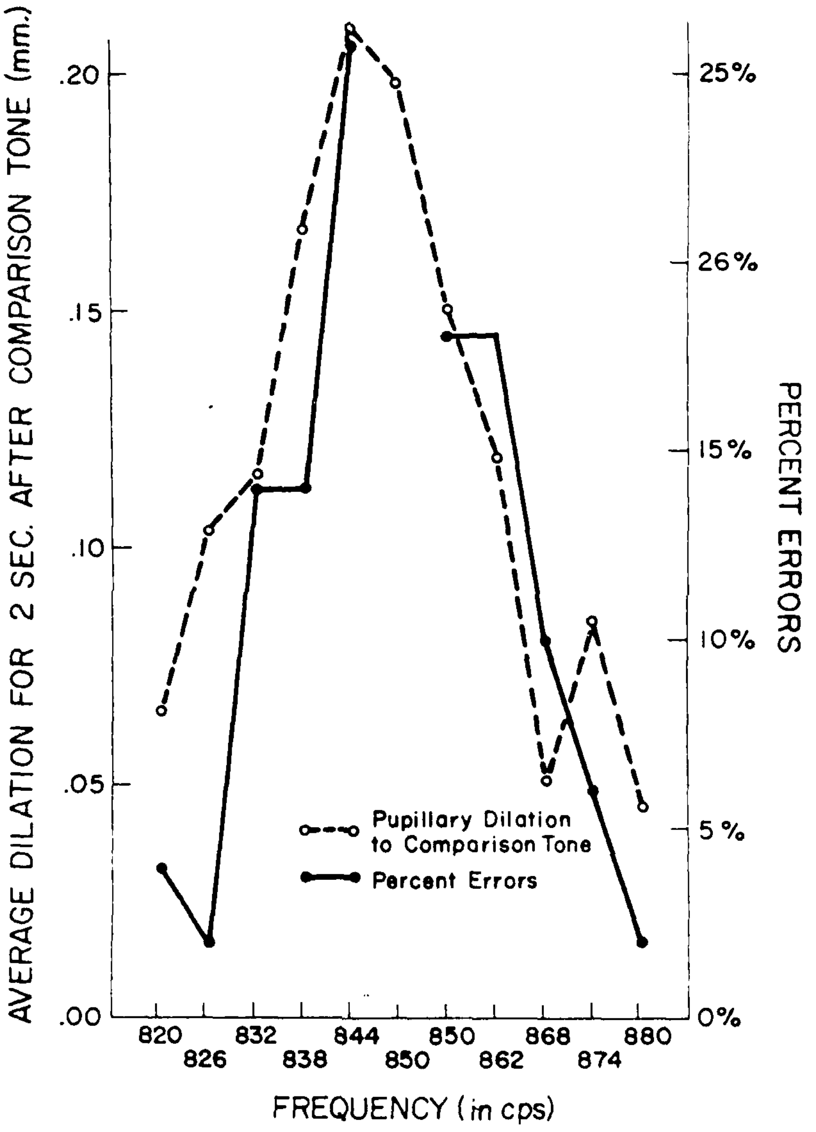
Figure 1. Average pupillary dilation during the decision period and percent errors as a function of the frequency of the comparison tone. The frequency of the standard was 850 cps. (From Kahneman & Beatty, 1967)

Figure 2. Upper graph: Average pupillary diameter during presentation and recall of strings of 3 to 7 digits, superimposed about the two second pause between presentation and recall. Slashes indicate the beginning and the end of the memory task. Lower graph: Pupillary diameter during presentation and recall of four digits, words and a digit transformation task. (From Kahneman & Beatty, 1966)

Figure 3. Task-evoked pupillary responses during mental multiplication as a function of task difficulty. (From Ahern, 1978)

Figure 4. Task-evoked pupillary responses in a sentence comprehension task as a function of sentence complexity. (From Ahern, 1978)

Figure 5. Magnitude of the peak task-evoked pupillary responses for a variety of qualitatively different mental tasks. The ordering suggests the feasibility of physiological measurement of processing load.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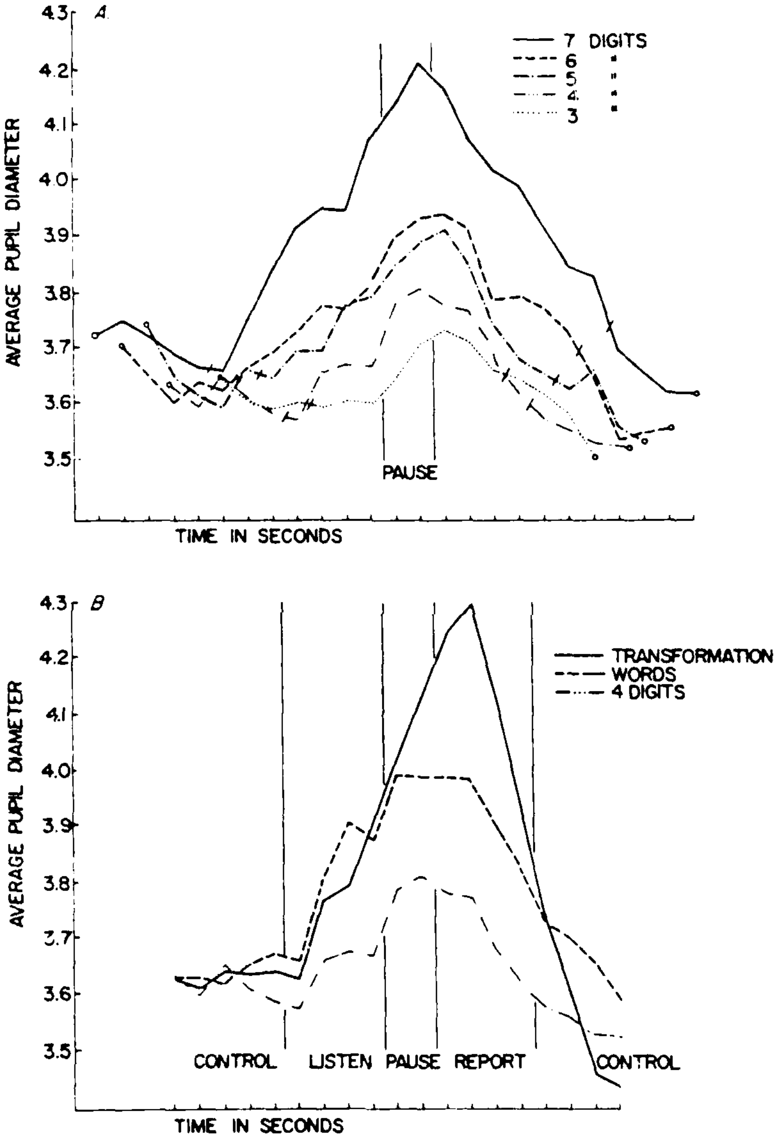
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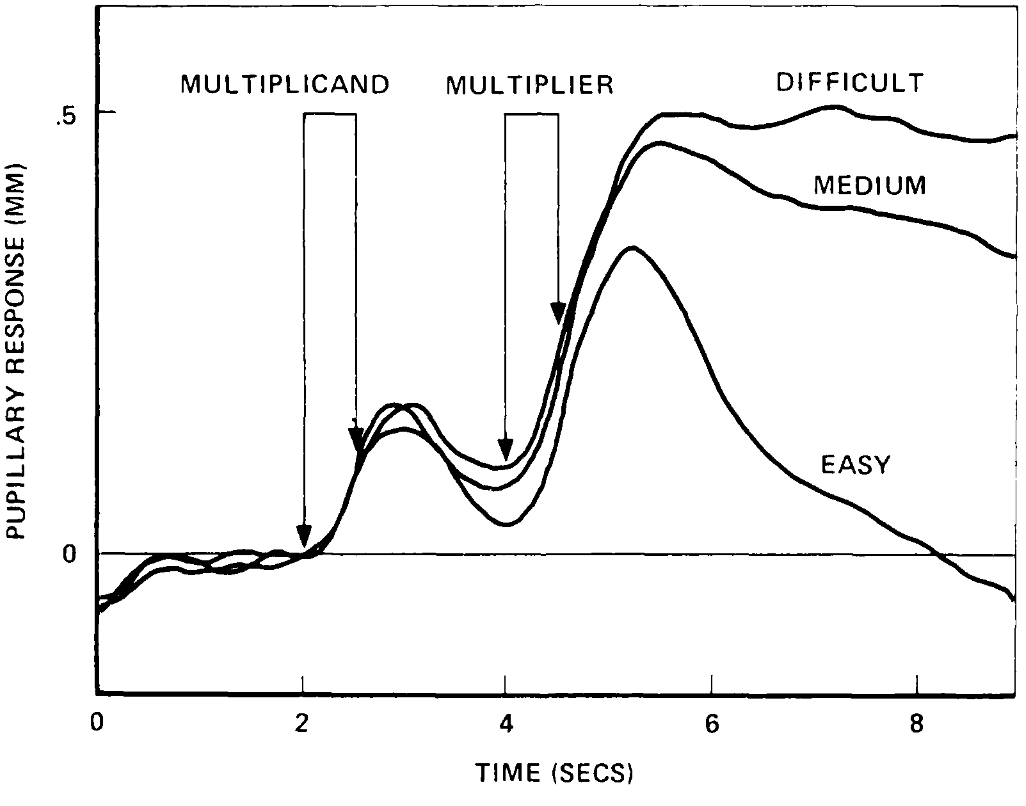
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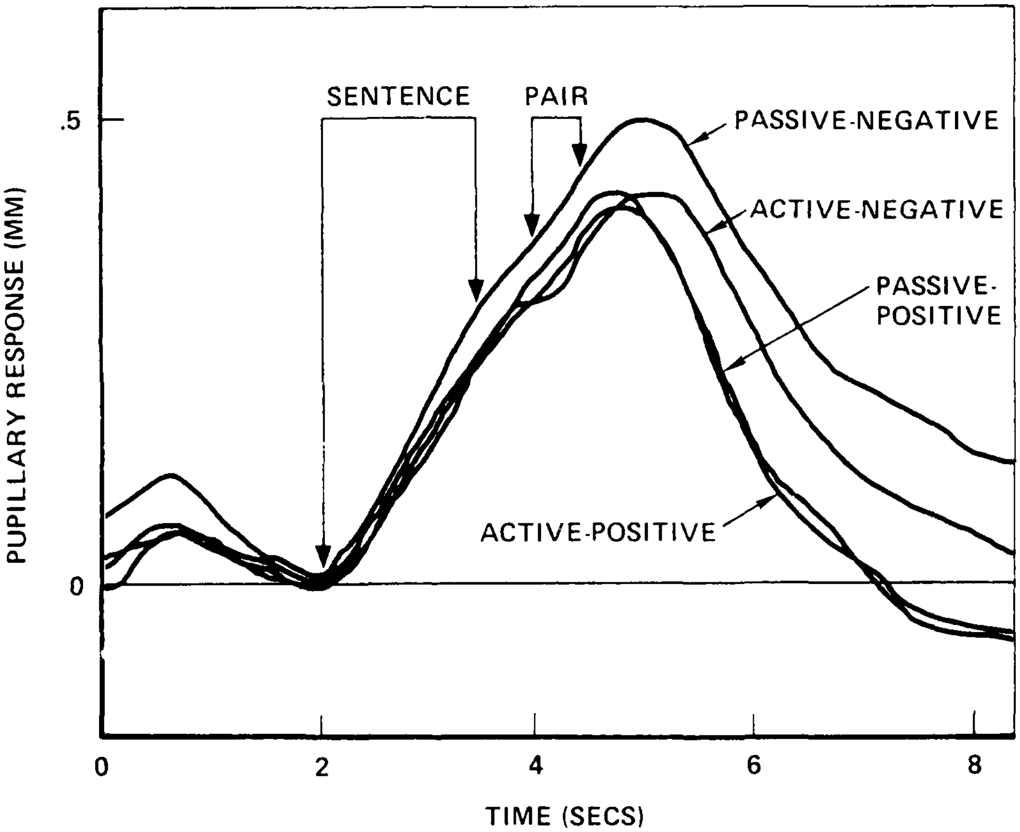

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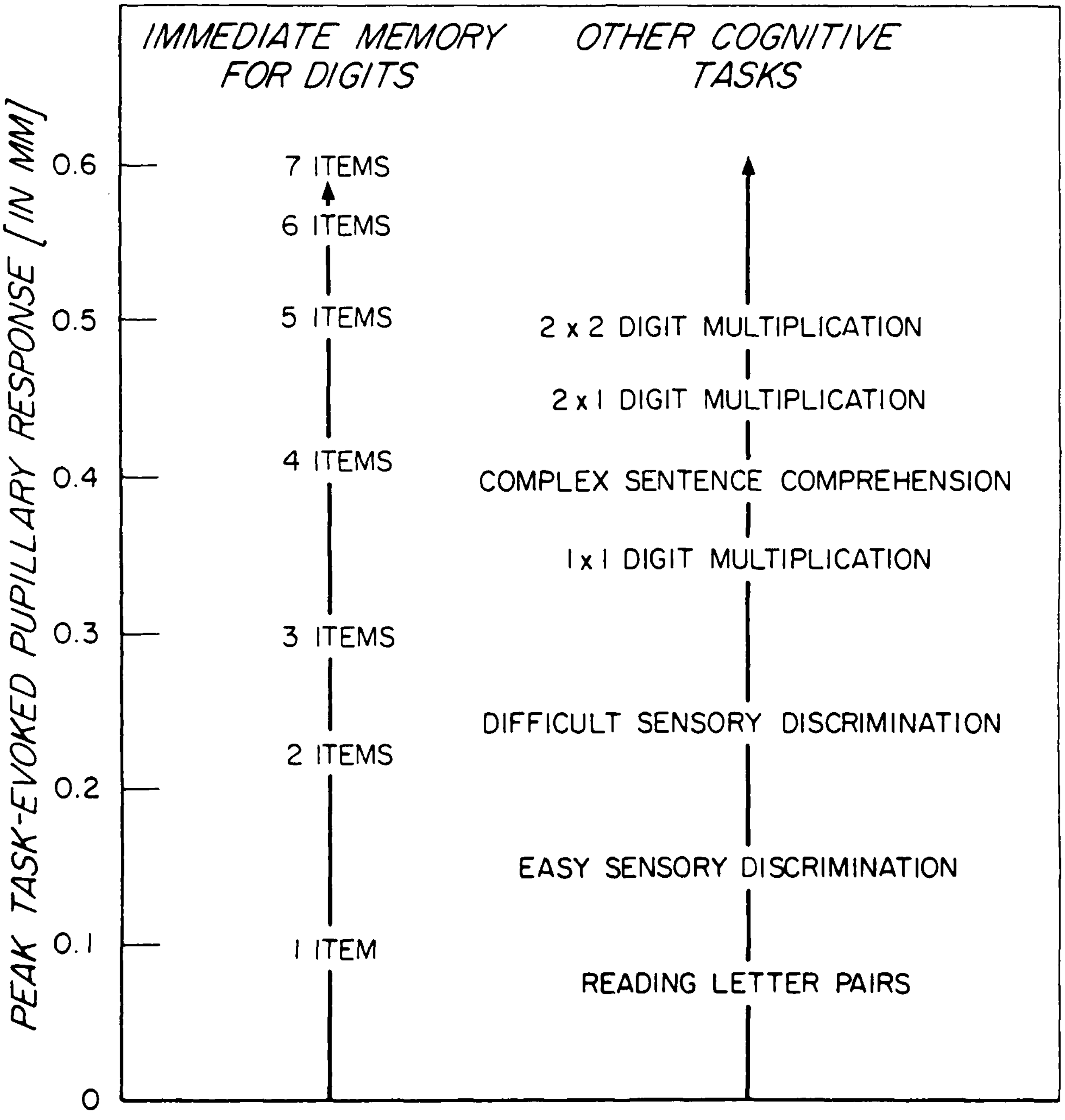
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1 x 1 DIGIT MULTIPLICATION
DIFFICULT SENSORY DISCRIMINATION
EASY SENSORY DISCRIMINATION
READING LETTER PAIRS