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PUPILLOMETRIC MEASUREMENT OF COGNITIVE WORKLOAD

JACKSON BEATTY
DEPARTMENT OF PSYCHOLOGY
UNIVERSITY OF CALIFORNIA AT LOS ANGELES

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PUPILLOMETRIC MEASUREMENT OF COGNITIVE 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 (reference 1), 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 (reference 2). 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 (reference 2) and theoretical (reference 3) difficulties preclude the utilization of secondary-task procedures in many situations. For this reason the more convenient method of subjective estimation of cognitive workload is still commonly employed (reference 4) 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 (references 5 and 6). Of the various indicators of activation, pupillometric measurement techniques (references 7, 8 and 9) appear to be most sensitive and reliable (reference 10).

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.

PERCEPTUAL PROCESSES

Perceptual processes appear to proceed quite effortlessly and place rather little demand upon the limited capacity of the human information-processing system (5). Thus Wickens (reference 11) 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 (reference 12) 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 (reference 13) provided a pupillometric analysis of activation in the detection of weak acoustic signals using a rating-scale response procedure (see reference 14). 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 (reference 15) 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 (reference 16), 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 (reference 17). 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 (reference 18) provided a demonstration that the momen-

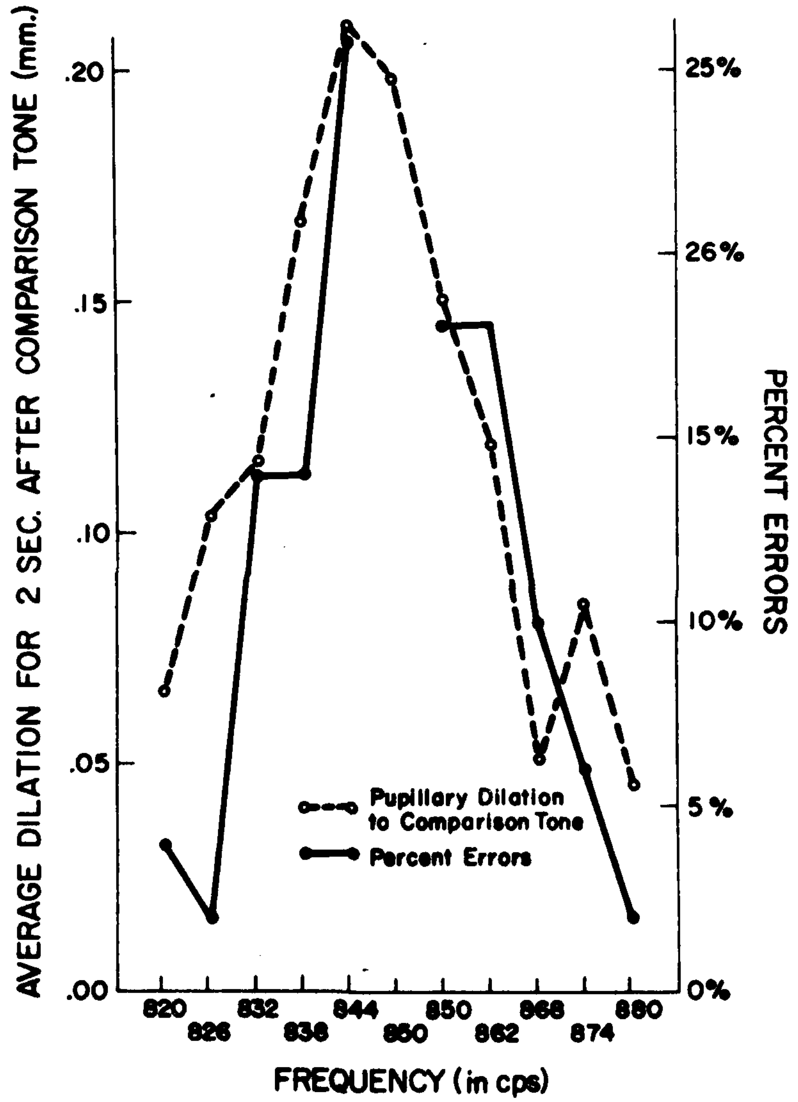

Figure 1. Average pupillary dilation during the decision period and percent errors as a function of the frequency of the comparison tone. The frequency of the standard was 850 cps. (From Kahneman & Beatty, 1967)

tary 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 paced 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 (reference 19) 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, Hess

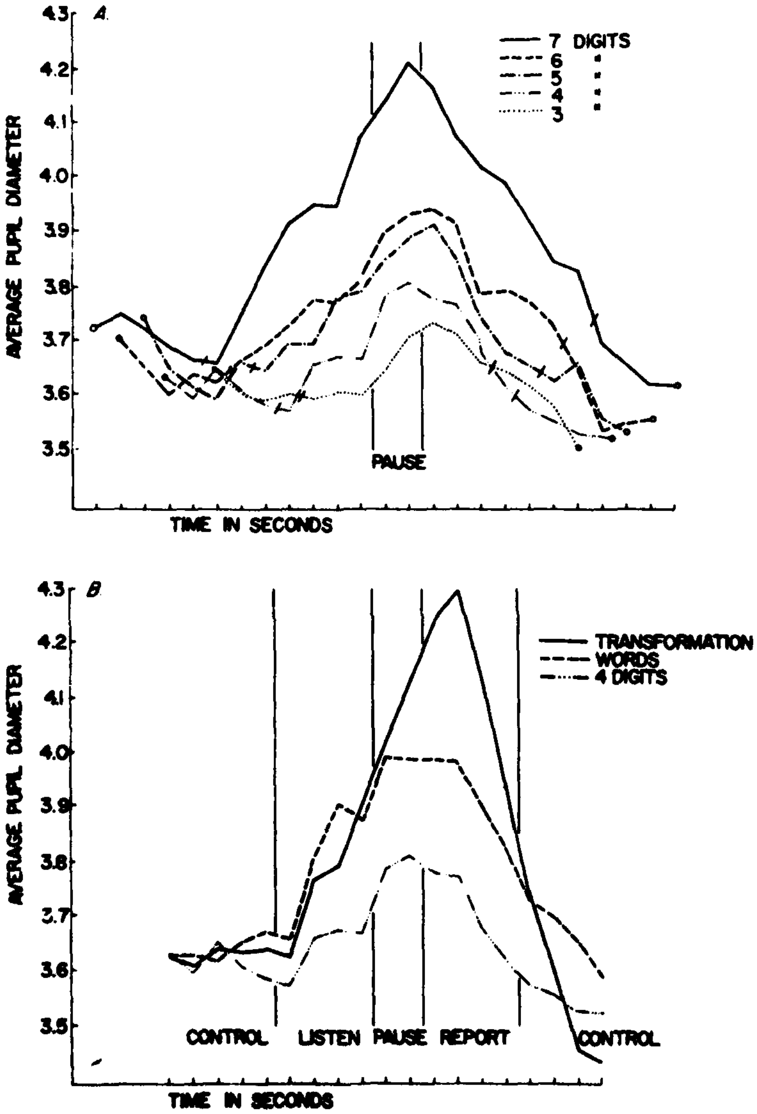

Figure 2. Upper graph: Average pupillary diameter during presentation and recall of strings of 3 to 7 digits, superimposed about the two second pause between presentation and recall. Slashes indicate the beginning and the end of the memory task. Lower graph: Pupillary diameter during presentation and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

and Polt (8) examined pupillary movements as multiplication problems were solved mentally. Pupillary diameter increased during the period preceding solution, and the magnitude of dilation was related to presumed problem difficulty. Payne, Parry, and Harasymiw (reference 20) also report a monotonic relation between mean pupillary diameter and problem difficulty, but note that this relationship is markedly nonlinear with respect to difficulty scales based upon percent correct solution, time to solution or subjective rating of difficulty. Pupillary diameter in mental multiplication appears to peak rapidly as a function of difficulty, with more difficult problems requiring more time until solution is reached. This suggests that cognitive capacity is quite fully taxed in complex mental arithmetic problems so that the workload per unit time remains relatively constant as problem difficulty is increased over moderate levels, but that the total time to solution is increased.

Other types of complex problem solving tasks show similar relationships between pupillary dilation and problem difficulty. For example, Bradshaw (reference 21) 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.

One problem for which pupillometric assessment procedures appear to be well-suited is that of display evaluation. Pupillometric methods permit reliable measurement of the small cognitive workloads associated with the processing of sensory information that may not be detectable by interference methods. One project underway in our laboratories examines the effects of display readability on the pupillary dilations accompanying information acquisition. A second experiment is concerned with pupillometrically measuring cognitive workload involved in processing computer-generated speech at various levels of intelligibility.

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. At present, however, we may only conclude that the pupillometric measures of activation are useful in measuring cognitive load for a range of cognitive processes. No evidence concerning the comparability of measurements made across diverse processes has yet appeared.

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