A PUPILLOGRAPHIC STUDY OF SHORT-TERM MEMORY SEARCH

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CHAPTER I

INTRODUCTION TO PUPILLOGRAPHY

In many great literary works, references have been made to some mystical quality of the human eye. For example Lord Byron wrote, "And oh, that eye was in itself a soul." Guillaume de Salluste wrote, "These lovely lamps, these windows of the soul" in reference to the pupil of the eye. The expression "evil eye" expresses a belief in the demoniacal powers of the eye. Likewise, medical practioners have focused interest on the eye since the dawn of recorded history, and their interests have not been limited to questions of visual functioning. Archimedes (212-187 B. C.) is thought to have constructed a device for measuring pupillary diameter. During Roman times, Plinius (23-79 A. D.) and Galen (131-201 A. D.) both used drugs to dilate the pupil prior to surgery for cataracts. The Arabic physician, Ar-Razi or Rhazes (850-923 A. D.) is usually credited with the report that the pupil of a normal healthy person contracts in bright light and dilates in dim illumination, as well as providing a description of abnormal pupillary conditions in his Encyclopedia of Medicine.

There have been several major historical reviews of the literature on pupillary reflexes within the last few years. The first to appear, and the most comprehensive, was by Loewenfeld (1958). She focused her attention on the study of the anatomical and physiological mechanisms of reflex dilation and constriction. A second literature review by

Loewenfeld (1966) dealt primarily with the effects of scotopic versus photopic receptor systems and near vision on pupillary diameter. Another significant review was by Hess (1968). He concentrated mainly on psychiatric and psychologic factors which produce changes in pupillary diameter. Hess mentions that the notion of the pupil as a sensitive index of sensory, emotional, and mental activity is relatively old. In fact, Hess credits Schiff with the statement of this concept in 1874. At about the turn of the century, there was an upsurge of interest in Germany concerning changes in pupillary diameter to nonvisual factors. For example, Hess cites Heinrich in 1869, and Roubinovitch in 1900, with studying pupillary dilation during mental arithmetic problem solving. Likewise, there was an interest in pupillary abnormalities as an overt symptom of mental illness. Thus, the term "catatonic pupil" referred to the sluggish constriction of the pupil to increases of light in schizophrenic cases. According to Hess, the most notable contributions to the study of pupillary changes in response to psychologic factors were performed by Redlich, Westphal, and Bumke.

After this initial flurry of interest, the topic of pupillary changes to psychologic factors lapsed into obscurity, while the question of the underlying mechanisms of pupillary reaction to light received considerable attention. In the 1960's, a renewed interest in psychogenic causes of pupillary dilation was sparked by Hess (1965). This renewed interest seems to be due to several interacting factors. First, technological advancements made it possible to obtain an accurate, objective recording of pupillary diameter over extended periods of time. Second, investigators became increasingly concerned with obtaining more "direct" real-time measures of psychological processes which previously were inferred from S's retrospective reports of such processes. Third, knowledge about the anatomical, neurological, and physiological mechanisms of pupillary control was becoming fairly extensive, and this knowledge indicated that there was an intimate relationship between pupil size and the state of the CNS, especially the autonomic nervous system.

Anatomy of the Pupillary System

In terms of general appearance, the pupil has an average diameter of between 3 to 4 mm. in the normal adult human under average daylight conditions. Small changes of 0.1 to 0.2 mm. in pupil diameter occur continuously even under constant light conditions (Adler, 1959).

The muscles of the iris are the unstriated sphincter pupillae and dilator pupillae. Embryologically, both muscles arise from epithelial tissue or ectoderm. The iris muscles deviate from the usual pattern in as much as most unstriated muscle tissue arises from mesoderm. The dilator pupillae is even more deviant in its development, each cell becomes only partly muscular in nature while retaining pigmentation characteristics of epithelial tissue.

The sphincter pupillae is a typical sphincter muscle composed of unstriated fibers. It lies in the posterior iris stroma just in front of the pigmented epithelium, next to the edge of the pupil. The range of movement of the pupil can be extraordinarily large. The pupil may be 1.5 mm. in diameter when maximally contracted in bright light to 8 mm. in diameter when maximally dilated in darkness. Thus, the sphincter may shorten by 87 percent of its length which is rarely found in any other muscle of the body (Adler, 1959).

Unlike the sphincter pupillae, whose existence was firmly established in the 1840's, the dilator pupillae has been a source of constant debate as to existence even in modern times (Loewenfeld, 1958; Lowenstein & Loewenfeld, 1962). Most authorities now agree that the dilator pupillae does exist. Part of the problem was due to the fact that the dilator retains some characteristics of epithelial tissue, and until appropriate bleaching and staining techniques were developed, its muscular qualities were not observable.

According to Lowenstein and Loewenfeld (1962), the dilator is composed of two parts, Bruch's membrane and radial reinforcement bundles. The cells of Bruch's membrane entwine with the fibers of the sphincter at the internal edge of the iris and form a thin layer on the posterior side of the iris which extends to the ciliary iris margin. There, these cells form entertwining muscle arcades from which insertion bundles merge into the ciliary muscles and pectinate ligament. In addition, the reinforcement bundles, which are anterior to Bruch's membrane and posterior to the iris stroma, form radical strands that course toward the iris margin as spokes in a wheel.

The innervation of the pupillary musculature is still a matter for some debate. Lowenstein and Loewenfeld (1962) state that the sphincter pupillae is innervated solely by cholinergic, parasympathetic fibers from the ciliary ganglion via the short ciliary nerves. Adler (1959) believes that the sphincter is innervated by sympathetic as well as parasympathetic fibers from the ciliary ganglion. On the other hand, Lowenstein and Loewenfeld state that the sympathetic fibers which enter the ciliary ganglion do not synapse with nerves destined for the sphincter, but pass on through the ciliary ganglion to other eye muscles.

In addition, Loewenfeld (1958) cites voluminous amounts of experimental research which indicate that the sphincter pupillae is not sympathetically innervated. In addition, she traces the concept of sympathetic innervation of the sphincter to the historically erroneous concept that pupillary activity was solely the function of the dually innervated (sympathetic and parasympathetic) sphincter.

Although there is debate over the innervation of the sphincter pupillae, the innervation of the dilator pupillae is a topic of considerable concensus. The fibers of the dilator pupillae are innervated by adrenergic, sympathetic nerves which run from the Gasserian ganglion via the nasociliary root of the opthalmic division of the fifth cranial nerve to the two long ciliary nerves, then to the eye itself (Adler, 1959; Lowenstein & Loewenfeld, 1962).

Before a description of the mechanisms controlling pupillary size can be made, it is necessary to briefly outline the central-neural anatomy involved. The afferent nerves of the light reflex begin with the ganglion cells of the retina. No distinction appears to be necessary between fibers involved in the light reflex and those involved with vision. At the level of the lateral geniculates, a "branching" occurs which leads afferent fibers of the light reflex to the pretectal nuclei where a synapsing occurs with fibers which proceed to the Edinger-Wesphal nuclei of the Oculomotor nucleus. At the level of the pretectal nuclei, a hemidecussation occurs with half of the internucial neurons proceeding contralaterally around the Aquaduct of Sylvius via the posterior commissure and ventrally to the Edinger-Wesphal nuclei. The other half, proceed ipsilaterally and ventrally to the Edinger-Wesphal nuclei. Thus, in man, the direct light reflex (constriction of the pupil of the eye stimulated) and the consensual light reflex (constriction of the pupil of the eye which is not stimulated) are equal (Adler, 1959; Lowenstein & Loewenfeld, 1962). From the Edinger-Wesphal nuclei parasympathetic, efferent fibers proceed to the ciliary ganglion via the third cranial nerve.

The exact origins of the efferent sympathetic innervations of the dilator pupillae have not been directly verified, but indirect evidence leads Lowenstein and Loewenfeld (1962) to conclude that "cortico-thalamo-hypothalamic" tracts are involved. On the other hand, it is rather well known that nerves leading the spinal cord between cervical VIII and thoracic IV are involved (primarily thoracic I and II) with pupillary activity. These preganglionic sympathetic nerves enter the peripheral sympathetic chain and travel upward to the inferior cervical ganglion, ansa Vieussens, middle cervical ganglion, and finally synapse in the superior cervical ganglion. Postganglionic nerves travel to the carotid plexus then across the typanic cavity and join the fifth cranial nerve near the peripheral end of the Gasserian ganglion (Loewenfeld, 1958).

Mechanisms of Pupillary Reflex Dilation

There are several pupillary reactions. Lowenstein and Loewenfeld (1962, p. 236) list the following: the light reflex, the reaction to near vision, pupillary reflex dilation, the darkness-reflex, the lid-closure reflex, and pupillary unrest or "hippus." The reaction of greatest interest to the present work is that of pupillary reflex dilation. Lowenstein and Loewenfeld (p. 236) define this as "Pupillary dilation elicited by sensory or emotional stimuli, or by spontaneous thoughts or emotion."

The mechanisms of pupillary reflex dilation has been the source of more bitter controversy than any other pupillary movement. The debates have involved arguments over the existence of the dilator pupillae, the innervation of the sphincter pupillae, and the relative importance of both muscles and their innervations in the production of pupillary dilation. As indicated in the section on pupillary anatomy and innervation, the debate has not been completely resolved.

Pupillary reflex dilation appears to be due to four factors (Lowenstein & Loewenfeld, 1962). Two of these factors are neural, and two are humoral mechanisms. The two neural factors are first, active sympathetic discharge which reaches the dilator pupillae and causes it to contract and second, inhibitory sympathetic impulses which suppress the activity of the Edinger-Wesphal nucleus and thereby cause the sphincter pupillae to relax. The two humoral factors involved are first, the release of adrenal epinephrine by a severely emotionally stressed organism and second, the release of nor-epinephrine by sympathetic nerve endings in the heart and its arteries in moderately aroused organisms (Loewenfeld, 1958).

Briefly, the four factors involved in controlling pupillary dilation can be distinguished on the basis of latency of dilation, rate of dilation, and duration of peak dilation (Loewenfeld, 1958). In cats, the adrenal epinephrine response has a long latency of about 9 to 15 seconds after stimulation with prolonged duration of dilation after onset. The fast acting humoral mechanism (nor-epinephrine) typically has a latency of onset in the neighborhood of 2 to 3 seconds developing fully in 7 seconds and declining about 10 seconds after stimulation.

Both humoral factors produce rather extensive dilations. The neural mechanism of active sympathetic discharge to the dilator pupillae is characterized by fast dilation to "psycho-sensory" stimulation with latencies in the range of 0.3 to 0.5 seconds in man. This mechanism is also characterized by a massive dilation of short duration usually followed by immediate recontraction of the pupil. The second neural mechanism which involves sympathetic inhibition of the Edinger-Wesphal nucleus is characterized by short latency on onset (approximately 0.3 seconds), slow rate of dilation, and the smallest increase of diameter produced by the various mechanisms.

It should be emphasized that in normal individuals the pupillary reaction is the result of the interaction of these mechanisms. Typically, the two humoral mechanisms play an important role only in cases involving moderately strong or stronger forms of stimulation, and thus, result in rapid and long lasting, massive dilations.

Pupillary reflex dilation is only one of several pupillary reactions that can occur simultaneously. The next most important reaction for the present work is the light reflex, and its controlling mechanisms. The relationship between the sphincter pupillae and its parasympathetic innervation and the dilator pupillae and its sympathetic innervation appears to be that of reciprocal inhibition involving a dynamic equilibrium between the two systems (Lowenstein & Loewenfeld, 1964; Lowenstein & Loewenfeld, 1952). For example, when an individual is sleeping his pupils are miotic and unresponsive to light stimulation. Upon awakening, the pupils dilate and become responsive to increases in light level. Thus, a certain amount of sympathetic activity is necessary before the parasympathetic constriction to light is possible.

There is still debate over the exact locus of the reciprocal inhibitory process. Adler (1959) concludes that since the sphincter pupillae is dually innervated, the locus of the reciprocal inhibition is located peripherally at the sphincter. Lowenstein and Loewenfeld (1962) are of the opinion that the locus of reciprocal inhibition is centrally located at the Oculomotor nucleus of the third cranial nerve. Wherever the locus of the reciprocal inhibitory process, there is fairly substantial agreement that pupillary size is a function of the relative balance between the sympathetic dilation component and the parasympathetic constriction component. Thus, light stimulation of the retinas produces an increment of parasympathetic activity with the resulting constriction of the iris via the sphincter pupillae against the dilator pupillae. Stimulation which leads to pupillary reflex dilation produces an increment in sympathetic activation which operates in two ways. First, there is active contraction of the dilator pupillae. Second, there is sympathetic inhibition of the Edinger-Wesphal nucleus resulting in a lessening of tone of the sphincter pupillae against which the dilator is contracting, resulting in an increase of pupillary diameter. As a result of these processes, the diameter of the pupil is a sensitive index of the ongoing shifts in autonomic balance between the sympathetic and parasympathetic divisions.

Proposed Topic of Investigation

As mentioned in an earlier section of this paper, the idea that pupillary size may serve as an index of mental activity is not new. Hess (1965) summarizes a series of studies on the usefulness of changes in pupillary diameter as an indicator of mental activity, preference for pictures, and attitudes toward political candidates. In brief, Hess concluded that changes in pupillary diameter should provide a sensitive measure of various mental activities.

The proposed topic of the present investigation is to further study the nature of pupillary responses (changes in diameter of the pupil) during mental activity. The type of activity chosen is that of short-term memory (STM) search. The major reasons for choosing memory search are as follows: First, STM processes have recently been the subject of a large amount of research using more orthodox response measures, and there exists a considerable amount of data as well as theoretical interpretations. Second, STM search is thought by some (Sternberg, 1969) to be crucial in retrieval of information from STM. Third, STM search processes are assumed to occur at extremely rapid rates. These properties of STM search should provide an excellent opportunity to evaluate the usefulness of pupillary responses as an indicator of several types of cognitive or mental processes.

CHAPTER II

A SELECTED REVIEW OF THE LITERATURE

As in many areas of research, certain papers stand as landmarks. Hess's _Attitude and Pupil Size_ (1965) deserves this distinction for pupillographic research in the latter half of this century. As was mentioned earlier, several individuals had noted that pupillary size seemed to be correlated with various psychological states or operations even in the Nineteenth century, but it was Hess's paper which gave rise to a flood of research on the topic.

Hess summarized a series of investigations on several diverse topics. In brief, he reported that pupillary size was correlated with the "interest value" that a particular pictorial stimulus evoked in a subject with a "pleasant interest" producing pupil dilation and an "unpleasant aversion" producing constriction. He also reported that attitudes toward particular political candidates led to particular patterns of pupillary response. When a subject (_S_) was shown a picture of a candidate he dilated if he had a positive attitude toward the candidate and constricted if he had a negative attitude toward the candidate. Lastly, Hess demonstrated that solving multiplication problems in "ones head" led to increasing dilation up to time of solution of the problem followed by constriction with dilation again when _S_ reported his answer.

Subsequent to Hess's paper, several articles were published which were critical of Hess's findings. Loewenfeld (1966, p. 294) stated, "Among all forms of psychosensory stimulation, visual stimuli strike us as especially unfortunate in the kind of experiment attempted. . . ." She was referring to the fact that the effects of brightness, color, area, and retinal distribution of the various images on pupil size were not controlled by Hess. Second, Loewenfeld commented, "The assumption that pleasant emotions dilate the pupil whereas unpleasant ones contract it is not merely unsupported, but is contrary to fact." She stated that all psychologic and sensory stimuli, with the exception of light, dilate the pupil and none of them contract it.

Woodmansee (1966) cited several methodological problems in Hess's research and in pupillographic research in general. For example, light reflex effects must be extremely well controlled in studies using visual stimuli. Likewise, Woodmansee noted that there are arousal decrement effects which involve decreasing pupillary diameter as an S becomes bored or tired during an experiment, and near-vision reflex effects due to S not maintaining a constant level of accommodation throughout a trial. Lehr and Bergum (1966) reported data which also indicate that there is a considerable decrease in absolute pupillary diameter during an experiment. They called this phenomenon "the pupillary adaptation effect." Dooley and Lehr (1967), after attempting replication of some of Hess's work and examination of his experimental designs, warned researchers not to be too quick to assume that the pupillary response was an unambiguous measure of affect. Hess and Polt (1967) answered Dooley and Lehr's criticisms by citing general results from unpublished research. An attempt to obtain information concerning all or part of the unpublished research was not successful (Clark, personal communication).

Several more studies have dealt with methodological factors other than those raised by Hess's article of 1965. Beck (1967) reported that individuals with blue eyes had larger pupils than brown-eyed persons and that people with blue eyes reacted with larger percent increases in pupillary diameter to auditory click stimulation than those with brown eyes. Krueger (1967) sought to demonstrate that Ss could voluntarily prevent pupil dilation while viewing sexually arousing slides. Results were negative. Clark and Johnson (1970) provided naive Ss with information concerning pupillary dilation and constriction during an STM task. Results indicated that the nature of the information that Ss had prior to the task did not effect the pupillary data.

As is apparent from the preceding discussing, one of the major contributions of Hess's article has been to stimulate investigations on possible confounding factors in pupillographic studies of psychological processes. Another major effect of Hess's article has been the delineation of subject matter for pupillographic work by psychologists. As a result, most later research has tended to remain within the problem areas originally defined by Hess. Thus, most research fits into the following categories: Studies of Affective States; Studies of Attitudes; Marketing Research; and Studies of Mental or Cognitive Processing. The remainder of this review shall deal mainly with studies of mental or cognitive processing.

Studies of Cognitive Processing

A number of studies of pupillary dilation during mental problem solving have been reported. Typically, these studies sought to establish some relationship between the type of problem, its difficulty level and degree of pupillary dilation. Hess (1965) and Hess and Polt (1964) reported that pupillary diameter increased as Ss mentally solved auditorially presented arithmetic multiplication problems with peak dilation occurring at the time of solution. Accommodation changes did not account for the dilations. It was also found that greater rates of dilation as well as higher peak dilations occurred when problems of subjectively greater difficulty were presented. Payne, Perry and Harasymiw (1968) compared percentage of pupillary dilation, latency of solution, number of correct responses, and S's judgment of item difficulty under four levels of difficulty of visually presented mental multiplication problems as defined by a multiplication algorithm. In brief, their results indicated that judgment of difficult and latency of solution were "better" measures of item difficulty than pupillary response or number of correct solutions. It should be noted that all four measures were significantly correlated with item difficulty, and that methodological problems in analyzing the pupillary data compromises any conclusions drawn from that data. Schaefer, Ferguson, Klein, and Rawson (1968) found that time estimation via silent counting elicited no pupillary changes, but memory for numbers, multiplication, and word definition reliably resulted in pupillary dilation. Remembering four digits which had been presented auditorially at a 1 per second rate over a 10 second interval resulted in a mean increase in pupillary size of 15 percent. Likewise, seven digit strings resulted in a mean increase of 29 percent.

Bradshaw (1967, 1968a, 1968b) has investigated pupillary dilation in a variety of mental problem solving situations. In general, he found that "easy problems" such as word games which permitted several acceptable answers, simple arithmetic division problems, and Wittenborn conditional "attention" problems presented at slow rates and with simple processing demands, typically produced less dilation than "harder" versions of the same types of problems. He also found that various types of overt indicators of problem solution had differential effects on the pupillary response. Typically, there was a dilation peak at the time that Ss solved a particular problem. In addition, an overt indicator of solution such as a verbal response or button pressing response tended to "magnify" the solution peak, but not replace it. After solution of a problem, there was usually a "post-solution" drop in pupillary size, but this did not occur when problems were not solved. In addition, Bradshaw, found an "adaptation effect" over trials in agreement with Woodmansee (1966) and Lehr and Bergum (1966).

The results of the foregoing studies indicate that pupillary diameter does increase significantly while an S solves various types of "mental" problems. In addition, there appears to be some positive relationship between amount of dilation and difficulty level of the problem with "more difficult problems" resulting in greater "cognitive load" and larger dilations. But, because of the heterogenous types of task employed and the lack of any adequate definition of "problem difficulty" a more definitive statement would be hazardous.

Other investigators have considered the problem of pupillary dilation during mental imagery tasks. Typically, the S was asked to generate "mental images" suggested by auditorially or visually presented words. Results revealed that pupil size typically increased during the activity of generating images and that the amount of dilation was related to the difficulty of the task with "concrete" words being easier and producing less dilation than "abstract" words (Paivio

& Simpson, 1966). Second, the response used to indicate task fulfillment (keypress) apparently contributed to the dilation effect and removal of the overt response decreased it (Bernick & Oberlander, 1968; Simpson & Paivio, 1968). In addition, removal of the overt response attenuated any differential dilation to "concrete" versus "abstract" stimuli (Paivio & Simpson, 1968; Simpson & Paivio, 1966). Third, the latency of the pupillary response, which was measured as the time from onset of the stimulus word to the time point at which maximum dilation was achieved, appeared to be related to the "concreteness"--"abstractness" of the stimuli with pupillary latency being shorter for "concrete" words as opposed to more "abstract" ones (Paivio & Simpson, 1968; Simpson, Molloy, Hale, & Climan, 1968). Finally, Colman and Paivio (1969) compared pupillary responses and GSR measures and found a significant difference between "abstract" and "concrete" nouns with regard to pupil size. The pupillary response and its latency appeared to be a more sensitive response measure during imagery tasks than the GSR.

Several studies have investigated pupillary dilation in situations where the verbal requirements of the cognitive task were minimal. These studies have used pitch discrimination tasks, stimulus detection tasks, and simple RT tasks. Kahneman and Beatty (1967) employing the method of constant stimuli in a pitch discrimination situation found that the amount of pupil dilation to a comparison tone was closely correlated with the difficulty of the discrimination task. In fact, pupil dilation appeared to be as good an index of difficulty of discrimination as rate of errors. Another important result from their study was the finding that although absolute pupil diameter greatly decreased within a block of 11 trials (adaptation effect), the magnitude of the deviations from a baseline value for each individual trial remained constant across trials and trial blocks. Finally, they reported that a secondary dilation peak accompanied S's report of whether the comparison tone was higher or lower than the standard. This secondary dilation was not associated with dilation during pitch discrimination. Simpson (1969) examined the effects of the relevancy of an overt response on pupil size in a modified paired comparison, pitch discrimination task. Results indicated that pupillary dilation did occur to the cognitive task of making a "same" or "different" decision, and that if the S had to indicate his decision by pressing a key, there was greater dilation than if he indicated his decision by not key pressing. Finally, there was even less dilation if the key pressing was unrelated to the S's judgment task.

Hakerem and Sutton (1966) have studied changes in pupil size in a detection-vigilance task with near threshold light stimuli. Briefly, results from a series of studies indicated that the pupil dilated only when a weak light pulse was reported as having been seen by S, and S had to make a detection. When light energy levels were high enough, a constriction wave was found on the dilation curve when Ss "saw" the stimulus, but the pupillary curve remained essentially flat when the stimulus was not detected. Hakerem and Sutton also reported larger dilations when Ss were required to make an immediate report of detection than when they were not so required. In a different type of detection task, Kahneman, Beatty, and Pollack (1967) had Ss monitor for the letter "K" in a Bina-view display that was flashing letters at a 5 per second rate (detection task), or listen to a string of four digits and transform them by adding one to each digit and report the result (transformation task), or both (double task). Pupillary diameter increased nearly linearly up to the second digit during reporting of the transformed results then decreased slightly for the two remaining digits in both the double task and transformation task. Transformation and double task pupillograms were nearly identical. The pupillogram for the detection task was much flatter than for the other two conditions. The time course for number of missed signals ("K") and amount of pupil dilation had nearly the same temporal pattern. These results did not appear to be due to any visual effects associated with pupillary size because Ss who viewed the display through a 2.5 mm. artificial pupil had lower error scores than those with an unobstructed view.

Bradshaw (1968c) monitored pupillary size in an RT task with varied stimulus uncertainty. Stimulus uncertainty was achieved by varying the sensory modality (auditory or visual) for the signal to respond, changing the length of the warning foreperiod, and concurrently presenting masking noise. At the greatest level of uncertainty, the pupil response showed an overall flattening of response peaks with a rise in baseline levels. There was also evidence of a small expectancy peak in pupillary response with a nonoccurring but anticipated signal. An increase in uncertainty led to an increase in RT. In a later study (Bradshaw, 1969), anticipatory pupil dilation again was found in the context of a nonoccurring but expected auditory signal to respond. In this study, Bradshaw used two different illumination levels (25 ft-L. and 0.56 ft-L.) and found that deviations from pupillary baselines during the RT task were nearly equal, although there was a 33 percent difference between baselines for the two illumination levels. In another auditory RT study (Bradshaw, 1970), three drug conditions (normal, amphetamine, and alcohol) were employed. The amphetamine condition produced higher pupillary baselines than the normal or alcohol conditions, but did not affect pupillary response peaks. The alcohol condition did not affect baseline values, but did flatten the response peaks. RTs in the alcohol condition were slower than those in the other two conditions.

These studies of pupillary change during pitch discrimination, stimulus detection, and simple RT tasks lead to some interesting conclusions. First, the hypothesis that pupillary dilation is solely dependent on covert verbal behavior receives little support, because the tasks employed do not apparently involve S using extensive covert verbal behavior during solution. Second, the hypothesis that pupillary dilation during cognitive processing is mainly due to the neural activity of performing an overt response indicative of task fulfillment fairs badly in the pitch discrimination studies (Kahneman & Beatty, 1967; Simpson, 1969) and the stimulus detection studies (Hakerem & Sutton, 1966; Kahneman, et. al., 1967). These studies required cognitive processing, but any overt response indicator was delayed until well after cognitive processing was completed. In addition, pupillary dilations tended to covary with indexes of task difficulty such as error rates (Kahneman & Beatty, 1967; Kahneman, et. al., 1967) even though overt response indicators were the same for different difficulty levels. Third, variations of absolute pupil size via adaptation effects, drug administration, and changes of illumination does not appear to influence the phasic dilation of the pupil during a cognitive task (Bradshaw, 1969, 1970; Kahneman & Beatty, 1967).

Various types of STM tasks have proven extremely useful for validating pupillary dilation as an index of momentary information-processing or cognitive load. Kahneman and Beatty (1966) found two distinct phases of pupillary activity when Ss learned single digits or words (high frequency monosyllabic nouns), aurally presented at a 1 per second rate, and then recalled the items after a 2 second pause. First, there was a loading phase during which the pupil dilated with every item heard. Second, there was the unloading phase during which the pupil contracted with every item reported. Peak pupillary diameters increased monotonically with the number of digits heard from three digits to seven digits. A transformation task (adding one to each digit heard) with four digits produced the largest amount of dilation among the different tasks, and the word memory task resulted in an intermediate amount of dilation. In this same study, a test for accommodation artifacts indicated that pupillary changes could not be attributed to loss of accommodation as the S engaged in the memory and transformation tasks. Kahneman and Beatty concluded that pupillary diameter was a measure of the amount of material which was under active processing at a particular time, and that changes of pupil size was related to the changing difficulty of the task during a trial.

Several other studies lend credence to Kahneman and Beatty's conclusions. Elshtain and Schaefer (1968) aurally presented letter-word sequences which differed in word frequency and average storage load (ASL). Their results indicated that pupil size increased slightly during "loading", and markedly during recall. Greater ASL (2.5; 4.5; and 6.5) resulted in more dilation in interaction with word frequency (high versus low) with low frequency words at the highest level of ASL eliciting the greatest dilation. Recall errors also increased with increasing ASL, but word frequency did not significantly effect recall error rates. Clark and Johnson (1970) and Johnson (1969) used high frequency, monosyllable nouns in an STM task and essentially replicated Kahneman and Beatty's (1966) results with words. Beatty and Kahneman (1966) compared STM and long-term memory (LTM) processes, and found that LTM recall elicited greater pupil dilation than STM recall. Johnson (1969) found that a signal to forget produced a brief wave of dilation followed by constriction toward baseline values. Recall data indicated that Ss did in fact forget the appropriate material resulting in a lessened cognitive load.

Kahneman, Onuska, and Wolman (1968) sought to identify the mechanism underlying cognitive loading in STM studies. They conjectured that covert verbal rehearsal was a likely suspect, and attempted to manipulate this mechanism by varying the manner in which strings of nine digits were presented to Ss for immediate recall. Pupillary data indicated that a steady dilation occurred when the digits were presented at a 1 per second rate, but that waves of dilation and constriction occurred when the digits were presented in groups of three. Dilation occurred after each group and constriction usually followed during pauses between groups. Similar results were obtained in a study (Kahneman & Peavler, 1969) where nouns were presented at a 1 per 4 second rate. These results are in accord with the general hypothesis concerning the occurrence of covert, verbal rehearsal in STM.

The notion that pupillary dilation is the product of a cognitive load imposed by an information-processing task on the CNS has not been received with complete acceptance. One competing notion is that such pupillary dilation is the result of changing anxiety or emotionality concerning performance during such a task (Bernick & Oberlander, 1968; Kahneman & Beatty, 1967). Other investigators (Simpson, 1969; Simpson & Paivio, 1966) have conjectured that pupillary dilation during cognitive activity is the product of some type of overt response artifact which is not directly related to cognitive activity. Kahneman, Peavler, and Onuska (1968) have stated three variations of this latter interpretation. First, the performance of a motor response is said to be directly associated with pupillary change, without mediation by any variable of psychological significance. Second, the organization of an overt act places a demand on the information-processing capacity of the person, and these increased demands are reflected in pupillary dilation. Third, when a cognitive task is performed with and without requirements for overt responding, it is not the same task. Response requirements probably alter an S's strategy in dealing with the cognitive task and thereby influence the amount of effort or degree of processing the S exerts.

In a series of studies, Kahneman, Peavler, and Onuska (1968) attempted to evaluate the emotionality--anxiety interpretation and the various overt response interpretations with regard to cognitive tasks. Using a digit transformation task (Add-0, or Add-1) with a string of four digits being presented, they found that overt responding did add a small amount of pupillary dilation, but major difference were due to variations in task difficulty. This conclusion is in fair agreement with an earlier conclusion reached in the evaluation of overt response indicators in studies of pitch discrimination and stimulus detection. It is also in agreement with the results from another study (Kahneman & Peavler, 1969) using a paired associate learning task. Pupillary dilation to "Blanks" (no overt recall of the response item) under high reward conditions was equal to that for intrusions and correct responses under the same reward condition. In the second part of their study, Kahneman, et. al. (1968) varied incentive conditions, two cents versus 10 cents for every correct digit in performing the transformation task. Incentive had no effect on the "Add-1" condition, but the greater incentive did result in slightly greater dilation in the "Add-0" condition (actually an STM condition). Again, task difficulty appeared to produce the major variations in pupillary diameter. Kahneman and Peavler (1969) found that there was a slight but consistently greater dilation to the response item during the study phase under a high reward condition than under a low reward condition. High reward also produced greater dilation during recall than did low reward.

What conclusions can be drawn from the results of the foregoing studies? First, the hypothesis that overt responses place additional information-processing demands on the individual and thus result in greater dilation appears to be the best supported of the overt response interpretations. Second, the hypothesis that pupillary dilation is solely the result of overt muscular activity in cognitive tasks receives little support. Third, the hypothesis that pupillary dilation is the result of a change in S's strategy due to the necessity of making an overt response appears to explain adequately the effects of making an overt response in imagery tasks. With regard to the effects of incentive and reward conditions on pupillary dilation, it would seem that the emotionality--anxiety interpretation would have to be revised to include a very finely tuned emotional system to account for the reported results. On the other hand, incentive and reward effects could also be explained by the assumption that higher rewards and incentives result in the individual exerting greater effort in the information-processing activity, and thus, resulting in larger dilations. This latter interpretation leads to the prediction of better performance under high reward conditions, and this result has been found (Kahneman & Peavler, 1969).

One final question. Is the pupillary system unique among autonomic systems for its responsiveness to information-processing activity of the CNS? A partial answer comes from a study by Kahneman, Tursky, Shapiro, and Crider (1969). They monitored cardiac rate, GSR, and pupillary diameter during a digit transformation task of "Add-0," "Add-1," and "Add-3." Their results indicated that the three sympathetically innervated systems responded similarly during the cognitive tasks, indicating an increase in sympathetic activity during information intake and processing and a corresponding decrease during report. The pupillary response system appeared to yield the most consistent results. Therefore, a reasonable conclusion seems to be that even though the "load" imposed on an individual by a mental task is small, the autonomic system and especially the pupillary system seems to respond with large and precisely modulated changes associated with such activity.

Short-term Memory Search Processes

Another area of research and theorizing that is relevant to the research problem under consideration is that of STM search processes. Sternberg (1969) has presented a comprehensive review of his research and theory in this area, and the present review will focus mainly on his theoretical contributions which constitutes much of the major work in the area.

Sternberg postulates three different types of STM search tasks. These are item-recognition, context-recall, and context-recognition. Of the three types of tasks, the item-recognition task is the most relevant for the problem to be investigated. Underlying these three tasks are two scanning processes. The first is scanning-to-match which is assumed to be the basic process in the item-recognition task. The second is scanning-to-locate which is assumed to be basic to both context-recall and context-recognition tasks. All STM scanning operations are assumed to take place in "active memory" or STM, and provision is made for the transfer of material from "inactive" or LTM to STM for scanning operations. Sternberg states that scanning operations in STM are not part of the general rehearsal mechanism which maintains items in STM and transfers STM material to LTM.

Of the two postulated scanning processes, high speed exhaustive scan or scanning-to-match is the least intuitive and the most controversial. Supposedly, scanning-to-match involves serially comparing each item in a stored list with a "target" or probe item. A decision of match or mismatch results from each comparison. The comparison process occurs at rates between 25 to 30 characters per second and exhausts the list of stored items before a response decision is made. The serial assumption about the scan process results in a linear relationship between the mean RT for a response which indicates whether the item was found or not in the list and the number of items in that list. The exhaustive assumption results in an equality of the mean RTs indicative of whether an item was or was not in the list of items.

In addition, this latter aspect is said to result in a linear function with zero slope between mean RTs and different serial locations of items in the list when they serve as probes.

Serial self-terminating search or scanning-to-locate is said by Sternberg to involve a comparison process which takes place serially at approximately 4 items per second. The scanning process stops when a match has been made between the probe item and one of the items in the stored list. Therefore, on the average, the function relating mean RTs to number of items in the list should be linear with positive slope. Sternberg does not consider the case where the probe item is not in the list for the scanning-to-locate process. The relationship between position of probe item in the list and the resulting mean RT function is variable. Sternberg says that if the S begins his scan at the first item in the list and proceeds serially, then the function relating mean RT to position in list should be linear with positive slope. On the other hand, if the S begins his scan at a randomly determined place in the list, then the function relating mean RT to position in list should be linear with zero slope. Sternberg conjectures that the rehearsal mechanism of STM may be involved in determining how the S enters the stored list.

In further conjecture, Sternberg says that the differences between the two types of scanning processes may indicate two types of memory representations. One representation is for order information, and the other is only for item information. Thus, two types of memory representations would be stored in STM with each being scanned by a different process.

Several other investigators (Morin, DeRosa, & Stultz, 1967; Morin, DeRosa, & Ulm, 1967) have failed to substantiate in detail Sternberg's theory of exhaustive search in item-recognition tasks. In reply, Sternberg states that fast presentation rates for the items to be stored and short latencies between the last item presented and the probe item may critically influence the nature and duration of comparison operations. Although this may be the case, Kennedy and Hamilton (1969) using nearly the same procedure as Sternberg (1966) have found a marked recency and primacy effect on mean RTs for position of probe in the stored list of items. The major difference between these two studies is that Sternberg used a visual modality whereas Kennedy and Hamilton used an auditory modality. A study by Chase and Calfee (1969) indicated that the search process as hypothesized by Sternberg was not severely altered by the use of an auditory modality as opposed to a visual modality. To add further to the confusion, DeRosa and Morin (1970) used consecutive digits and found that the RTs to items in the middle of a list were much faster than RTs to items at either end of the list. In addition, they found that with nonconsecutive digits the function between position of probe in the list and RT was extremely "noisy" and on the average had zero slope if it could be assumed to be linear. Methodologically, they duplicated Sternberg's (1967) procedure where the S memorized a set of digits after which a series of probe digits are presented without presenting the digit string before each probe. Finally, Wingfield and Branca (1970) substantiated Sternberg's theory of exhaustive serial scanning for sets of items up to six in number, but found a reversal in trend for larger lists which they attributed to S's searching the smaller complement of the presented set.

Problems for Investigation

In general, the pupil response has been demonstrated to be a fruitful indicator of various cognitive processes. The research literature indicates that the pupil response is a measure of some of the information-processing activities taking place in STM storage and retrieval. Be this as it may, a question remains as to whether or not the cognitive process of STM search would have an effect on pupil size because of the proposed rapidity of the process, and the non-phonemic state of the material in the scanning-to-match search. It should be noted that the latencies for reflex pupillary dilation and the RT of both verbal and motor responses to probe items are nearly the same (Loewenfeld, 1958; Sternberg, 1969). It is likely that if any pupil response occurs, it would follow the actual search process and coincide with the overt response or slightly follow it. It is rather difficult to exactly predict the form of the pupil response to STM search, but since the search process is typically postulated to involve a burst of very rapid information-processing, the most likely form would be a very rapid dilation immediately after probe item presentation followed by a rapid decrease in size.

If pupil dilation does occur to STM search, what would be some of the implications for understanding the process of STM search as proposed by Sternberg? The scanning-to-match search is postulated to be serial and exhaustive. If the pupil response is sensitive to this process, then the magnitude of dilation to the probe item should be a monotonic function of set size (number of items to be stored and searched) with positive slope. In addition, the magnitude of the dilations to positive and negative probes should be equal since the scanning process is postulated to be exhaustive.

A second major purpose of the investigation is to evaluate further the assumption that the pupil response does serve as a sensitive indicator of the amount of information-processing that an S performs at the time that he performs it during a trial. For example, cuing an S to forget a set of immediately preceding items typically produces a wave of pupillary dilation then constriction shortly after the S hears the signal to forget even though he must continue to store later items for recall (Johnson, 1969). Cuing an S that he is going to be required to perform an STM search task on a list of items that he has just heard might be expected to result in a different amount of cognitive processing than cuing him that he is not going to be required to perform such a task. The pupil response should reflect such differences as they occur. In addition, if an S knows that he is going to be required to recall a set of items a short time later, he may process those items differently than an S who knows that he will not be required to recall them. Possibly, an S who does not have to recall the items will engage in little if any covert verbal rehearsal of the items, whereas an S who does have to recall might engage in a considerable amount of such rehearsal. Therefore, if the pupil response does reflect changing levels of cognitive processing, then it would be expected to vary within a trial with both instructions to perform an STM search and to recall.

CHAPTER III

METHODOLOGY

Subjects

A total of 16 Ss, 5 male and 11 female, participated completely in the investigation. All were undergraduate students at Oklahoma State University and had volunteered. In terms of some possibly important variables, the following S characteristics were noted. Average age was 20.38 years with range of 18 to 30 years. All Ss had "light" colored irises. Individuals with "dark" irises were rejected because of the lack of photographic contrast between pupil and iris. Such a lack of contrast makes the scoring of the pupillograms difficult and subject to error. Fourteen of the Ss were right handed, one was left handed, and one was ambidextrous. All Ss were given a Snellen Eye Test, and only individuals who scored 20/30 or better in both eyes were used.

A total of eight Ss were eliminated because they blinked over 50 percent of the time when they were required to make an overt response. One S each was eliminated for emotionality, ptosis, and an inability to maintain a steady fixation. All these Ss were eliminated during the practice session.

Apparatus

The basic unit of apparatus was the pupillometer. This unit was similar in some respects to the unit employed by Hess (1965), but had several modifications. Essentially, it was a rectangular box constructed of ½ inch plywood. It measured 58 cm. wide by 58 cm. deep by 123 cm. long. At one end, a 46.36 cm square rear projection screen was mounted in a tightly fitting wooden frame. The other end was completely enclosed except for provision for S's viewing. This provision consisted of a soft plastic, welder's goggle mounted in the center of the square end piece so that S's line of sight was about the central long axis of the box. Mounted in the goggle was a mask with eye holes of such dimensions that S's eye and head placement was nearly the same and also to eliminate the camera lens and other pieces of equipment from S's view. An adjustable chin rest was also provided to aid in maintaining a constant head position from trial to trial. On the S's right, as he faced the pupillometer, a cine camera was mounted 39 cm. from the front end and 29.5 cm. from the bottom of the unit. The camera mount was fully adjustable both vertically and horizontally. The camera lens fitted tightly to a system of sliding panels so that no extraneous light was transmitted into the interior of the pupillometer.

The interior of the pupillometer consisted of a half-silvered mirror mounted in a wooden frame which snuggly fitted all four walls of the box. The mirror was positioned with the left edge against the S's end of the box and running away from the S at a 45^{o} angle to the vertical plane of S's line of sight. This arrangement resulted in the image of S's right eye being reflected into the camera lens system from a distance of 64.8 cm. All interior surfaces were painted flat black to reduce stray reflectances. When the pupillometer was appropriately illuminated the S had an unobstructed view of the rear projection screen.

The camera system employed was a Beaulieu R16ES with a Vemar 135 mm. f/2.8 telephoto lens. The complete lens system had the additional elements of a "T" to "C" mount adapter and 30 mm. of extension tubes which resulted in an approximate 3.6:1 reduction ratio of real image size to film image size. Camera speed was set at approximately 2 frames per second with an exposure duration of 0.2 second per frame. The camera power supply was a specially designed 7.2 volt, 1.5 ampere, AC to DC unit. The film used was Kodak Double "X" Negative in 100' rolls.

The rear projection screen was illuminated by a Kodak Carousel Projector, Model 650, with an f/3.5, 4 to 6 inch zoom lens. The projector was equipped with a blank slide and positioned 83 cm. from the rear of the pupillometer with the projector's lens system centered on the central long axis of the pupillometer. A 30 cm. square light field was focused on the screen with a fixation cross attached to the screen in the exact center of the field. The arms of the fixation cross were 10 mm. long and 2 mm. wide. The distance from S's eye to the fixation cross was approximately 125.8 cm., and the illumination level at S's right eye was 15 ft-c. This illumination served as the photographic light source, as well as general visual light source. All Ss were run in a light adapted state.

All stimulus materials were presented auditorially at a comfortable and constant intensity level to the S via Clevite-Brush monophonic headphones from the right channel of a Wollensak, Model 5730, stereophonic tape recorder. The tape recorder also played the stimulus material over an external speaker to aid E in monitoring trial events and to mask any extraneous noises. On the left channel of the tape a 6.5 KHz. tone was recorded in appropriate temporal relationship with the trial events on the right channel. This tone was fed into a Kodak Carousel, Model 1, Programmer which actuated the starting and stopping of the cine camera at the appropriate time points during the presentation of a trial.

A Grason-Stadler, Model E7300A-1, voice relay was used to actuate a Hunter Model 120A Klock Kounter on the occurrence of a particular digit. The clock was stopped by S throwing a toggle switch to either the right or left from a neutral center position. This switch was mounted on the pupillometer at the bottom right corner in such a position that S's right hand rested comfortably on the table while he held the toggle switch between his thumb and index finger.

The entire study was run in a small 20' by 7' air-conditioned room with no windows. The room was evenly illuminated by florescent lighting. Resultant illumination at the S's eye level was 125 ft-c. External noise levels were extremely low.

Stimulus Materials

The first nine monosyllable digits were "randomly" arranged into lists of four, five, and six digits each. A single digit was paired with each list. This latter digit (probe digit) was either the same as one of the digits in the list (positive probe), or it was different from all the digits in the list (negative probe). Twelve different lists were generated for each of the different lengths of lists (set size). Within each of these set sizes, six lists had negative probes paired with them, and six had positive probes paired with them. The position of the positive probe in the list of digits was systematically varied so that two lists each had the positive probe at the first position, the "middle" position, and last position in the list. The relation of the negative probe to its lists was allowed to vary randomly.

Thus, 36 lists of digits and probes were generated for the experimental trials with one list corresponding to one trial. The restrictions on the "random" generation of the lists and probes were such that each digit occurred with a total frequency of 24 times, with a frequency as a positive probe 2 times, and with a frequency as a negative probe 2 times. In addition, 12 lists each for set sizes two and three with probes were generated for use as practice trials. All digit lists and probes were recorded in a monotone on magnetic tape. The recording of all materials was paced by a Hunter Interval Timer wired to recycle itself at a 1 per second rate.

On the first recording of the digit lists and probes, a 600 Hz. tone was recorded immediately after the last digit in the list and well before the probe digit for 18 of the lists. The remaining 18 lists were not followed by a tone. On a second recording, the lists which previously had not been followed by a tone had a tone recorded after the last digit and vice versa. The tone (or lack of it) served during the experiment as a signal to perform an STM search of the list of digits.

Following the recording of the digit lists, tones, etc., there was a 2 second pause before the probe digit was recorded. After the probe digit another 2 second pause occurred then a series of 600 Hz. tones were recorded. The total number of tones after the probe digit was one greater than the number of digits preceding the probe. These tones were used to initiate and pace S's recall when required.

In summary, the S heard the following events on each trial. First, a period of silence that lasted 4 seconds. Second, a string of digits read in monotone at a 1 per second rate. Third, a tone or no tone occurred immediately after the last digit in the list. Fourth, there was a 2 second period of silence preceding the probe digit. Fifth, the probe digit was presented. Sixth, another 2 second pause followed the probe digit. Seventh, a series of tones was heard. Finally, a 2 second period of silence followed the tones before the trial was ended.

Two randomly ordered series of trials were recorded from each of the two master tapes for the experimental trials. Thus, there were four different sets of 36 trials used in the experiment. The order of the trials was randomized to prevent any systematic confounding or order effects with the within-Ss variables.

A camera control signal was recorded on the remaining channel of the tape opposite each trial. The signal began 4 seconds before the first digit of each list and continued until 2 seconds after the last tone for recall on each trial.

Experimental Task and Design

The basic task of the S was an STM search. This task required that the S respond as rapidly as he could to the occurrence of the probe digit indicating by his response whether the probe digit was or was not in the preceding set of digits. In this study, the S's response was throwing a toggle switch to either the right or left depending on his instructions.

The basic design of the study involved the factorial combination of three within-Ss variables and one between-Ss variable. The within-Ss variables consisted of whether the S was cued to make an STM search on a particular trial, the number of digits (four, five, or six) in the presented list, and whether the probe digit was in the previously presented list or not. The between-Ss variable consisted of whether the S was or was not instructed to recall the digit string in correct serial order in time with the series of tones following the probe. The first of these tones served as a warning signal to the S to begin recall on the next tone. Half of the Ss received instructions to recall.

Several other variables were manipulated between Ss. These variables were not of theoretical interest, but were manipulated to control sources of variability and to provide checks on certain possible sources of error. For one half of the Ss, the occurrence of a tone following the digit list was an instruction to search; for the other half, the absence of the tone served as the search instruction. In the performance of the search task, half of the Ss in each subgroup were instructed to throw the toggle switch to the left if the probe digit was positive and to the right if it was negative. The other half of the Ss in each subgroup received the opposite instructions. Finally, half of the Ss received one random series of trials whereas the other half received another series.

Experimental Procedures

All Ss were randomly assigned to the appropriate treatment conditions prior to their arrival at the laboratory. Upon S's arrival, he was asked if he knew anything about eye changes and psychological events. He was also asked if he had any known eye abnormalities or whether he was having headaches, trouble in reading texts, etc. The S was then given an eye test.

The S was seated at the pupillometer and told he could look at and in the equipment. The chin rest, head set, camera focus and f-stop were adjusted, and the equipment turned on. The S was then read the appropriate instructions by E, and asked if he had any questions. A copy of the instructions read to each S can be found in the Appendix.

An identification number was photographed for each S prior to beginning the series of 24 practice trials. No pupillometric data was recorded for the practice trials, but in all other aspects the practice trials were the same as the experimental trials. At the end of the practice session E asked S if he had any further questions. Testing then commenced with the appropriate set of experimental trials.

Each trial began by E asking S to get into correct position at the pupillometer, then E started the tape recorder and the trial was run. At the end of the trial, E stopped the tape recorder and asked S to lean back and relax. E recorded S's response and RT, if appropriate, and informed S if his response was correct. Next, E advanced the film in the camera two frames to separate each trial from the other, and reset the timing equipment if necessary. The time interval between trials was approximately 15 to 20 seconds. At the end of the 22nd experimental trial, the S was given an approximately 1 minute rest to relieve fatigue and boredom. Testing then continued until the end of the session. At the end of the experimental trials, all trials in which a decision error had been committed by the S were rerun in the order in which they occurred.

Response Measurements

Three response variables consisting of change in pupillary diameter (pupil response), RT to probe digit, and recall errors were measured. The pupil response involved the increase or decrease of of pupil size from a baseline value during a trial. Each frame of film was projected at a 10 power magnification of real size via a modified film strip projector on to a flat white screen. Millimeter graduated rules were used by E to measure pupil diameter to the nearest whole millimeter. Resulting data was real pupillary diameter measured to the nearest 0.1 mm. The first nine frames on each trial were averaged for a baseline mean. This mean was subtracted from the absolute diameter values from all frames of that trial. These latter deviation values constituted the pupil response data. It was discovered after the experiment was finished that camera speed was faster than 2 frames per second (actually approximately 2.2 frames per second). A frame elimination algorithm was employed which "eliminated" excess frames for each trial. The result was that no frame deviated from its ideal time of occurrence by more than 0.245 seconds, and only a few frames deviated by that amount.

The RT to the probe digit was measured to the nearest millisecond on trials where S made a correct decision. No RT measures were included in the data calculations from trials in which S made a wrong decision. During recall, an error was counted when the S failed to give the correct digit in its correct position in sequence. Such a stringent criterion was employed because of the small number of items to be recalled as well as the moderately easy nature of the material (digits).

CHAPTER IV

RESULTS

Pupillary Response

The statistical design of the study involved the factorial combination of several between-Ss and within-Ss variables. The between-Ss dimension included the variables of direction of toggle switch throw (left versus right), order of experimental trials (two random orders), type of signal for performing search (tone or the absence of a tone), and recall instruction (recall required or not). One Ss served in each of the 16 between-Ss treatment combinations. The within-Ss dimension included the variables of frames during a trial (number varied according to the size of the list of digits), search (STM search required or not), type of probe (negative versus positive), and set size (number of digits in the presented list).

Each treatment combination contained three trials which were averaged to produce one mean for each treatment combination. As a result, the pupil response measure for three corresponding frames were averaged and the result was a mean pupil response (MPR) value for each frame. Some of the MPRs were based on less than three values due to eye blinks and Ss' shift of fixation point. Less than 2.03 percent of the total number of frames were eliminated by these events. The MPR for the first eight frames and the last frame were eliminated from the data analysis. The result was that set size four contained 26 frames, set size five contained 30 frames, and set size six contained 34 frames.

The MPRs for the two levels of direction of toggle switch throw, order of experimental trials, and type of signal for performing search were averaged for each set size. A comparison of the three pairs of means for each set size via t tests produced no significant differences ($p < 0.10$). Since these variables were not of theoretical interest, they were eliminated from all further data analyses.

Next, an analysis of the overall effects of the experimental treatments on the pupil response was performed. In Table I, an analysis of variance of the averaged MPRs across frames for each set size revealed that the recall and search main effects and the set size by recall interaction were significant. The F ratios for within-Ss effects were tested for significance with the dfs corrected for hetereogeniety and lack of symmetry of the population variance--covariance matrices (Kirk, 1968, pp. 256-263). This correction involves a reduction in the dfs used in evaluating the F ratio for significance, and results in a statistically conservative test. This correction was employed in all tests where appropriate.

Since the initial analysis indicated that there were some significant treatment effects on the pupil response, further analyses were performed on the MPRs with the frames variable included. The inclusion of the frames variable added a "temporal" dimension to the analyses. The occurrence of events during a trial are placed on the abscissas of Figures 1 through 6. The symbol "D" represents the presentation of a digit, "P" a probe digit, "W" a warning signal for recall, and "R" the recall of a digit. It was assumed that different cognitive processes were dominant during different temporal intervals (phases) of a trial.

TABLE I

AOV OF AVERAGE PUPIL RESPONSE OVER THREE SET SIZES

Source	df	MS	F (df corrected)[1]
Total	191	0.04486	
Between Ss	15	0.35713	
R (Recall)	1	4.38681	63.302***
Ss w. Grps.	14	0.06930	
Within Ss	176	0.01825	
P (Probe)	1	0.00804	0.648
E (Search)	1	0.64284	32.966***
PE	1	0.04222	3.228#
X (Set Size)	2	0.06504	3.523#
PX	2	0.00732	0.881
EX	2	0.01634	1.853
PEX	2	0.00201	0.142
PR	1	0.00220	0.177
ER	1	0.08008	4.107#
PER	1	0.00068	0.052
XR	2	0.08617	4.668*
PXR	2	0.00032	0.039
EXR	2	0.01881	2.132
PEXR	2	0.01037	0.732
Ss w. Grps. P	14	0.01241	
Ss w. Grps. E	14	0.01950	
Ss w. Grps. PE	14	0.01308	
Ss w. Grps. X	28	0.01846	
Ss w. Grps. PX	28	0.00831	
Ss w. Grps. EX	28	0.00882	
Ss w. Grps. PEX	28	0.01416	

[1]See text for explanation. Note: Significance levels are represented in all tables by the following: # = $0.05 < p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. All tests are one-tail unless otherwise noted.

Four phases were identified. The first phase was "Digit Loading." This phase began and ended with the presentation of the list of digits. During this phase, the Ss were assumed to be listening to the lists of digits and "storing" them in some manner. The second phase was "Rehearsal." This phase began after the sequence of the last digit and search cue were presented, and it ended with the presentation of the probe digit. During this phase, it was presumed that Ss who had to recall were covertly rehearsing the list of digits. In addition, it was presumed that Ss who would be required to search might engage in some form of list processing. The third phase was "Probe." This phase began after the occurrence of the probe digit and ended 1.5 seconds later. Presumably, Ss who had to search were engaged in that process during this phase. The fourth and last phase was "Recall." This phase began immediately after the "warning" signal to prepare to begin recall and ended 1 second after the last signal for the recall of the last digit. Naturally, the dominant cognitive process for Ss who had to recall was assumed to be recalling of the digit list. Subsequent analyses were performed to evaluate the affects of the different cognitive processes on the pupil response during a trial.

Initially, separate analyses for each set size were performed because of the differing number of frames for each set size. In Table II, an analysis of variance for set size four revealed that the recall, frames, and search main effects were significant, as well as the frames by search and the frames by recall interactions. These effects can be seen in Figures 1 (search) and 2 (no search) by comparing treatment conditions. Typically, recall resulted in greater dilation in nearly all frames as compared to no recall. Search resulted in greater

TABLE II

AOV OF PUPIL RESPONSE TO SET SIZE FOUR

Source	df	MS	F (df corrected)
Total	1663	0.08598	
Between Ss	15	2.13816	
R (Recall)	1	24.48393	45.171***
Ss w. Grps.	14	0.54203	
Within Ss	1648	0.06730	
F (Frames)	25	1.69134	44.556***
E (Search)	1	9.55946	27.455***
FE	25	0.42930	30.796***
P (Probe)	1	0.30479	1.462
FP	25	0.01090	1.146
EP	1	0.36899	0.744
FEP	25	0.00677	0.693
FR	25	0.24808	6.535*
ER	1	0.00246	0.007
FER	25	0.02721	1.952
PR	1	0.00152	0.007
FPR	25	0.00428	0.450
EPR	1	0.03402	0.069
FEPR	25	0.02151	2.202
Ss w. Grps. F	350	0.03796	
Ss w. Grps. E	14	0.34819	
Ss w. Grps. FE	350	0.01394	
Ss w. Grps. P	14	0.20849	
Ss w. Grps. FP	350	0.00951	
Ss w. Grps. EP	14	0.49627	
Ss w. Grps. FEP	350	0.00977	

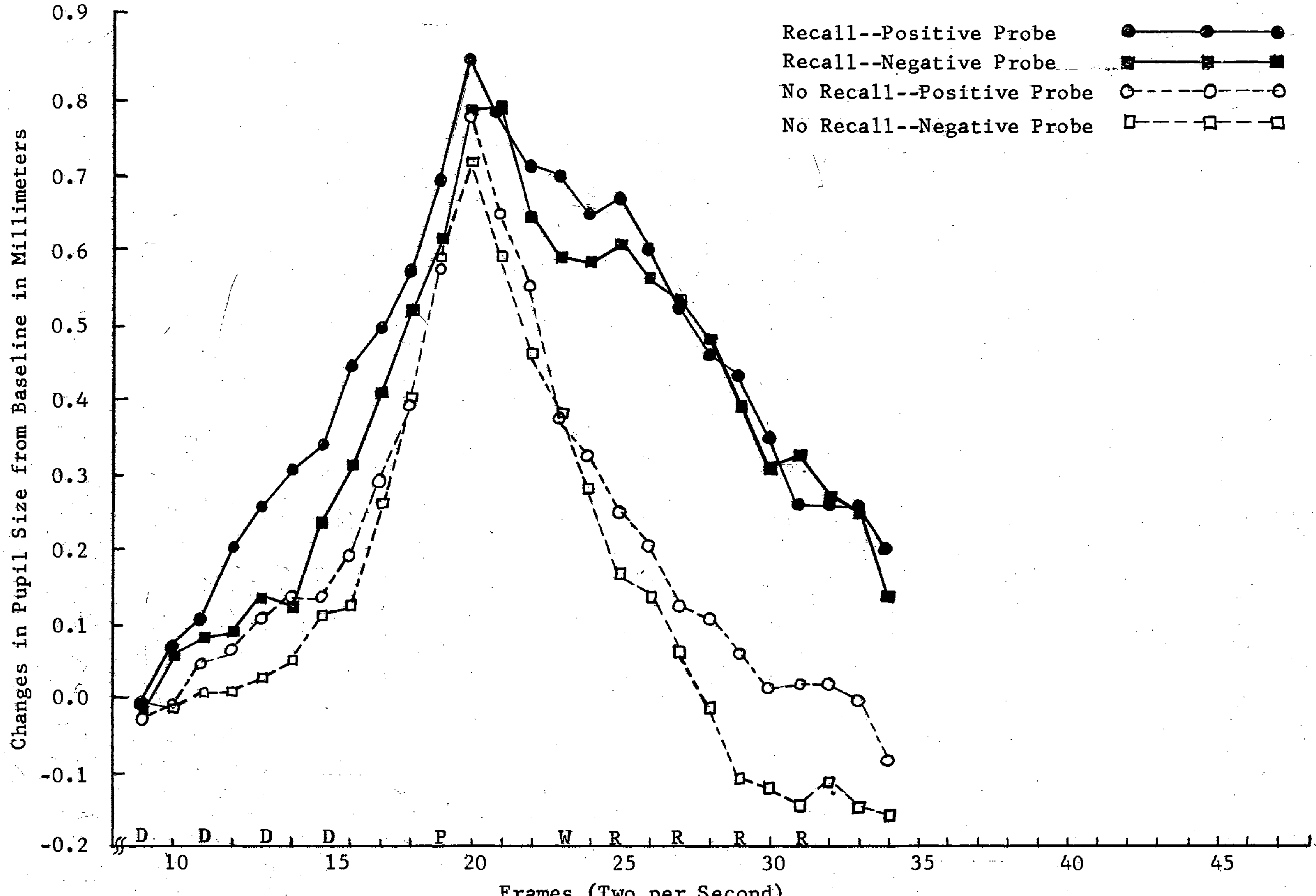

Figure 1. Pupil Response During Recall and No Recall for Search Trials with Set Size Four

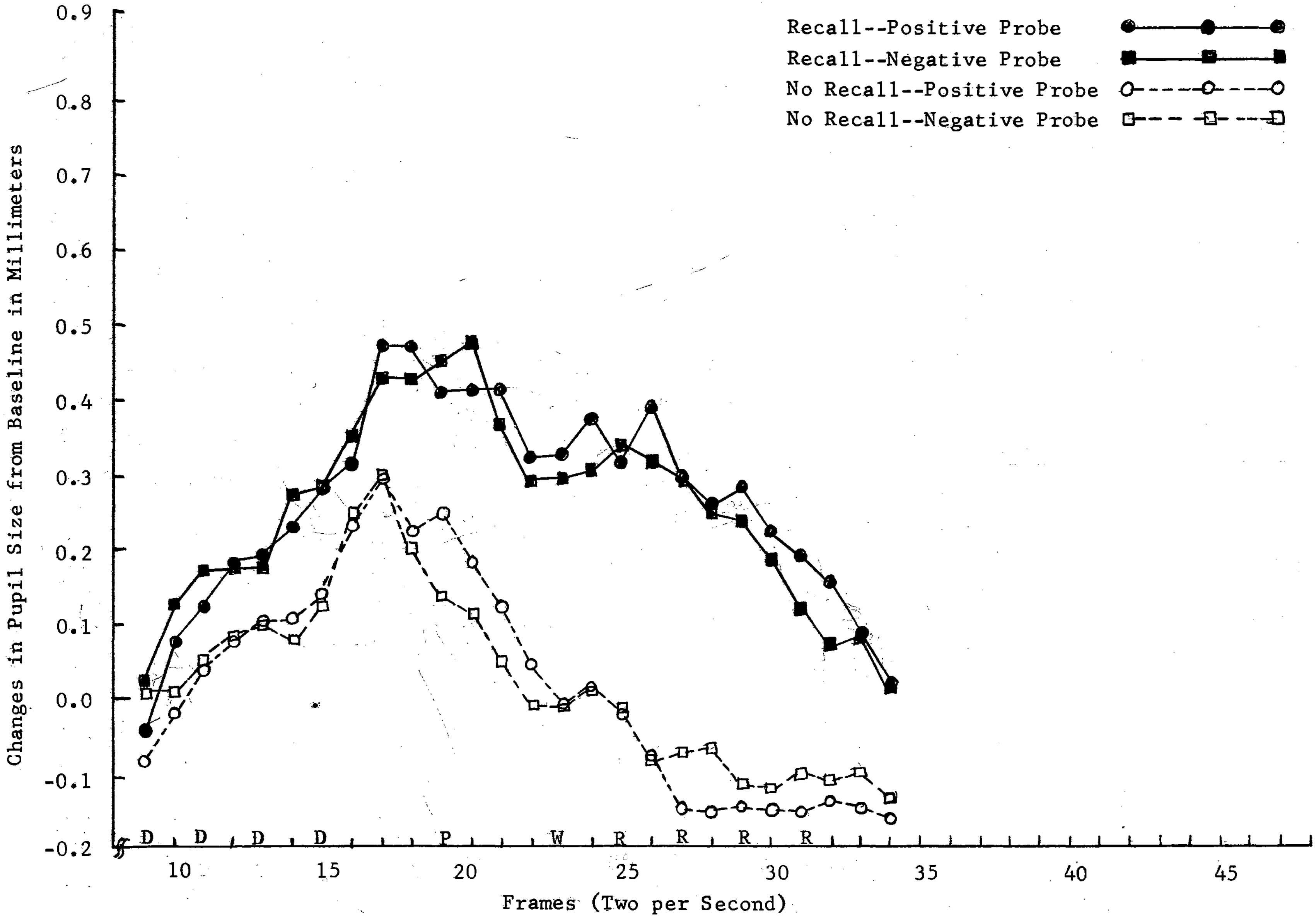

Figure 2. Pupil Response During Recall and No Recall for No Search Trials with Set Size Four

dilation from frame number 17 until the end of the trial.

In order to evaluate the significant interactions, separate analyses of variance were performed for recall, no recall, search, and no search conditions. Tables III and IV present the results of this analysis for recall and no recall conditions. The frames and search main effects and the frames by search interactions were significant in both conditions. Tables V and VI present the results of the analysis of the search and no search conditions. The recall and frames main effects were significant in both. The frames by recall interaction was significant only in the search condition. Briefly, these results indicate that the dilation and constriction of the pupil during trials is significant. Second, the difference between the shapes of the pupillograms for search and no search in Figures 1 and 2 for recall are significant, and the same is true for the no recall condition. Third, the difference between the shapes of the recall and no recall pupillograms in Figure 1 for search are significant, but the same is not true for the no search condition in Figure 2.

The pupillograms for set size five are presented in Figures 3 and 4. The analysis of this data, presented in Table VII, indicates that the recall, frames, and search main effects and the frames by search and the frames by recall interactions were significant. Separate analyses for recall (Table VIII), no recall (Table IX), search (Table X), and no search (Table XI) were performed to evaluate the main analysis interactions. Within the recall condition, the frames main effect and the frames by search interaction were significant, whereas in the no recall condition the frames and search main effects and the frames by search interaction are significant. In both the search and

TABLE III

AOV OF PUPIL RESPONSE TO SET SIZE FOUR WITH RECALL

Source	df	MS	F (df corrected)
Total	831	0.07683	
Between Ss	7	1.01439	
Within Ss	824	0.06886	
F (Frames)	25	0.99705	19.961**
E (Search)	1	4.62748	26.153**
FE	25	0.16504	13.396**
P (Probe)	1	0.17464	0.877
FP	25	0.00674	0.611
EP	1	0.08946	0.121
FEP	25	0.01097	1.111
Ss w. F	175	0.04995	
Ss w. E	7	0.17694	
Ss w. FE	175	0.01232	
Ss w. P	7	0.19912	
Ss w. FP	175	0.01104	
Ss w. EP	7	0.73800	
Ss w. FEP	175	0.00988	

TABLE IV

AOV OF PUPIL RESPONSE TO SET SIZE FOUR WITH NO RECALL

Source	df	MS	F (df corrected)
Total	831	0.06577	
Between Ss	7	0.06968	
Within Ss	824	0.06574	
F (Frames)	25	0.94237	36.301***
E (Search)	1	4.93444	9.499*
FE	25	0.29147	18.732**
P (Probe)	1	0.13166	0.605
FP	25	0.00843	1.056
EP	1	0.31355	1.232
FEP	25	0.01730	1.791
Ss w. F	175	0.02596	
Ss w. E	7	0.51943	
Ss w. FE	175	0.01556	
Ss w. P	7	0.21785	
Ss w. FP	175	0.00798	
Ss w. EP	7	0.25454	
Ss w. FEP	175	0.00966	

TABLE V

AOV OF PUPIL RESPONSE TO SET SIZE FOUR WITH SEARCH

Source	df	MS	F (df corrected)
Total	831	0.09954	
Between Ss	15	1.21828	
R (Recall)	1	11.99757	26.761***
Ss w. Grps.	14	0.44833	
Within Ss	816	0.07897	
F (Frames)	25	1.65136	67.985***
P (Probe)	1	0.67225	1.663
FP	25	0.00906	0.852
FR	25	0.15812	6.510*
PR	1	0.01059	0.026
FPR	25	0.01641	1.542
Ss w. Grps. F	350	0.02429	
Ss w. Grps. P	14	0.40416	
Ss w. Grps. FP	350	0.01064	

TABLE VI

AOV OF PUPIL RESPONSE TO SET SIZE FOUR WITH NO SEARCH

Source	df	MS	F (df corrected)
Total	831	0.06102	
Between Ss	15	1.24502	
R (Recall)	1	12.48884	28.262***
Ss w. Grps.	14	0.44189	
Within Ss	816	0.03926	
F (Frames)	25	0.46928	16.997**
P (Probes)	1	0.00153	0.005
FP	25	0.00861	0.997
FR	25	0.11717	4.244#
PR	1	0.02495	0.083
FPR	25	0.00937	1.085
Ss w. Grps. F	350	0.02761	
Ss w. Grps. P	14	0.30059	
Ss w. Grps. FP	350	0.00864	

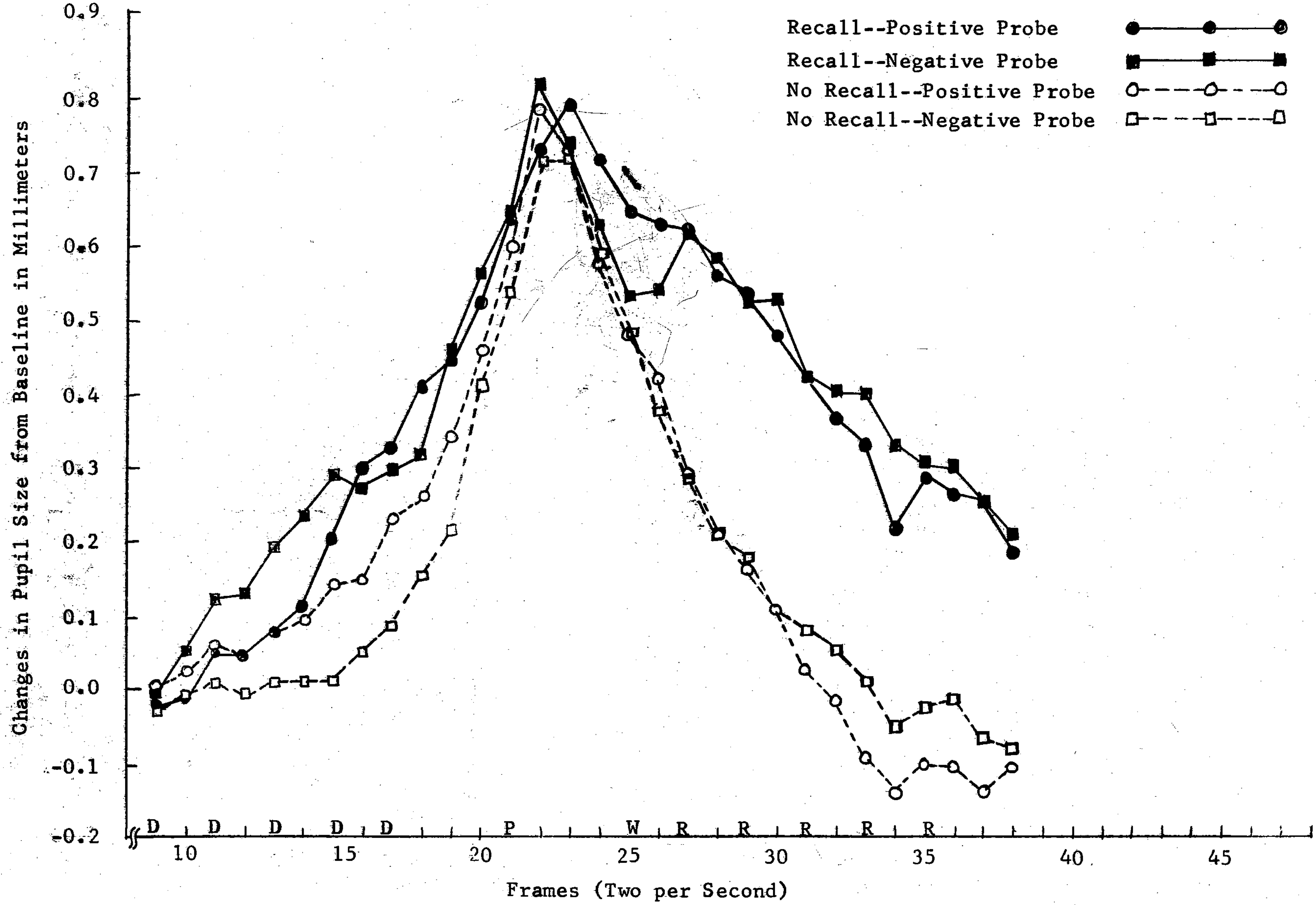

Figure 3. Pupil Response During Recall and No Recall for Search Trials with Set Size Five

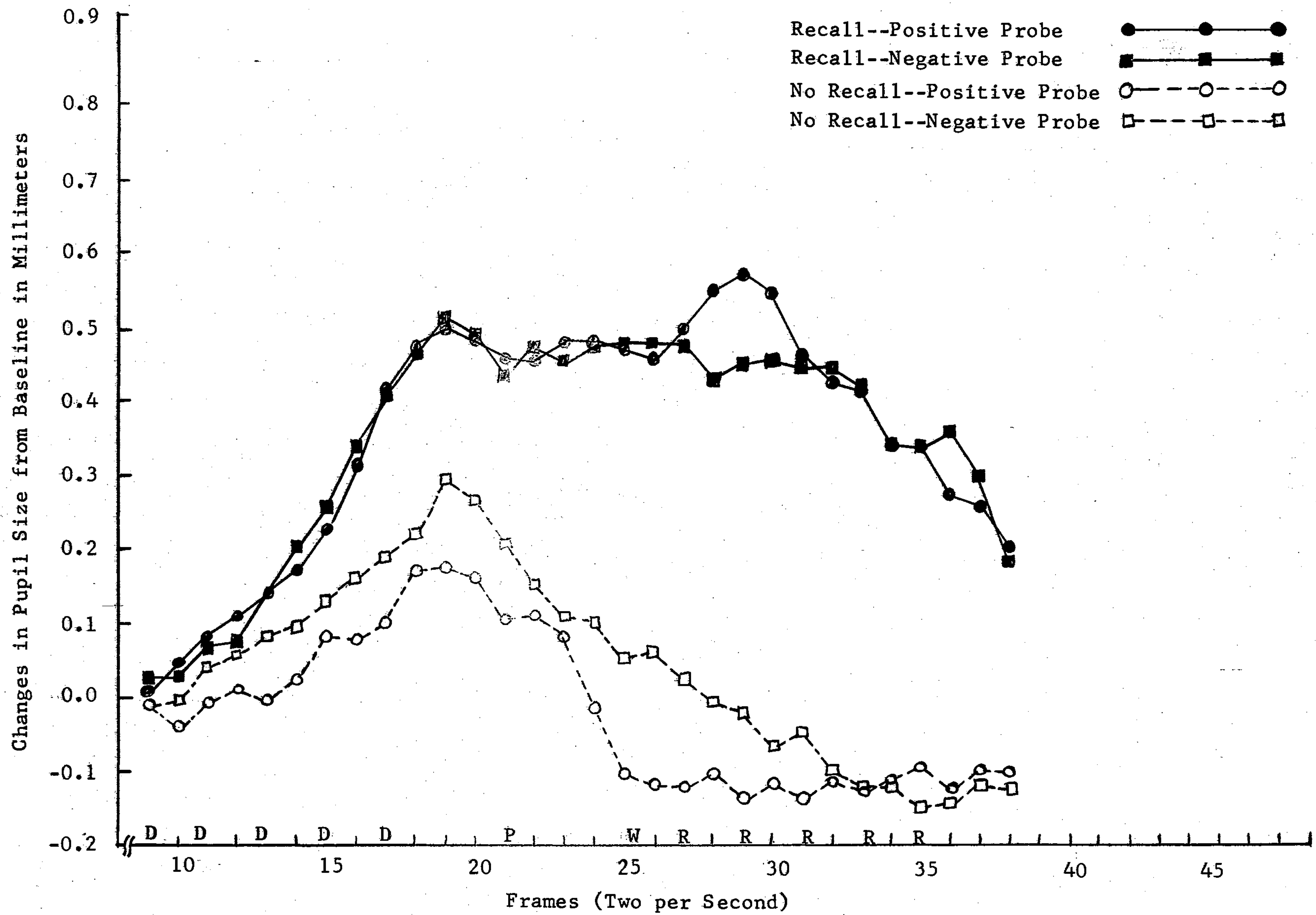

Figure 4. Pupil Response During Recall and No Recall for No Search Trials with Set Size Five

TABLE VII

AOV OF PUPIL RESPONSE TO SET SIZE FIVE

Source	df	MS	F (df corrected)
Total	1919	0.09797	
Between Ss	15	3.75050	
R (Recall)	1	37.66011	28.350***
Ss w. Grps.	14	1.32838	
Within Ss	1904	0.06828	
F (Frames)	29	1.54170	37.411***
E (Search)	1	5.32537	9.532**
FE	29	0.38379	17.727***
P (Probe)	1	0.06537	0.214
FP	29	0.00740	0.529
EP	1	0.16194	0.601
FEP	29	0.01952	1.572
FR	29	0.36588	8.878**
ER	1	2.24177	4.013#
FER	29	0.05523	2.551
PR	1	0.02873	0.094
FPR	29	0.01568	1.120
EPR	1	0.32868	1.220
FEPR	29	0.01550	1.248
Ss w. Grps. F	406	0.04121	
Ss w. Grps. E	14	0.55866	
Ss w. Grps. FE	406	0.02165	
Ss w. Grps. P	14	0.30591	
Ss w. Grps. FP	406	0.01400	
Ss w. Grps. EP	14	0.26945	
Ss w. Grps. FEP	406	0.01242	

TABLE VIII

AOV OF PUPIL RESPONSE TO SET SIZE FIVE WITH RECALL

Source	df	MS	F (df corrected)
Total	959	0.06985	
Between Ss	7	1.56773	
Within Ss	952	0.05884	
F (Frames)	29	1.04973	31.637***
E (Search)	1	0.32839	0.884
FE	29	0.09326	7.425*
P (Probe)	1	0.00371	0.011
FP	29	0.01094	0.075
EP	1	0.01460	0.048
FEP	29	0.01195	0.963
Ss w. F	203	0.03318	
Ss w. E	7	0.37171	
Ss w. FE	203	0.01457	
Ss w. P	7	0.33920	
Ss w. FP	203	0.01457	
Ss w. EP	7	0.30284	
Ss w. FEP	203	0.01241	

TABLE IX

AOV OF PUPIL RESPONSE TO SET SIZE FIVE WITH NO RECALL

Source	df	MS	F (df corrected)
Total	959	0.08511	
Between Ss	7	1.08904	
Within Ss	952	0.07773	
F (Frames)	29	0.85785	17.425**
E (Search)	1	7.23874	9.709*
FE	29	0.34576	11.248*
P (Probe)	1	0.09039	0.332
FP	29	0.01215	0.904
EP	1	0.47602	2.017
FEP	29	0.02307	1.855
Ss w. F	203	0.04923	
Ss w. E	7	0.74561	
Ss w. FE	203	0.03074	
Ss w. P	7	0.27262	
Ss w. FP	203	0.01344	
Ss w. EP	7	0.23606	
Ss w. FEP	203	0.01244	

TABLE X

AOV OF PUPIL RESPONSE TO SET SIZE FIVE WITH SEARCH

Source	df	MS	F (df corrected)
Total	959	0.11331	
Between Ss	15	1.91712	
R (Recall)	1	10.76265	8.374*
Ss w. Grps.	14	1.28529	
Within Ss	944	0.08465	
F (Frames)	29	1.58537	37.524***
P (Probe)	1	0.01076	0.028
FP	29	0.01591	1.065
FR	29	0.14992	3.548#
PR	1	0.08153	0.213
FPR	29	0.01572	1.052
Ss w. Grps. F	406	0.04225	
Ss w. Grps. P	14	0.38291	
Ss w. Grps. FP	406	0.01494	

TABLE XI

AOV OF PUPIL RESPONSE TO SET SIZE FIVE WITH NO SEARCH

Source	df	MS	F (df corrected)
Total	959	0.07537	
Between Ss	15	2.50425	
R (Recall)	1	29.13931	48.424***
Ss w. Grps.	14	0.60175	
Within Ss	944	0.03677	
F (Frames)	29	0.34012	16.503**
P (Probe)	1	0.21655	1.125
FP	29	0.01102	0.959
FR	29	0.27118	13.158**
PR	1	0.27588	1.434
FPR	29	0.01547	1.346
Ss w. Grps. F	406	0.02061	
Ss w. Grps. P	14	0.19244	
Ss w. Grps. FP	406	0.01149	

no search conditions, the recall and frames main effects were significant. In addition, the frames by recall interaction was significant in the no search condition. In terms of the pupillograms, these results indicate that there are significant differences between the search (Figure 3) and no search (Figure 4) curve shapes when recall was required, and in addition, there are significant differences between the forms of the curves for search and no search when recall was not required. Under the search condition in Figure 3, the curve shapes for recall and no recall are not significantly different, but under the no search condition in Figure 4, they are significantly different. This latter result is the reverse of that found for set size four.

The main analysis of the data for set size six is presented in Table XII. The significant effects in the analysis of variance were recall, frames, search, frames by search interaction, frames by recall interaction, and the search by recall interaction. Separate analyses of variance were performed for the recall and search variables. In the recall analysis, presented in Table XIII, the frames main effect was the only significant effect. In the no search analysis, presented in Table XIV, the frames and search main effects and the frames by search interaction were significant. In both the search (Table XV) and the no search (Table XVI) analyses, the recall effects, frames effects, and the frames by recall interactions were significant. The significant search by recall interaction in the main analysis appears to be due to the shift in the size of the effect of the search variable from relatively small under recall to relatively large under no recall. This interaction was not significant in the other set size main analyses.

TABLE XII

AOV OF PUPIL RESPONSE TO SET SIZE SIX

Source	df	MS	F (df corrected)
Total	2175	0.11212	
Between Ss	15	6.65827	
R (Recall)	1	80.31863	57.501***
Ss w. Grps.	14	1.39682	
Within Ss	2160	0.06667	
F (Frames)	33	1.49360	44.020***
E (Search)	1	4.43014	25.377***
FE	33	0.36732	22.604***
P (Probe)	1	0.29928	0.814
FP	33	0.00759	0.844
EP	1	0.90599	1.998
FEP	33	0.01394	1.061
FR	33	0.73108	21.547***
ER	1	1.45704	8.347*
FER	33	0.07171	4.413#
PR	1	0.06190	0.168
FPR	33	0.01031	1.147
EPR	1	0.31126	0.687
FEPR	33	0.00694	0.528
Ss w. Grps. F	462	0.03393	
Ss w. Grps. E	14	0.17457	
Ss w. Grps. FE	462	0.01625	
Ss w. Grps. P	14	0.36778	
Ss w. Grps. FP	462	0.00899	
Ss w. Grps. EP	14	0.45343	
Ss w. Grps. FEP	462	0.01314	

TABLE XIII

AOV OF PUPIL RESPONSE TO SET SIZE SIX WITH RECALL

Source	df	MS	F (df corrected)
Total	1087	0.08500	
Between Ss	7	2.43820	
Within Ss	1080	0.06975	
F (Frames)	33	1.32189	34.175***
E (Search)	1	0.40294	2.588
FE	33	0.07145	4.719#
P (Probe)	1	0.31671	1.101
FP	33	0.00928	0.875
EP	1	1.13967	1.634
FEP	33	0.01304	0.775
Ss w. F	231	0.03868	
Ss w. E	7	0.15568	
Ss w. FE	231	0.01514	
Ss w. P	7	0.28778	
Ss w. FP	231	0.01061	
Ss w. EP	7	0.69741	
Ss w. FEP	231	0.01682	

TABLE XIV

AOV OF PUPIL RESPONSE TO SET SIZE SIX WITH NO RECALL

Source	df	MS	F (df corrected)
Total	1087	0.06546	
Between Ss	7	0.35544	
Within Ss	1080	0.06358	
F (Frames)	33	0.90279	30.949***
E (Search)	1	5.48423	28.348**
FE	33	0.36758	21.186**
P (Probe)	1	0.04448	0.099
FP	33	0.00862	1.168
EP	1	0.07759	0.371
FEP	33	0.00784	0.828
Ss w. F	231	0.02917	
Ss w. E	7	0.19346	
Ss w. FE	231	0.01735	
Ss w. P	7	0.44778	
Ss w. FP	231	0.00738	
Ss w. EP	7	0.20944	
Ss w. FEP	231	0.00947	

TABLE XV

AOV OF PUPIL RESPONSE TO SET SIZE SIX WITH SEARCH

Source	df	MS	F (df corrected)
Total	1087	0.12243	
Between Ss	15	2.84960	
R (Recall)	1	30.06999	33.216***
Ss w. Grps.	14	0.90529	
Within Ss	1072	0.08427	
F (Frames)	33	1.48758	54.791***
P (Probe)	1	1.12336	1.899
FP	33	0.01112	0.791
FR	33	0.35903	13.224**
PR	1	0.32539	0.550
FPR	33	0.00815	0.580
Ss w. Grps. F	462	0.02715	
Ss w. Grps. P	14	0.59142	
Ss w. Grps. FP	462	0.01406	

TABLE XVI

AOV OF PUPIL RESPONSE TO SET SIZE SIX WITH NO SEARCH

Source	df	MS	F (df corrected)
Total	1087	0.09784	
Between Ss	15	4.06874	
R (Recall)	1	51.70581	77.626***
Ss w. Grps.	14	0.66609	
Within Ss	1072	0.04228	
F (Frames)	33	0.37334	16.218**
P (Probe)	1	0.08192	0.357
FP	33	0.01041	1.288
FR	33	0.44376	19.277***
PR	1	0.04777	0.207
FPR	33	0.00909	1.125
Ss w. Grps. F	462	0.02302	
Ss w. Grps. P	14	0.22978	
Ss w. Grps. FP	462	0.00808	

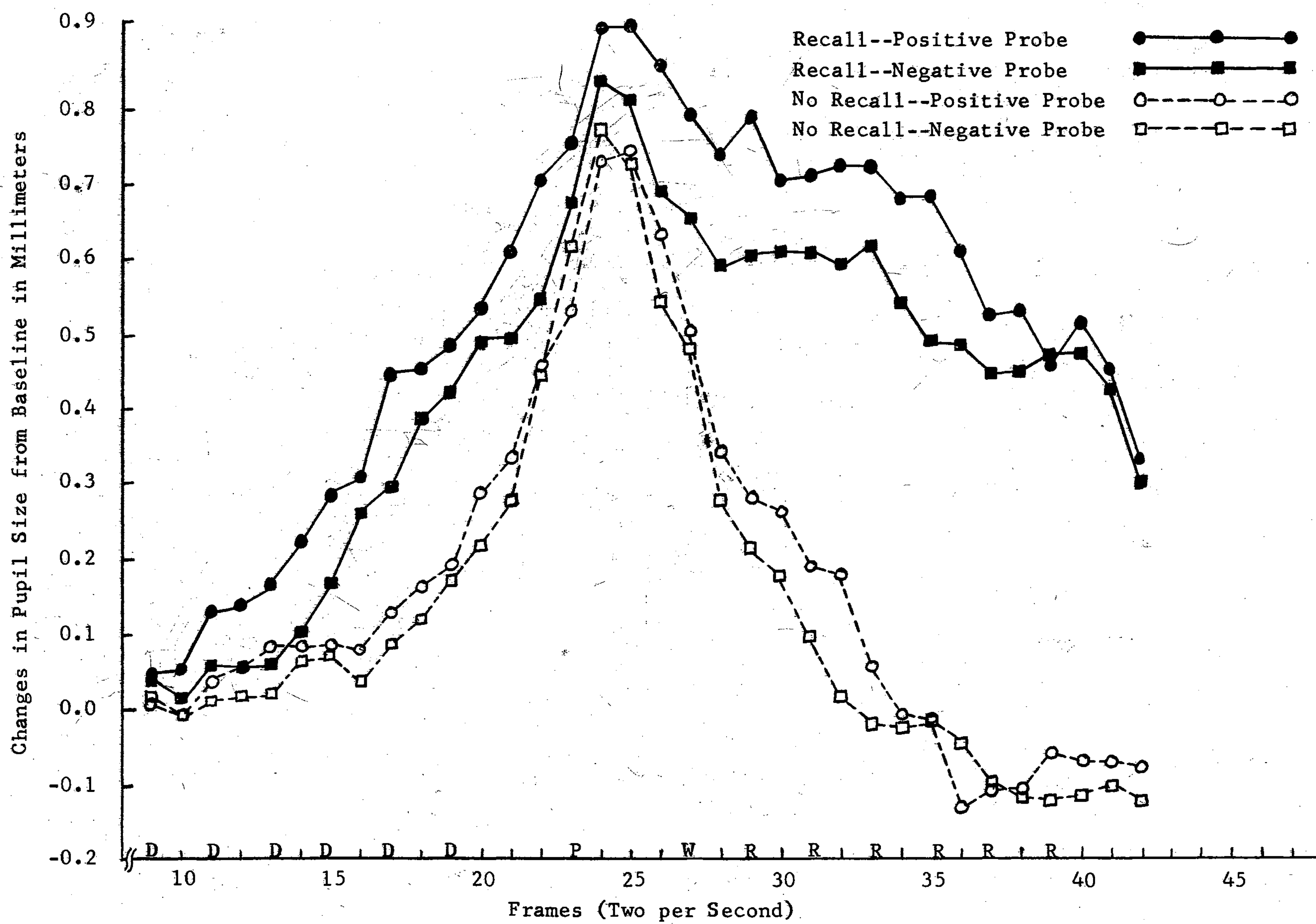

Figure 5. Pupil Response During Recall and No Recall for Search Trials with Set Size Six

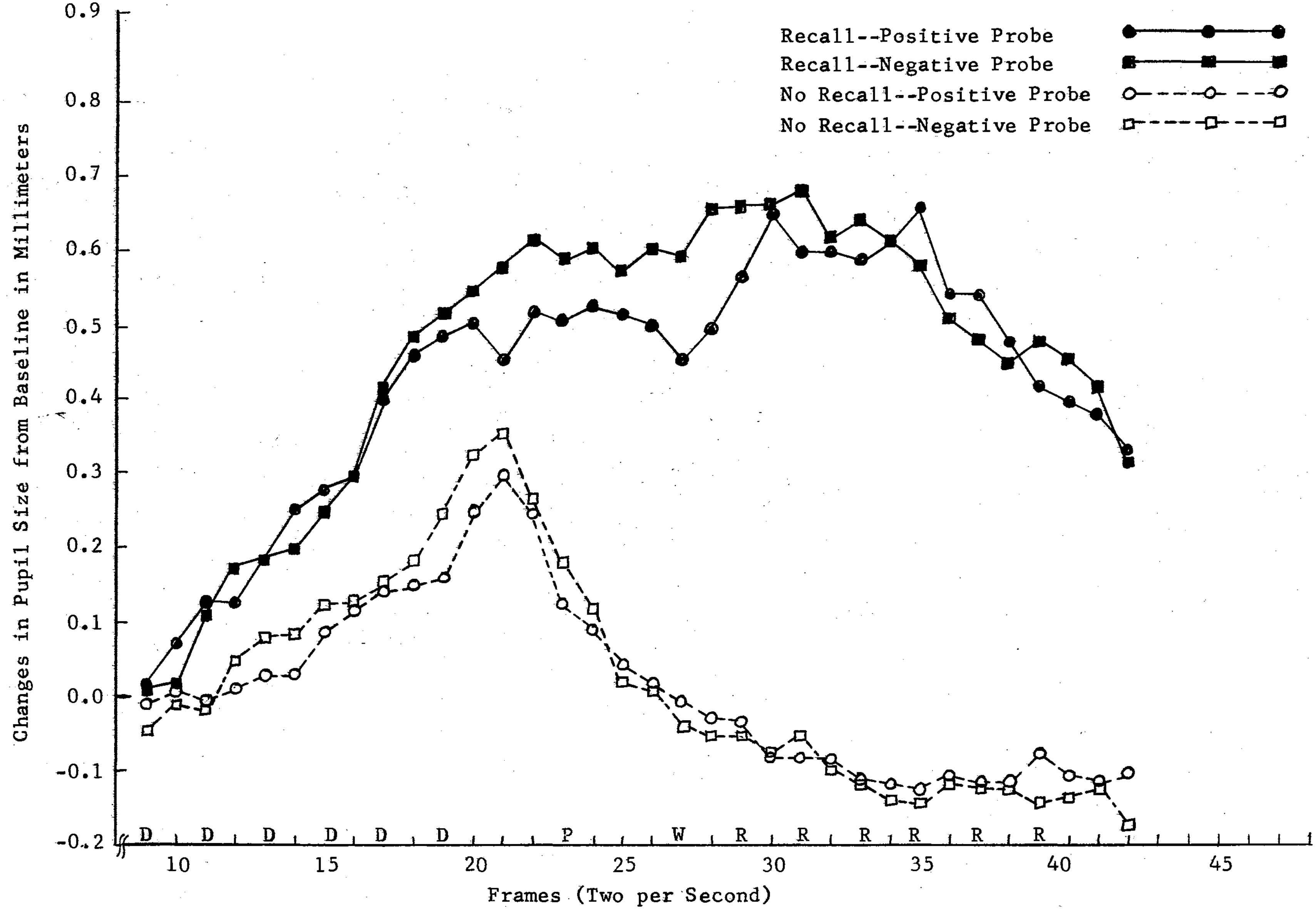

Figure 6. Pupil Response During Recall and No Recall for No Search Trials with Set Size Six

The pupillograms for set size six are presented in Figures 5 and 6. The shapes of the recall and no recall curves are significantly different in both the search condition (Figure 5) and in the no search condition (Figure 6). The curve forms for recall under the search condition (Figure 5) and no search condition (Figure 6) are not significantly different, but the shapes of the curves produced when no recall was required are significantly different under search as opposed to no search.

Several patterns of significant effects appear across set sizes. First, in the main analyses for each set size, the search by recall interaction was nonsignificant is set size four, marginal in set size five, and significant in set size six. Second, in the sub-analyses within each set size there are a number of trends. In the analyses of the recall conditions, the search and the frames by search interaction effects were significant in set size four; the frames by search interaction was significant in set size five; and the search and the frames by search interaction effects were both nonsignificant in set size six. In the analyses of the no search condition, the frames by recall interaction was nonsignificant in set size four, and increasingly significant in set sizes five to six. In all set size analyses, the frames main effect was significant, and in many cases frames was involved in significant interactions with search and recall variables. The probe variable was never significant neither as a main effect nor in interaction with other variables.

As stated in the Review Chapter, one of the apparently unique properties of the pupil response is that it can be regarded as a "real-time" indicator of cognitive processes during a trial. The preceding analyses have indicated that the variables of recall and search did interact with the time dependent variable of frames. As mentioned earlier, each trial was conceptualized as being composed of four phases. The Digit Loading phase began with the frame corresponding to the presentation of the first digit in each list and ended with the frame corresponding to the last digit in the list. To equate the number of frames in this phase among the different set sizes, certain frames were systematically eliminated in set sizes five and six. In set size five, these were the eleventh and fifteenth frames. In set size six, these were the tenth, thirteenth, fifteenth, and eighteenth frames. The Rehearsal phase began with the frame immediately following the presentation of the digits in the list and ended with the frame that corresponded to the occurrence of the probe digit. The Probe phase began with the frame immediately following the probe digit and ended with the third frame following the occurrence of the probe digit. The Probe phase began with the frame immediately following the probe digit and ended with the third frame following the occurrence of the probe digit. The Recall phase began with the frame immediately following the warning signal to begin recall and continued until two frames after the last tone for recall. To equate the number of frames in this phase for the differing number of digits recalled among the different set sizes, a systematic elimination scheme was again employed. The twenty-eighth and thirty-fifth frames were eliminated in set size five. The thirtieth, thirty-third, thirty-sixth, and thirty-nineth frames were eliminated in set size six.

An analysis of variance, presented in Table XVII, was performed on the data for the Digit Loading phase. The search and probe variables

TABLE XVII

AOV OF PUPIL RESPONSE DURING DIGIT LOADING PHASE

Source	df	MS	F (df corrected)
Total	1343	0.0321	
Between Ss	15	0.63251	
R (Recall	1	5.25590	17.388***
Ss w. Grps.	14	0.30227	
Within Ss	1328	0.02533	
F (Frames)	6	1.79162	57.094***
X (Set Size)	2	0.38116	5.335*
FX	12	0.03979	4.949*
FR	6	0.21598	6.883*
XR	2	0.11243	1.574
FXR	12	0.01473	1.832
Ss w. Grps. F	84	0.03138	
Ss w. Grps. X	28	0.07144	
Ss w. Grps. FX	168	0.00804	
Residual	1008	0.01386	

were eliminated as systematic sources of variation in this analysis because they were "applied" in later phases of a trial. The recall, frames, and set size main effects were significant. The frames by set size and the frames by recall interactions were significant. Table XVIII presents a simple effects analysis of the frames by recall interaction. The frames variable was statistically significant under both recall and no recall conditions. In Figure 7, these effects are represented by increasing dilation with each succeeding frame in both recall and no recall conditions. In addition, the divergence of these curves is represented in the simple effects analysis by the increasingly large and more significant differences for each succeeding frame. Table XIX presents the simple effects analysis of the frames by set size interaction. The frames variable is significant in all set sizes. The set size variable is significant at the three latter frames. In Figure 8, these effects represent greater dilation with each succeeding frame in each set size condition. In addition, the differences among the curves for each set size at the three latter frames are significant.

Table XX presents the analysis of variance of the data for the Rehearsal phase. The search variable was included in the analysis because on half of the trials the S received a signal just after the last digit that instructed him to perform an STM search when the probe digit occurred 2 seconds later. In the analysis, the recall, frames, search, and set size main effects were significant. The frames by search and the frames by search by recall interactions were statistically significant. The three factor frames by search by recall interaction is presented in Figure 9, and the simple effects analysis of the interaction is presented in Table XXI. The frames variable was significant under

TABLE XVIII

SIMPLE EFFECTS OF THE FR INTERACTION DURING DIGIT LOADING PHASE

Source	df	MS	F
Between F at R	6	1.61576	51.490***
Between F at No R	6	0.39185	12.487***
Ss w. Grps. F	84	0.03138	
Between R at F1	1	0.04192	0.598
Between R at F2	1	0.35278	5.033*
Between R at F3	1	0.33102	4.723*
Between R at F4	1	0.64053	9.139**
Between R at F5	1	0.99622	14.213***
Between R at F6	1	1.96092	27.977***
Between R at F7	1	2.22844	31.794***
Ss w. Grps. + Ss w. Grps. F	98	0.07009	

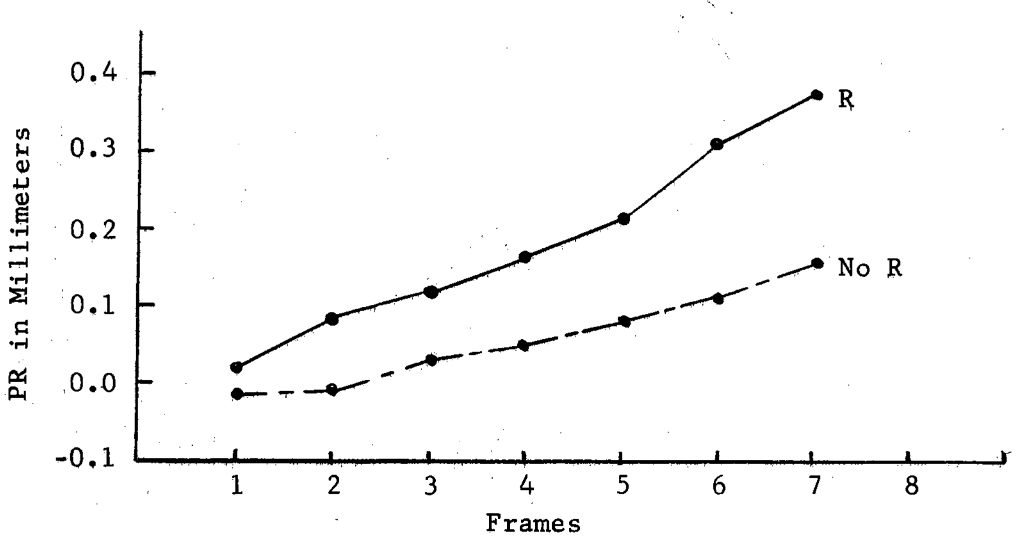

Figure 7. The Frames (F) by Recall (R) Interaction of the Pupil Response (PR) During the Digit Loading Phase

TABLE XIX

SIMPLE EFFECTS OF THE FX INTERACTION DURING DIGIT LOADING PHASE

Source	df	MS	F
Between F at X4	6	0.40753	25.760***
Between F at X5	6	0.58926	37.248***
Between F at X6	6	0.87441	55.272***
Ss w. Grps. +			
Ss w. Grps. FX	252	0.01582	
Between X at F1	2	0.02113	1.236
Between X at F2	2	0.03507	2.051
Between X at F3	2	0.01039	0.608
Between X at F4	2	0.02961	1.732
Between X at F5	2	0.11166	6.530**
Between X at F6	2	0.15468	9.046***
Between X at F7	2	0.25736	15.050***
Ss w. Grps. X +			
Ss w. Grps. FX	196	0.01710	

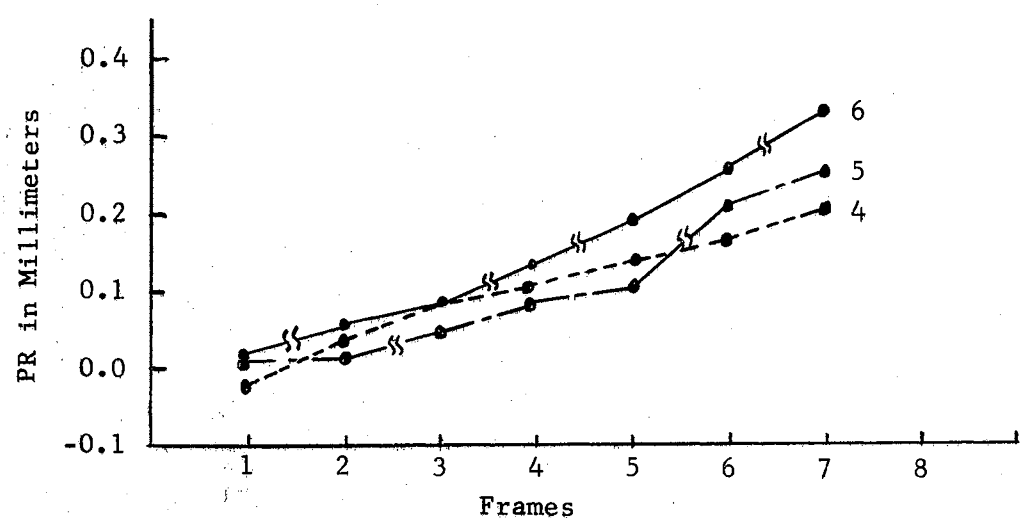

Figure 8. The Frames (F) by Set Size (X) Interaction of Pupil Response (PR) During the Digit Loading Phase

TABLE XX

AOV OF PUPIL RESPONSE DURING REHEARSAL PHASE

Source	df	MS	F (df corrected)
Total	767	0.05888	
Between Ss	15	1.32748	
R (Recall)	1	8.15660	9.714**
Ss w. Grps.	14	0.83968	
Within Ss	752	0.03358	
F (Frames)	3	0.74661	32.760***
E (Search)	1	2.11928	19.766***
FE	3	1.12544	57.626***
X (Set Size)	2	0.38180	4.933*
FX	6	0.02105	2.699
EX	2	0.00027	0.004
FEX	6	0.00227	0.551
FR	3	0.00353	0.155
ER	1	0.31134	2.904
FER	3	0.12554	6.428*
XR	2	0.11451	1.479
FXR	6	0.01148	1.472
EXR	2	0.05945	0.971
FEXR	6	0.01109	2.692
Ss w. Grps. F	42	0.02279	
Ss w. Grps. E	14	0.10722	
Ss w. Grps. FE	42	0.01953	
Ss w. Grps. X	28	0.07740	
Ss w. Grps. FX	84	0.00780	
Ss w. Grps. EX	28	0.06124	
Ss w. Grps. FEX	84	0.00412	
Residual	384	0.01893	

TABLE XXI

SIMPLE EFFECTS OF THE FER INTERACTION DURING REHEARSAL PHASE

Source	df	MS	F
Between F at E R	3	0.58988	27.877***
Between F at No E R	3	0.02889	1.365
Between F at E No R	3	1.26481	59.774***
Between F at No E No R	3	0.11755	5.555**
Ss w. Grps. F +			
Ss w. Grps. FE	84	0.02116	
Between E at F1 R	1	0.00920	0.222
Between E at F2 R	1	0.00145	0.035
Between E at F3 R	1	0.17743	4.281*
Between E at F4 R	1	0.96531	23.289***
Between E at F1 No R	1	0.01917	0.462
Between E at F2 No R	1	0.00002	0.001
Between E at F3 No R	1	0.95367	23.008***
Between E at F4 No R	1	4.05731	97.884***
Ss w. Grps. E +			
Ss w. Grps. FE	56	0.04145	
Between R at F1 E	1	1.09397	8.150**
Between R at F2 E	1	0.91137	6.790*
Between R at F3 E	1	0.61550	4.585*
Between R at F4 E	1	0.21597	1.609
Between R at F1 No E	1	1.00682	7.501**
Between R at F2 No E	1	0.97669	7.276**
Between R at F3 No E	1	1.79528	13.375***
Between R at F4 No E	1	2.23953	16.684***
Ss w. Grps. +			
Ss w. Grps. F +			
Ss w. Grps. E +			
Ss w. Grps. FE	112	0.13423	

TABLE XXI (Continued)

Source	df	MS	F
Between FE at R	3	0.25012	12.807***
Between FE at No R	3	1.00086	51.247***
Ss w. Grps. FE	42	0.01953	
Between FR at E	3	0.06548	3.095*
Between FR at No E	3	0.06359	3.005*
Ss w. Grps. F +			
Ss w. Grps. FE	84	0.02116	
Between ER at F1	1	0.00090	0.022
Between ER at F2	1	0.00057	0.014
Between ER at F3	1	0.15420	3.720#
Between ER at F4	1	0.53228	12.841***
Ss w. Grps. E +			
Ss w. Grps. FE	56	0.04145	

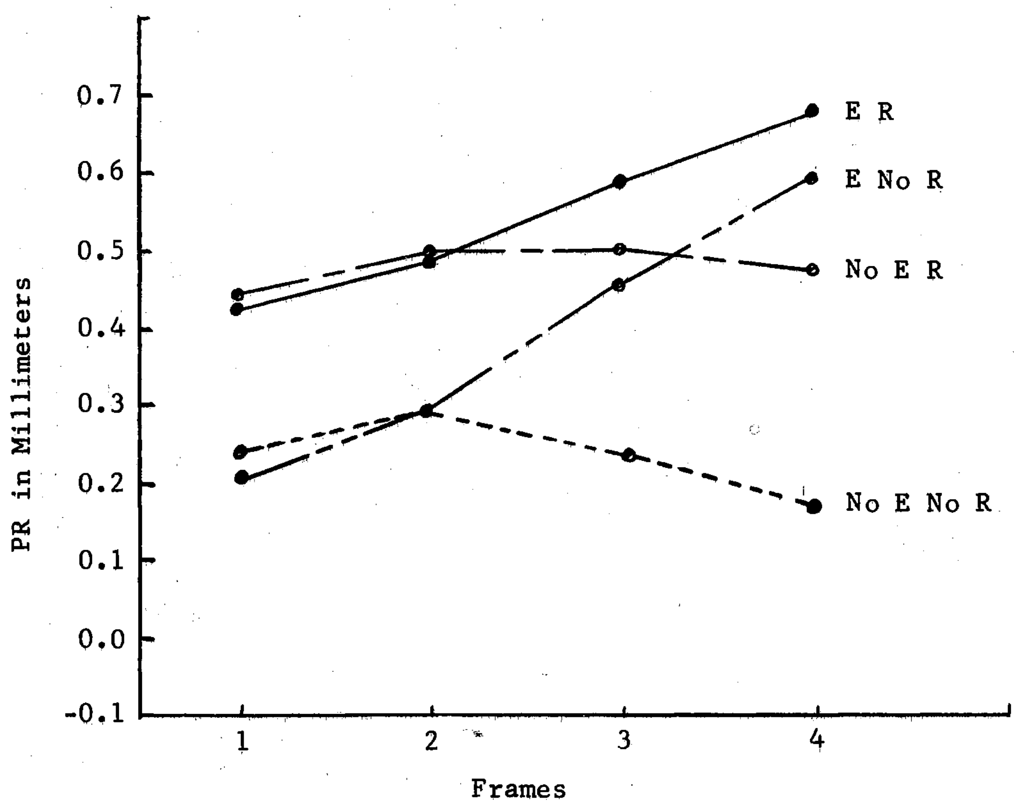

Figure 9. The Frames (F) by Search (E) by Recall (R) Interaction of the Pupil Response (PR) During the Rehearsal Phase

the conditions of search and recall, search and no recall, and no search and no recall. The search variable was significant at frame numbers three and four under either recall or no recall. The recall variable was significant at frame numbers one through three under the search condition and frame numbers one through four under the no search condition. The frames by search interaction was significant under both recall and no recall conditions, and the frames by recall interaction was significant under both search and no search conditions. The search by recall interaction was significant only at frame number four. In terms of the pupillary curves depicted in Figure 9, the simple effects analysis of the frames by search by recall interaction indicates that the dilation under the search and recall condition and the dilation under the search and no recall condition is significant. There is no significant change of pupil size under the no search and recall condition, but there is a significant increase and decrease in pupil size under the no search and no recall condition. At the end of the Rehearsal phase, the search and recall condition is not significantly different from the search and no recall condition, but the former is significantly different from the no search and recall condition. The pupil response in the no search and recall condition is significantly greater than the pupil response in the no search and no recall condition at frame number four.

The next trial segment was the Probe phase. In the analysis of this phase, the probe variable was included in addition to the variables included in the Rehearsal phase. During the Probe phase, the S was performing an STM search and making his overt response when so instructed. Table XXII presents the analysis of variance of the Probe

TABLE XXII

AOV OF PUPIL RESPONSE DURING PROBE PHASE

Source	df	MS	F (df corrected)
Total	575	0.12831	
Between Ss	15	1.48009	
R (Recall)	1	9.40783	10.295**
Ss w. Grps.	14	0.91383	
Within Ss	560	0.09211	
F (Frames)	2	0.67643	52.518***
E (Search)	1	29.88852	106.467***
FE	2	0.10097	9.340**
P (Probe)	1	0.03111	0.487
FP	2	0.01180	1.134
EP	1	0.13071	2.509
FEP	2	0.01310	1.127
X (Set Size)	2	0.23759	2.514
FX	4	0.03005	3.442#
EX	2	0.00393	0.084
FEX	4	0.00613	0.850
PX	2	0.03178	0.917
FPX	4	0.00397	0.611
EPX	2	0.02285	0.366
FEPX	4	0.00408	0.539
FR	2	0.06598	5.123*
ER	1	2.82108	10.049**
FER	2	0.00224	0.207
PR	1	0.00228	0.036
FPR	2	0.00732	0.703
EPR	1	0.01551	0.298
FEPR	2	0.00077	0.066
XR	2	0.17173	1.817
FXR	4	0.00425	0.487
EXR	2	0.18144	3.877#
FEXR	4	0.00975	1.352
PXR	2	0.01360	0.393
FPXR	4	0.01214	1.868
EPXR	2	0.04606	0.737
FEPXR	4	0.01099	1.452

TABLE XXII (Continued)

Source	df	MS	F (df corrected)
Ss w. Grps. F	28	0.01288	
Ss w. Grps. E	14	0.28073	
Ss w. Grps. FE	28	0.01081	
Ss w. Grps. P	14	0.06385	
Ss w. Grps. FP	28	0.01041	
Ss w. Grps. EP	14	0.05209	
Ss w. Grps. FEP	28	0.01162	
Ss w. Grps. X	28	0.09450	
Ss w. Grps. FX	56	0.00873	
Ss w. Grps. EX	28	0.04680	
Ss w. Grps. FEX	56	0.00721	
Ss w. Grps. PX	28	0.03464	
Ss w. Grps. FPX	56	0.00650	
Ss w. Grps. EPX	28	0.06252	
Ss w. Grps. FEPX	56	0.00757	

phase data. The recall, frames, and search main effects were significant. The frames by search, the frames by recall, and the search by recall interactions were also significant. In Tables XXIII, XXIV, and XXV, the respective simple effects analyses for these interactions are presented. All simple effects for the frames by recall and the frames by search interactions were statistically significant. In the search by recall interaction, the differences between search conditions under both recall and no recall conditions were significant. The recall variable was significant only under the no search condition. Figure 10 illustrates these interactions.

The last trial segment was the Recall phase. Table XXVI presents the analysis of variance for the Recall phase data. The recall, frames, and search main effects were statistically significant. The frames by search and the set size by recall interactions were significant. The simple effects analyses for these intereactions are presented in Tables XXVII and XXVIII. For the frames by search interaction, there was a significant decrease in pupil response across frames under both the search and no search conditions. The difference between the search conditions was significant from frame number one through frame number six during recall. In Figure 11, these effects are represented by constriction of pupil size with the search condition constricting more rapidly than the no search condition until frame number seven where the curves representing the two conditions are no longer significantly different. In the set size by recall interaction simple effects analysis, the difference between recall conditions was significant for all three set sizes. In addition, the differences among the set size means were significant under the recall condition, but nonsignificant under

TABLE XXIII

SIMPLE EFFECTS OF THE FE INTERACTION DURING PROBE PHASE

Source	df	MS	F
Between F at E	2	0.62696	52.953***
Between F at No E	2	0.15046	12.708***
Ss w. Grps. F +			
Ss w. Grps. FE	56	0.01184	
Between E at F1	1	10.93575	108.511***
Between E at F2	1	11.36318	112.752***
Between E at F3	1	7.79160	77.313***
Ss w. Grps. E +			
Ss w. Grps. FE	42	0.10078	

TABLE XXIV

SIMPLE EFFECTS OF THE FR INTERACTION DURING PROBE PHASE

Source	df	MS	F
Between F at R	2	0.16123	12.518***
Between F at No R	2	0.58119	45.123***
Ss w. Grps. F	28	0.01288	
Between R at F1	1	2.33635	7.460**
Between R at F2	1	3.04134	9.711**
Between R at F3	1	4.16211	13.289***
Ss w. Grps. +			
Ss w. Grps. F	42	0.31319	

TABLE XXV

SIMPLE EFFECTS OF THE ER INTERACTION DURING PROBE PHASE

Source	df	MS	F
Between E at R	1	7.17233	25.549***
Between E at No R	1	25.53736	90.968***
Ss w. Grps. E	14	0.28073	
Between R at E	1	0.96273	1.612
Between R at No E	1	11.26621	18.863***
Ss w. Grps. + Ss w. Grps. E	28	0.59728	

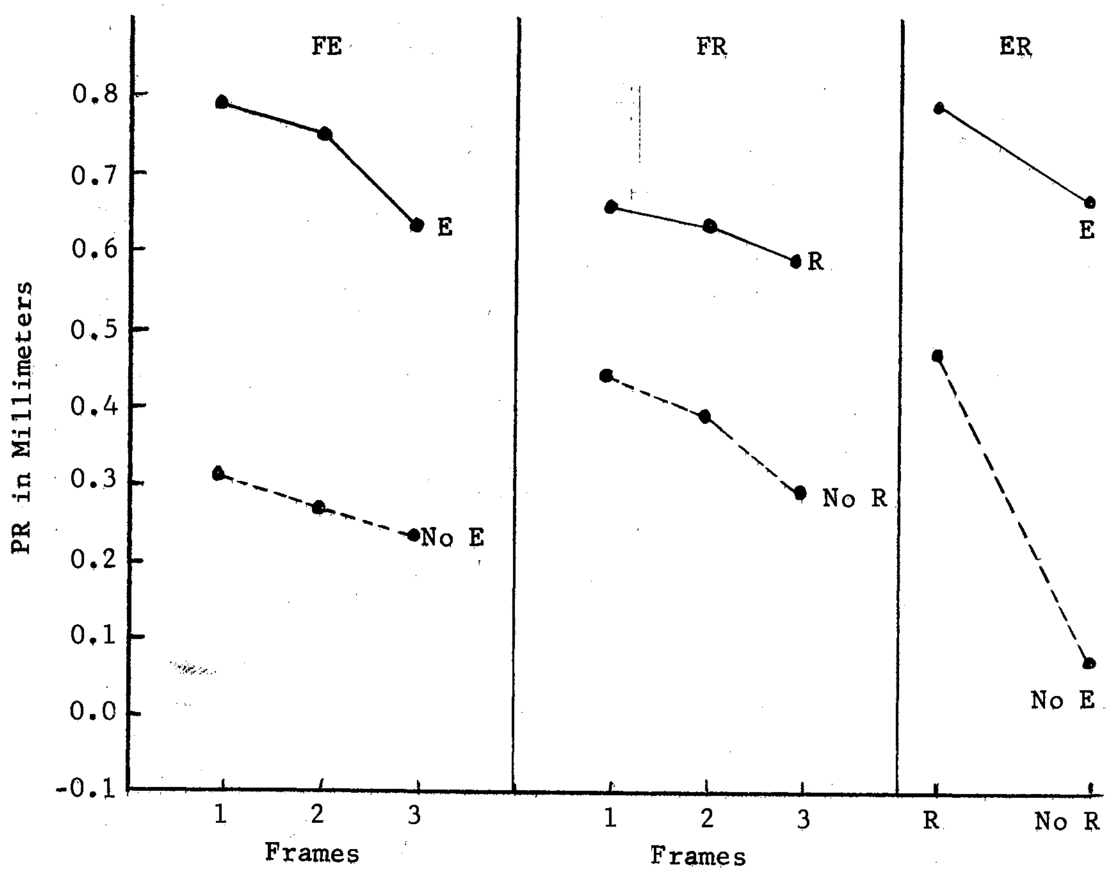

Figure 10. The Frames (F) by Search (E); Frames (F) by Recall (R); and Search (E) by Recall (R) Interactions of the Pupil Response During the Probe Phase

TABLE XXVI

AOV OF PUPIL RESPONSE DURING RECALL PHASE

Source	df	MS	F (df corrected)
Total	1919	0.11435	
Between Ss	15	7.75583	
R (Recall)	1	106.73271	155.576***
Ss w. Grps.	14	0.68605	
Within Ss	1904	0.05415	
F (Frames)	9	1.78654	27.634***
E (Search)	1	6.78409	13.473**
FE	9	0.30676	21.112***
P (Probe)	1	0.09782	0.526
FP	9	0.00233	0.242
EP	1	0.39570	1.692
FEP	9	0.01964	1.639
X (Set Size)	2	1.84521	4.367#
FX	18	0.01182	1.248
EX	2	0.46457	2.924
FEX	18	0.00965	1.242
PX	2	0.20023	1.326
FPX	18	0.00885	0.904
EPX	2	0.07653	0.384
FEPX	18	0.01445	1.365
FR	9	0.14102	2.181
ER	1	0.80882	1.606
FER	9	0.06075	4.181#
PR	1	0.03964	0.213
FPR	9	0.01078	1.121
EPR	1	0.04371	0.187
FEPR	9	0.01298	1.084
XR	2	2.20452	5.217*
FXR	18	0.01301	1.374
EXR	2	0.48789	3.071
FEXR	18	0.00842	1.084
PXR	2	0.02925	0.194
FPXR	18	0.00976	0.997
EPXR	2	0.20986	1.053
FEPXR	18	0.01423	1.344

TABLE XXVI (Continued)

Source	df	MS	F (df corrected)
Ss w. Grps. F	126	0.06465	
Ss w. Grps. E	14	0.50352	
Ss w. Grps. FE	126	0.01453	
Ss w. Grps. P	14	0.18594	
Ss w. Grps. FP	126	0.00962	
Ss w. Grps. EP	14	0.23393	
Ss w. Grps. FEP	126	0.01198	
Ss w. Grps. X	28	0.42258	
Ss w. Grps. FX	252	0.00947	
Ss w. Grps. EX	28	0.15886	
Ss w. Grps. FEX	252	0.00777	
Ss w. Grps. PX	28	0.15098	
Ss w. Grps. FPX	252	0.00979	
Ss w. Grps. EPX	28	0.19937	
Ss w. Grps. FEPX	252	0.01059	

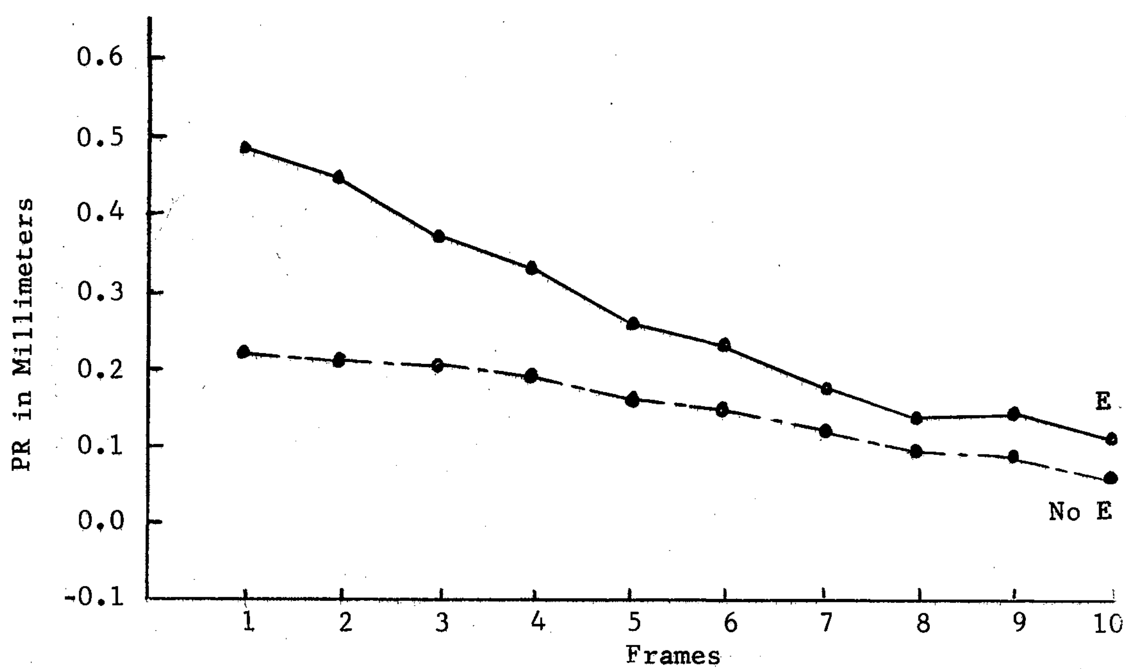

Figure 11. The Frames (F) by Search (E) Interaction of the Pupil Response (PR) During the Recall Phase

TABLE XXVII

SIMPLE EFFECTS OF THE FE INTERACTION DURING RECALL PHASE

Source	df	MS	F
Between F at E	9	1.75694	44.378***
Between F at No E	9	0.33636	8.496***
Ss w. Grps. F + Ss w. Grps. FE	252	0.03959	
Between E at F1	1	3.27506	51.633***
Between E at F2	1	2.54993	40.201***
Between E at F3	1	1.34853	21.260***
Between E at F4	1	1.11763	17.620***
Between E at F5	1	0.45537	7.179**
Between E at F6	1	0.28101	4.430*
Between E at F7	1	0.12018	1.895
Between E at F8	1	0.06414	1.011
Between E at F9	1	0.21657	3.414#
Between E at F10	1	0.11653	1.837
Ss w. Grps. E + Ss w. Grps. FE	140	0.06343	

TABLE XXVIII

SIMPLE EFFECTS OF THE XR INTERACTION DURING RECALL PHASE

Source	df	MS	F
Between R at X4	1	22.22175	43.538***
Between R at X5	1	31.07534	60.884***
Between R at X6	1	57.84512	113.333***
Ss w. Grps. + Ss w. Grps. X	42	0.51040	
Between X at R	2	4.00939	9.488***
Between X at No R	2	0.04035	0.095
Ss w. Grps. X	28	0.42258	

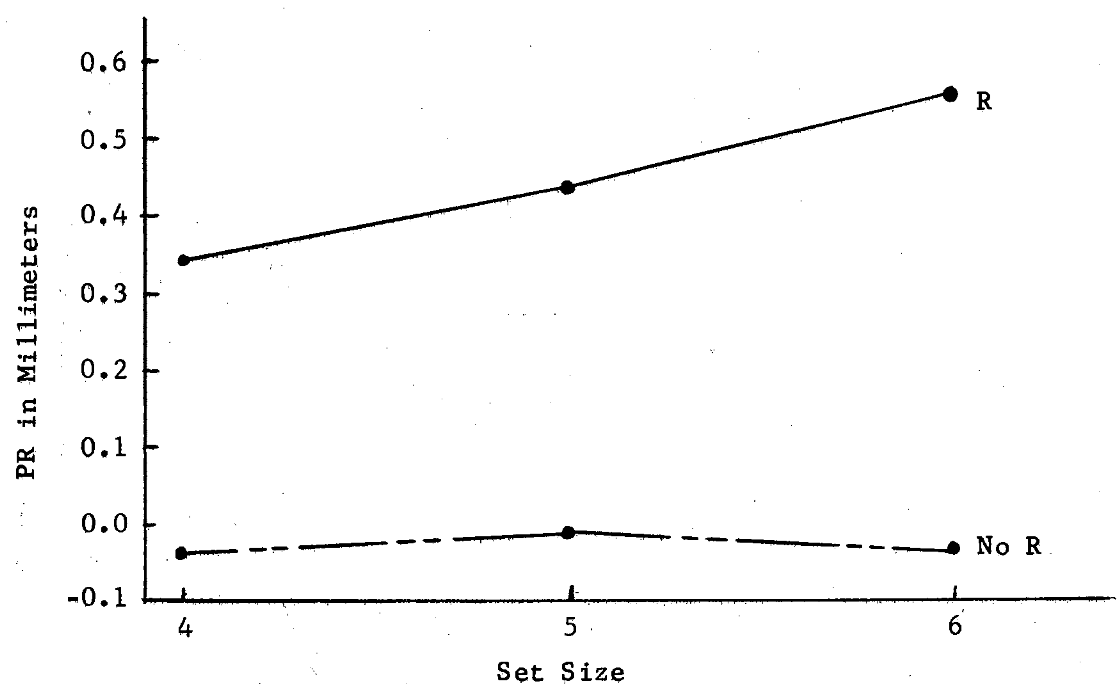

Figure 12. The Set Size (X) by Recall (R) Interaction of the Pupil Response (PR) During the Recall Phase

the recall condition. In Figure 12, it appears that the addition of one digit to memory load results in approximately 0.1 mm. increase in pupil size during recall. The no recall curve is essentially flat with respect to set size as should be expected since the Ss were not engaged in recall activity.

Since several studies have indicated that there are significant decreases in absolute pupil size during the course of an experiment, the mean absolute pupil diameter for baseline was computed for the first trial to the last trial. In Figure 13, it appears that absolute pupil diameter did decrease during the course of the experiment. A Runs test confirmed that this was a significant effect ($R = 12$, $p = 0.025$).

Reaction Time and Recall Error Results

Table XXIX presents an analysis of variance of the RT data. The only significant result was the recall main effect. In Figure 14, this result represents a difference of approximately 275 msec. between the curves for recall and no recall.

Sternberg (1969) has typically presented his results with the RT to the probe digit as a function of set size. Figures 14 and 15 present the RT data in this manner. It should be noted that there were no significant interactions between the set size variable and other variables in the RT data. Least squares regression lines were fitted to the data in the conditions of recall, no recall, positive probe, and negative probe. The slope constant for the recall condition represents a search rate of about 21 digits per second, whereas in the no recall condition, the slope constant represents a search rate of about 111 digits per second. The slope constant for the negative probe condition

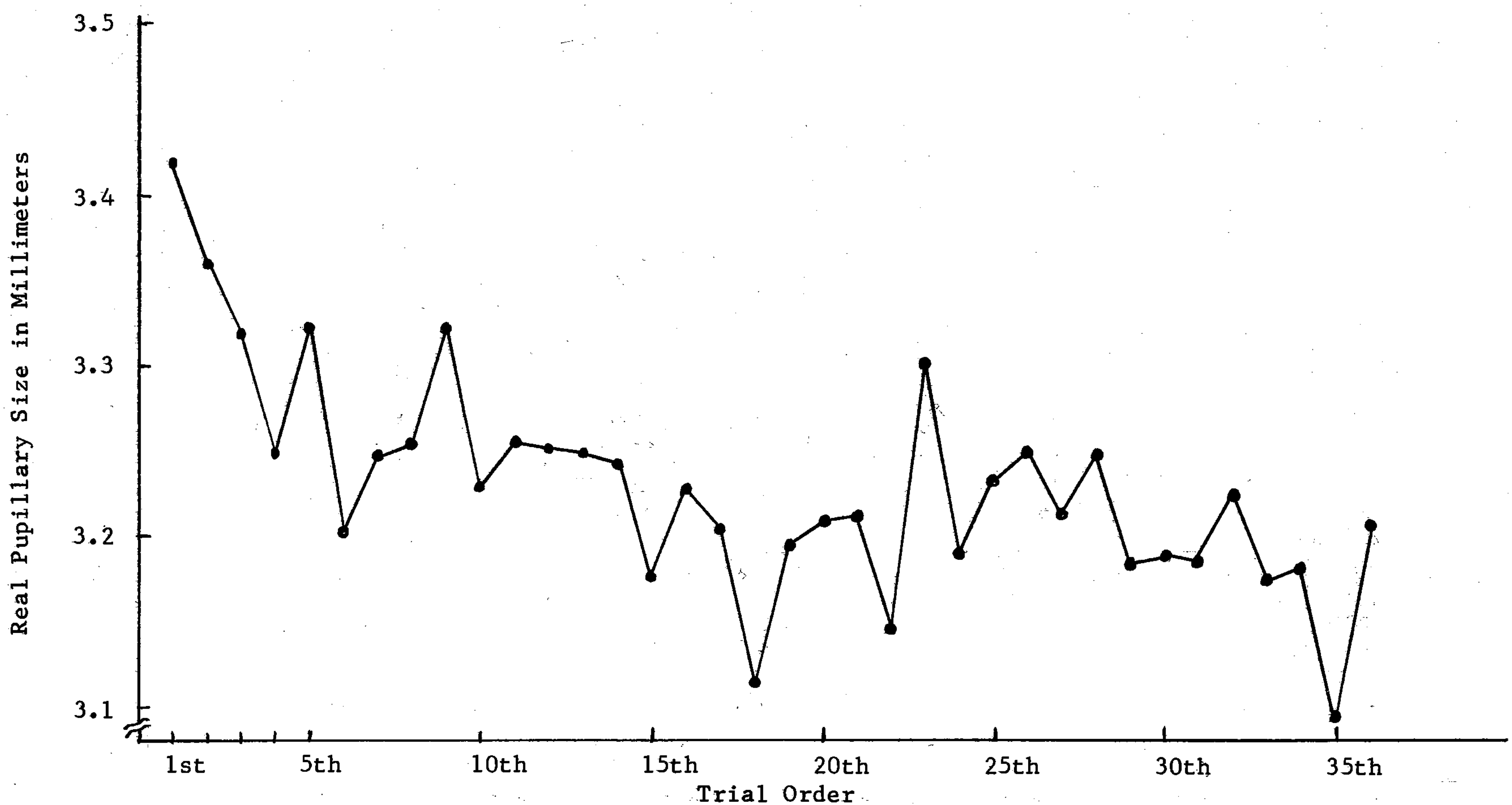

Figure 13. Average of the Baseline Means for the Experimental Trials

TABLE XXIX

AOV OF REACTION TIMES TO PROBE DIGITS

Source	df	MS	F (df corrected)
Total	287	0.07729	
Between Ss	15	0.62146	
R (Recall)	1	5.16168	17.370***
Ss w. Grps.	14	0.29716	
Within Ss	272	0.04728	
P (Probe)	1	0.04114	2.396
X (Set Size)	2	0.09697	1.679
PX	2	0.08722	1.657
PR	1	0.00565	0.329
XR	2	0.03540	0.613
PXR	2	0.03453	0.656
Ss w. Grps. P	14	0.01717	
Ss w. Grps. X	28	0.05777	
Ss w. Grps. PX	28	0.05265	
Residual	192	0.04673	

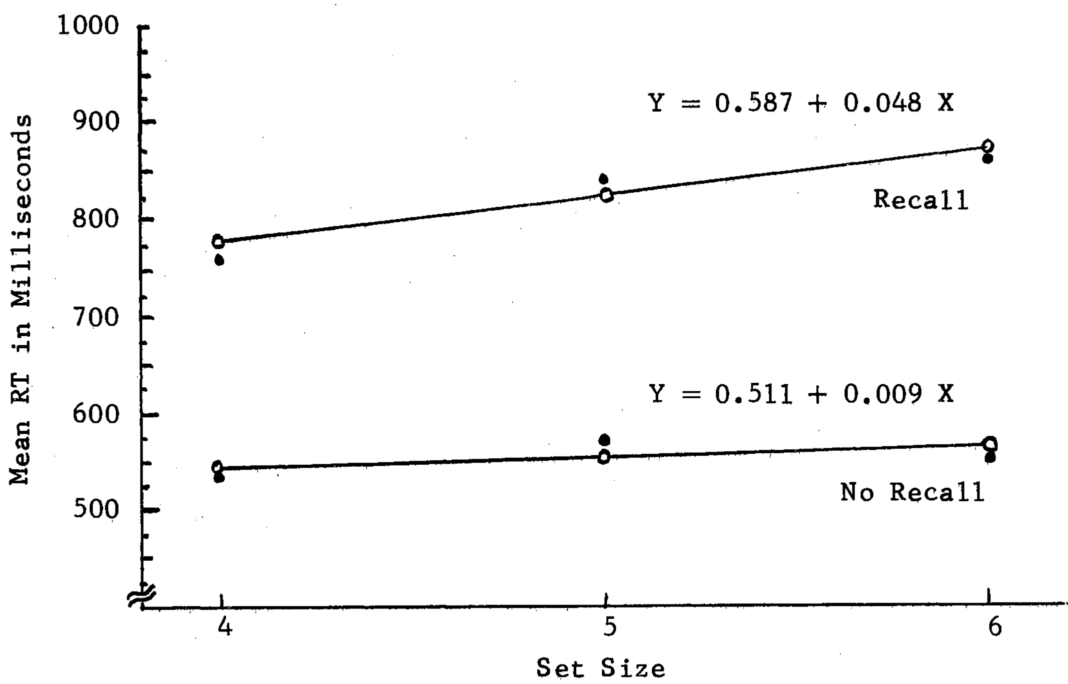

Figure 14. Mean RT Across Set Size as a Function of Recall Condition

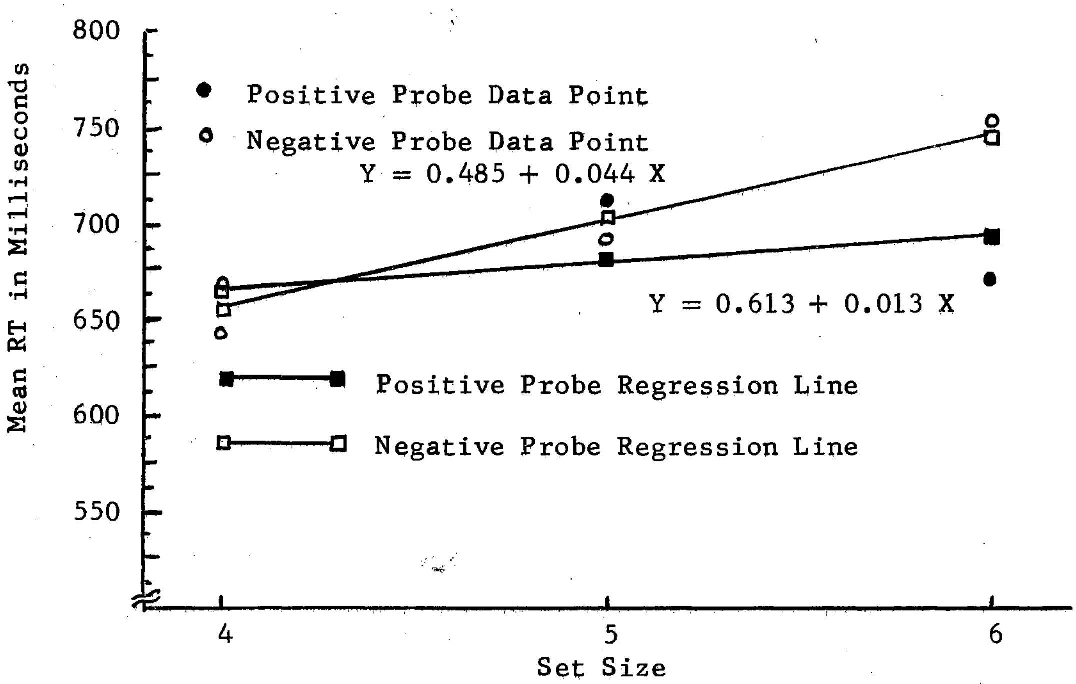

Figure 15. Mean RT Across Set Sizes as a Function of Probe Condition

represents a search rate of approximately 23 digits per second, and the slope constant for the positive probe condition represents a search rate of approximately 77 digits per second. The difference between the mean RTs for the two conditions of direction of toggle switch throw, nature of signal instructing search, and order of experimental trials resulted in no significant differences via t tests ($p < 0.10$).

The average number of recall errors for set size four was 8.59 percent, for set size five was 18.13 percent, and for set size six was 39.76 percent. A two-way contingency table with the number of digits correctly and incorrectly recalled versus the three set sizes indicated that there was a statistically significant dependency ($\chi = 136.498$, $df = 2$, $p < 0.0005$) between set size and the proportion of digits correctly recalled. There was a 2.8 percent error rate of incorrect RT responses to the probe digit. This rate is about the same as the error rate reported by Sternberg (1969) for STM search tasks for item-recognition.

CHAPTER V

DISCUSSION

One of the major purposes of the investigation was to answer the question of whether or not STM search would affect the pupil response. In the separate analyses for each set size, the frames by search interaction was significant in all three set sizes. This pattern of significant effects indicates that there was a significant increase in pupil size during trials when STM search was performed as opposed to trials where STM search was not performed. In addition, the pattern of significant effects for the frames by search interactions in the analyses of the no recall conditions across set sizes indicates that STM search resulted in pupil dilation without the operation of the recall variable. The significance of the frames by search and the search by recall interactions in the Probe phase analyses add support to the above conclusions. During the Probe phase, the search condition resulted in an average of 0.45 mm. more dilation than the no search condition.

These results do not allow a completely unambigious answer to the question at hand for one reason. Several studies (Kahneman, Peavler, & Onuska, 1968; Simpson & Paivio, 1966) have shown that the requirement of an overt response indicative of cognitive task fulfillment might result in an increment to pupil dilation over and above that found for the task when no overt response was required. In general, it has been suggested that the pupil response during cognitive processing is the sum of a large response produced component and a small, insignificant, cognitive processing component. In addition, the large response component is implied to be of little psychological significance (Simpson, 1969). On the other hand, Kahneman, et. al. (1968) conclude that the performance of an overt response by itself results in little pupil dilation. They contend that the effect of an overt response on pupil size is an integral part of the total cognitive task which produces pupil dilation. Therefore, an alternative hypothesis is to consider the effect of an overt response on pupil size as one of several interacting cognitive factors which produce pupil dilation.

Several results from the present study tend to support the latter hypothesis. For example, in the recall subanalyses for each set size, the search and the frames by search interactions were significant in set size four; the frames by search interaction was significant in set size five; and neither were significant in set size six. Thus, the addition of material to memory attenuated the contribution of search to the total pupillogram. The attenuation of the search effect did not occur in the no recall subanalyses. In the no search subanalyses, the contribution of additional digits to memory load resulted in an increase in the size of the frames by recall interaction with each larger set size. In addition, in the search subanalyses, the pattern of results does not suggest that the requirement of an overt response resulted in an additive increment to pupillary dilation over and above that for ongoing cognitive processing. In brief, all of these results suggest that increasing memory load interacted with the performance of search in producing pupil dilation. Next, the Probe phase analysis revealed a significant search by recall interaction. The simple effects analysis of this interaction revealed that there was no significant difference between the means for recall and no recall in the search condition, but that these same means were significantly different in the no search condition. Also, the difference between the means for search and no search under the no recall condition was approximately twice that found for these same means under the recall condition. Thus, the simple effects analysis of the search by recall interaction indicates that the performance of search and its corresponding overt response did not add equal increments to pupil size for the two recall conditions. Taking all of the previously mentioned results into consideration, the hypothesis that pupil dilation during search is the sum of a large response component and a small cognitive processing component does not appear to be supported. On the other hand, these results do appear to support the notion that the pupil response during search is a product of several interacting cognitive factors one of which is the performance of the search task with its overt response.

Sternberg (1969) bases his theory of serial exhaustive, item-recognition search on the positive linear relationship between RTs to probe items and set size with no substantial difference between positive and negative probes. Sternberg's exhaustive assumption requires that search continue until all list items are compared with the probe item before a decision is made. Thus, there should be no difference between positive and negative probes in terms of the amount of cognitive processing involved, and therefore, no differences in terms of pupil dilation. Sternberg's serial assumption requires that search involve the "one at a time" comparison of list items with the probe. Thus, the addition of items to the list to be searched should involve the addition of equal increments of cognitive processing for each successively larger set size, and therefore result in greater dilation during search for each larger set size.

The pupillographic data were equivocal with regard to Sternberg's theory. The probe variable was never significant in any analysis neither by itself nor in interaction with any other variable studied. This result supports Sternberg's exhaustive assumption. On the other hand, the search variable was never in interaction with the set size variable which indicates no systematic relationship between the two. This result is contradictory to Sternberg's serial assumption. Likewise, the RT data provided equivocal support with regard to Sternberg's theory. The result for the set size variable did not indicate any systematic increase in RT with increasing set size, but there was no significant difference between the probe conditions as Sternberg predicts. The one significant variable in the RT data was the difference between recall and no recall conditions with the average RT in the recall condition being over 250 msec. slower than the average RT in the no recall condition. There was no significant relationship between the recall variable and set size.

The second purpose of the investigation was to evaluate the sensitivity of the pupil response to changing cognitive loads during a trial. It was hypothesized that different instructional conditions such as requiring recall as opposed to no recall and search versus no search might change the pattern of S's pupil response during a trial.

Several lines of evidence support this hypothesis. First, the analysis of the average pupil response for a trial across set sizes revealed that the instructional variables of recall and search were highly significant. In addition, the recall variable interacted with set size which indicated that greater cognitive load was imposed by increasing set size and requiring recall.

Second, the analyses of the pupillograms for each set size resulted in different pupil response curves during a trial as a function of the changing cognitive load imposed by different combinations of the instructional variables. For example, in the analyses of the complete pupillograms, the subanalysis of the recall condition for set size four resulted in different pupil response curves during trials where search was required as opposed to trials where it was not required. The same result was found in set size five, but not in set size six. In the subanalysis where no recall was required, there were different pupil response curves for the search condition as opposed to the no search condition in all set sizes. In the subanalysis of the search condition, there were differential pupil response curves during trials for set sizes four and six which depended on whether recall was required or not. In the no search condition, the pupil response curves for recall were significantly different from those for no recall in set sizes five and six. In all cases, the performance of STM search and/or recall resulted in greater dilation than not requiring their performance.

The results of the Digit Loading phase analysis provide more support for the hypothesis. The Ss who had to recall dilated more rapidly than those who did not. In addition, the larger the set size the greater the dilation especially near the end of the presentation of the digits. This latter result agrees with the results reported by Kahneman and Beatty (1966).

The Rehearsal phase analysis provides even further support for the hypothesis. The pupillogram for the Ss who did not search, but were required to recall level off during this phase. The Ss who were instructed that they would not need to remember the digits for either recall or search briefly dilated then started constricting. This finding replicated the results of a study by Johnson (1969). In comparison, the Ss who were instructed not to recall, but were required to perform a search dilated very rapidly during this phase. It seems probable that under this treatment condition, the Ss did not "process" the digit list as extensively during its presentation as Ss who had to recall. Thus, when they were cued to get ready to perform a search on the material, they engaged in a very rapid and intense period of cognitive processing of the material in preparation for search. This latter result is the opposite of the case where the Ss found that they no longer needed the "stored" material for any task and began "dumping" it from memory, thus resulting in a brief dilation then constriction of pupil size. In the condition where Ss were required to perform both tasks, there was dilation during the Rehearsal phase, but not at as great a rate as in the search but no recall condition. This result seems explainable on the basis that these Ss had already "processed" the digit list rather completely and further processing loads were lessened in comparison. It should be noted that the decreased rate of dilation for the search and recall condition is probably not due to a "ceiling effect." The magnitude of the dilations (approximately 0.65 mm.) were not as large as some that have been reported (Kahneman & Beatty, 1966), and the absolute pupil diameter (approximately 4.2 mm.) was far from the physiological maximum of 8 mm. In brief, the pupil response appeared to monitor the changing cognitive or information-processing load as it occurred during the Rehearsal phase due to variation of S's instructions.

In the Probe phase analysis, the variable of major importance was whether the S engaged in search or not. The significant frames by recall interaction was the result of the relatively large constriction by those Ss who had to neither search nor recall as compared to the other treatment conditions.

The only significant result in the RT data for this phase was the much slower response of the Ss who were required to recall as compared to those who did not. This result in conjunction with the pupillary data suggests that the Ss who had to recall were engaged in a different type of digit list processing than those who did not have to recall. A study by Stanners, Meunier, and Headley (1969) indicated that covert verbal rehearsal increased an S's RT to a buzzer as compared to a condition where presumably such rehearsal was absent. Thus, it seems likely that the Ss in the recall condition were engaged in the cognitive process of covert verbal rehearsal. The processing activity of the Ss who did not have to recall was of such a nature that it did not retard the RT as much as covert rehearsal.

In the Recall phase analysis, the performance of search resulted in larger pupil size during the recall period than did the condition where no search was required. This result appears to be a "residual" effect due to the larger dilations of the individuals who performed the search task prior to recall than those who did not. In other words, the pupils of Ss who searched had not had time to recover before the beginning of recall. The results of relevance to the hypothesis at hand is the interaction of set size with recall. The performance of the recall task resulted in larger dilations for each larger set size. The no recall condition resulted in no pupil response. In addition, the recall error scores indicated that recall was more difficult for the larger set sizes. Thus, the pupil response appears to accurately reflect the cognitive load of recall.

There are several conclusions that can be drawn with regard to the questions posed earlier. First, the pupil response apparently did rapidly increase and decrease in response to the cognitive task of STM search, but a residual dilation tended to carry over into the Recall phase. The peak dilation during search revealed no systematic relationship with set size or probe type. As a result, the pupillary evidence for Sternberg's theory of serial exhaustive, item-recognition search is equivocal. Second, the pupil response did prove to be a sensitive measure of other variations in cognitive processing within a trial as they occurred. Manipulations of recall, search and set size variables resulted in identifiable effects on pupillary size. The results of the present study support the hypothesis that the pupil response is a sensitive measure of cognitive processes involved in STM storage and retrieval, but cognitive processes which occur with extreme rapidity, such as STM search, are apparently not monitored with the same fidelity.

CHAPTER VI

SUMMARY

The purpose of the investigation was to study changes in pupillary size as Ss engaged in an STM search task. The 16 Ss, 11 female and 5 male, used in the study were auditorially presented with 36 experimental trials. During each trial, the Ss heard a list of monosyllable digits, presented at 1 per second, followed 2 seconds later by a single probe digit. An equal number of trials were presented in which the digit list was four, five, or six digits in length. On half of the trials, the Ss heard a cue immediately after the last digit in the list which instructed them to respond as rapidly as possible to the probe digit by moving a toggle switch. The direction of movement of the switch served to indicate whether the S throught the probe digit was (positive probe) or was not (negative probe) in the previously heard list. On the other half of the trials, the Ss were cued to ignore the probe digit. In addition, half of the Ss were required to recall the list of digits in correct serial order 3 seconds after the probe digit. Recall was paced by a series of tones which occurred at 1 per second.

Three different response variables were measured. Changes in pupil size were monitored cinematographically during all experimental trials at approximately 2 frames per second. In the appropriate treatment conditions, RTs to probe digits were measured to the nearest millisecond, and recall errors were counted.

The major conclusions to be drawn from the study are as follows: First, significantly larger pupil dilation did occur, following the probe digit, on trials where Ss engaged in an STM search task than on trials where they did not. With regard to Sternberg's (1969) theory of serial exhaustive, item-recognition search, the pupillary data were equivocal. There was no significant difference in the amount of dilation between negative and positive probes which is in line with the exhaustive search aspect of Sternberg's theory. However, there were no significant differences in pupil dilation during search for different length of lists. Differences would be predicted by Sternberg's theory since the longer the list, the greater should be the amount of cognitive processing.

Second, the pupil response proved to be sensitive to several variables which would be expected to affect the amount of cognitive processing that an S performed during the course of a trial. For example, Ss who had to recall dilated more rapidly as the digit list was presented than Ss who did not have to recall. The amount of dilation at the close of presentation of the lists, but prior to search, was greatest for the six-digit lists with the five-digit lists resulting in an intermediate amount and the four-digit lists resulting in the smallest amount. During the pause between the last digit of the list and the probe digit, the Ss who had to search but not recall dilated the fastest; the Ss who only had to recall maintained their previous dilation level; and the Ss who did not have to recall or search briefly dilated then started constricting. The search condition resulted in larger dilations following the probe digit than did the other treatment conditions where only recall was required or where neither recall nor search was required. There was no significant difference just prior to the onset of the probe between conditions where Ss had to search and recall as compared to those who had to search but not recall.

When Ss performed the recall task, the six-digit lists resulted in the largest dilation, the five-digit lists resulted in the next larger and the four-digit lists resulted in the smallest. The length of the digit list significantly affected the proportion of recall errors with six-digit lists resulting in proportionally more errors than five-digit lists, and five-digit lists resulting in proportionally more errors than four-digit lists. Thus, error scores and pupil dilation reflected the greater difficulty of recalling the longer lists.

The only significant effect in the RT data was the much slower RT to the probe digit by the Ss who had to recall as compared to those who did not. In conjunction with the pupillary data and other reported research (Stanners, Meunier, & Headley, 1969), it was concluded that Ss who had to recall were apparently engaged in covert verbal rehearsal of the digit list which slowed their RTs. The Ss who did not have to recall apparently were not engaged in covert verbal rehearsal, but were engaged in some type of intense list processing immediately before the probe digit which allowed them to respond more rapidly to the probe.

In conclusion, the pupil response appeared to accurately reflect "real-time" variations in cognitive processing during a trial as imposed by various combinations of instructions to recall or not recall, to search or not search, short lists of digits.

A SELECTED BIBLIOGRAPHY

Adler, F. H. *Physiology of the eye.* (3rd ed.) St. Louis: Mosby, 1959.

Beatty, J., & D. Kahneman. Pupillary changes in two memory tasks. *Psychonomic Science*, 1966, *5*, 371-372.

Beck, B. B. The effect of the rate and intensity of auditory click stimulation on pupil size. Paper presented at the American Psychological Association Convention, Washington, September, 1967.

Bernick, N., & M. Oberlander. Effect of verbalization and two different modes of experiencing on pupil size. *Perception & Psychophysics*, 1968, *3*, 327-330.

Bradshaw, J. Pupil size as a measure of arousal during information processing. *Nature*, 1967, *216*, 515-516.

_______. Load and pupillary changes in continuous processing tasks. *British Journal of Psychology*, 1968, *59*, 265-271. (a)

_______. Pupil size and problem solving. *Quarterly Journal of Experimental Psychology*, 1968, *19*, 116-122. (b)

_______. Pupillary changes and reaction time with varied stimulus uncertainty. *Psychonomic Science*, 1968, *13*, 69-70. (c)

_______. Background light intensity and the pupillary response in a reaction time task. *Psychonomic Science*, 1969, *14*, 271-272.

_______. Pupil size and drug state in a reaction time task. *Psychonomic Science*, 1970, *18*, 112-113.

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

Clark, W. R., & D. A. Johnson. Effects of instructional set on pupillary responses during a short-term memory task. *Journal of Experimental Psychology*, 1970, in press.

Colman, F. D., & A. Paivio. Pupillary response and galvanic skin response during an imagery task. *Psychonomic Science*, 1969, *16*, 296-297.

DeRosa, D. V., & R. E. Morin. Recognition reaction time for digits in consecutive and nonconsecutive memorized sets. Journal of Experimental Psychology, 1970, 83, 472-479.

Dooley, R. P., & D. J. Lehr. Critique of a pupillary response experiment. Perceptual & Motor Skills, 1967, 25, 603-604.

Elshtain, E. L., & T. Schaefer, Jr. Effects of storage load and word frequency on pupillary responses during short-term memory. Psychonomic Science, 1968, 12, 143-144.

Hakerem, G., & S. Sutton. Pupillary response at visual threshold. Nature, 1966, 212, 485-486.

Hess, E. H. Pupillometric assessment. In John M. Shiler (Ed.), Research in Psychotherapy, Vol. 3. Washington: American Psychological Association, 1968.

_______. Attitude and pupil size. Scientific American, 1965, 212, 46-54.

Hess, E. H., & J. M. Polt. Pupil size in relation to mental activity during simple problem-solving. Science, 1964, 143, 1190-1192.

_______. Reply to "Critique of a pupillary response experiment" by Roger P. Dooley and Donald J. Lehr. Perceptual & Motor Skills, 1967, 25, 659-660.

Johnson, D. L. Pupillary responses during a short-term memory task with instructions to forget. Unpublished doctoral dissertation, Oklahoma State University, 1969.

Kahneman, D., & J. Beatty. Pupil diameter and load on memory. Science, 1966, 154, 1583-1585.

_______. Pupillary responses in a pitch-discrimination task. Perception & Psychophysics, 1967, 2, 101-105.

Kahneman, D., J. Beatty, & I. Pollack. Perceptual deficit during a mental task. Science, 1967, 157, 218-219.

Kahneman, D., L. Onuska, & R. E. Wolman. Effects of grouping on the pupillary response in a short-term memory task. Quarterly Journal of Experimental Psychology, 1968, 20, 309-311.

Kahneman, D., & W. S. Peavler. Incentive effects and pupillary changes in association learning. Journal of Experimental Psychology, 1969, 79, 312-318.

Kahneman, D., W. S. Peavler, & L. Onuska. Effects of verbalization and incentive on the pupil response to mental activity. Canadian Journal of Psychology, 1968, 22, 186-196.

Kahneman, D., B. Tursky, D. Shapiro, & A. Crider. Pupillary, heart rate, and skin resistance changes during a mental task. Journal of Experimental Psychology, 1969, 79, 164-167.

Kennedy, R. A., & D. Hamilton. Time to locate probe items in short lists of digits. American Journal of Psychology, 1969, 82, 272-275.

Kirk, R. E. Experimental design: Procedures for the behavioral science. Belmont, Cal.: Wadsworth, 1968.

Krueger, L. M. Voluntary control of pupillary responses to visual stimuli. Dissertation Abstracts, 1967, 28 (6-B), 2644.

Lehr, D. J., & B. O. Bergum. Note on pupillary adaptation. Perceptual & Motor Skills, 1966, 23, 917-918.

Loewenfeld, I. E. Mechanisms of reflex dilation of the pupil: Historical review and experimental analysis. Documents Opthalmologica, 1958, 12, 185-448.

_______. Comment on Hess' findings. Survey of Opthalmology, 1966, 11, 291-294.

_______. Pupillary movements associated with light and near vision: An experimental review of the literature. In M. A. Whitcomb (Ed.), Recent developments in vision research. Washington: National Academy of Sciences, 1966.

Lowenstein, O., & I. E. Loewenfeld. The pupil. In H. Davson (Ed.), The eye, Vol. 3. New York: Academic Press, 1962.

_______. The sleep-waking cycle and pupillary activity. Annals of the New York Academy of Sciences, 1964, 117, 142-156.

Morin, R. E., D. V. DeRosa, & V. Stultz. Recognition memory and reaction time. Acta Psychologica, 1967, 27, 298-305.

Morin, R. E., D. V. DeRosa, & R. Ulm. Short-term recognition memory for spatially isolated items. Psychonomic Science, 1967, 9, 617-618.

Paivio, A., & H. Simpson. The effect of word abstractness and pleasantness on pupil size during an imagery task. Psychonomic Science, 1966, 5, 55-56.

_______. Magnitude and latency of the pupillary response during an imagery task as a function of stimulus abstractness and imagery ability. Psychonomic Science, 1968, 12, 45-46.

Payne, D. T., M. E. Parry, & S. J. Harasymiw. Percentage of pupillary dilation as a measure of item difficulty. Perception & Psychophysics, 1968, 4, 139-143.

Schaefer, T. Jr., B. J. Ferguson, J. A. Klein, & E. B. Rawson. Pupillary responses during mental activities. Psychonomic Science, 1968, 12, 137-138.

Simpson, H. M. Effects of a task-relevant response on pupil size. Psychophysiology, 1969, 6, 115-121.

Simpson, H. M., F. M. Molloy, S. M. Hale, & M. H. Climan. Latency and magnitude of the pupillary response during an imagery task. Psychonomic Science, 1968, 13, 293-294.

Simpson, H. M., & A. Paivio. Changes in pupil size during an imagery task without motor response involvement. Psychonomic Science, 1966, 5, 405-406.

_______. Effects on pupil size of manual and verbal indicators of cognitive task fulfillment. Perception & Psychophysics, 1968, 3, 185-190.

Stanners, R. F., G. F. Meunier, & D. R. Headley. Reaction time as an index of rehearsal in short-term memory. Journal of Experimental Psychology, 1969, 82, 566-570.

Sternberg, S. High speed scanning in human memory. Science, 1966, 153, 652-654.

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

_______. Memory scanning: Mental processes revealed by reaction-time experiments. American Scientist, 1969, 57, 421-457.

Wingfield, A., & A. A. Branca. Strategy in high-speed memory search. Journal of Experimental Psychology, 1970, 83, 63-67.

Woodmansee, J. J. Methodological problems in pupillographic experiments. Proceedings of the 74th Annual Convention of the American Psychological Association, 1966, 1, 133-134.

APPENDIX

INSTRUCTIONS TO SUBJECTS

The following instructions were read by E to all Ss.

> Before you, there is a viewing box with camera, and reaction time switch, etc. I want you to place your right hand so that it rests on the table and so that you can get a good grasp of the switch between your thumb and index finger. I will be photographing your eyes while you perform a rather simple mental task. Before each trial, I will ask you to place your chin in the rest provided, with your forehead in the head-rest. You are to grasp the switch and get ready for the trial. During the trial, I want you to six a steady gaze upon the small cross on the screen at the opposite end of the box. No visual stimuli will be presented so concentrate on what you hear.

The following instructions were also read to all Ss who were required to perform an STM search when they heard a tone following the last digit in the list. Half of these Ss were asked to throw the toggle switch to the left if the probe digit was in the list, and to the right if it was not. The direction of toggle switch throw for the other half of the Ss is indicated in brackets.

> The series of events you will hear during a trial are as follows: A series of digits or numbers, a slight pause, a single digit, another pause, a series of tones. The task you are about to perform requires that you listen carefully to the series of digits. After the series of digits a tone may or may not occur. If you hear a short tone just after the series of digits, you must pay close attention to the following single digit. If this single digit is included in the series you have just heard, you are to respond to the single digit by throwing the switch in your right hand to the left [right]. If the digit is not included in the series, you are to respond to the digit by throwing the switch to the right [left]. Respond as quickly as possible, but avoid making any errors.
>
> Remember, if a tone follows the string or series of digits, you must respond to the single digit as quickly as

> you can. Left [right] if the single digit is included in the string of digits, and right [left] if it is not.
>
> If there is no tone immediately after the string of digits, you are to pay no attention to the following, single digit. You are not to respond. Remember, no tone--no hand response.
>
> At the end of each trial, I will tell you if you performed correctly or not. Please leave the switch in position after you have thrown it, I will tell you when to reset it.

The above instructions were also read to all Ss who were required to perform an STM search when they did not hear a tone following the digit list, except that all positive references to hearing a tone were changed to negative references, and likewise, all negative references to hearing a tone were changed to positive references. The same counterbalancing scheme for direction of responding was maintained.

The Ss who were required to recall were read the following instructions after they were read the appropriate "search instructions."

> Next, you will be ask to recall the series of digits, in correct order. As you remember, after the single digit there is a pause during which you make a response if appropriate. Then, following this pause, there is a series of tones. The first tone is a warning signal for you to get ready to recall the series of digits in correct order. After the first warning tone, recite, rather loudly, the series of digits in time with the subsequent tones. In other words, after the first tone, say one digit in time with each of the following tones. If you cannot remember all of the digits, recite those you can remember in their correct positions.

The Ss who did not have to recall were read the following instructions after the "search instructions."

> After the single digit you will hear a series of tones. These tones are for equipment operation and are not important for your task in any way.

Last of all, these final instructions were read to all Ss:

> At the end of each trial, I will ask you to lean back and rest while I prepare the equipment for the next trial. Are there any questions?

VITA

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