PUPILLARY RESPONSES, COGNITIVE PSYCHOPHYSIOLOGY AND PSYCHOPATHOLOGY

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I. Introduction

This section has two objectives: 1) to provide a brief overview of the pupillary response in relation to cognitive processes in normal and abnormal populations, and 2) to provide an update of papers during the past decade that have not been reviewed in summary papers. The reference list includes papers published from 1990 onward; not all of these papers are summarized in the review.

The following sections briefly review findings for components of information processing as reflected in the human pupillary response, and the relation of these measures to psychological phenomena in normal and neuropsychiatric patient groups. Both the constriction of the pupil to light (miosis), as well as the dilation (dilatation; mydriasis) resulting from information delivery, have provided useful adjuncts in the study of psychopathology, especially with reference to schizophrenia. Following summaries of some of the seminal findings, more recent papers are referenced. (Papers dealing with sensory reactions, or neurological reactivity unrelated to cognitive activation, are not usually included in this overview or the reference section).

Review Papers: Previous journal or book chapters which review pupillary data in relation to psychology include a brief paper by Tryon (1975), Goldwater (1982), Hakerem (1967), Hess (1972; 1975; 1987), and Beatty (1982 ;1986; Beatty and Wagoner, 2000),.

Books: Janisse (1974) published the proceedings of the Manitoba Pupil symposium of 1973, with relevant chapters by Hakerem, Peavler, Hess and Goodwin, Bernick, and Rubin. Books dealing with the psychology of the pupillary response have been published by Hess (1975), Janisse (1977), and Loewenfeld (1993; see chapters 14 and 45, respectively, dealing with psychology and psychiatry). A particularly good recent overview has been provided by Andreassi (2000).

A review of pupillary reactions in schizophrenia was provided by Zahn, Frith, & Steinhauer (1991), following earlier reviews of psychophysiology and psychopathology by Spohn and Patterson (1979) and Zahn (1986). Much of the following review is adapted from

Steinhauer and Hakerem (1992). More recent findings related to relatives of schizophrenic subjects have been summarized by Steinhauer and Friedman (1995).

Integrative findings on pupillography have been presented at the International Colloquia on the Pupil, beginning in 1963. The most recent meeting was held at Asilimar, California in September, 2001. The next meeting will be held in Crete in 2003. For details, and information on Pupillary studies, see the Pupil page of Peter Howarth http://www.jiscmail.ac.uk/files/PUPIL/.

II. General Background and Historical Perspective

For centuries, the pupillary aperture has been thought of as a figurative window to the mind; with the advancement of medical sciences, the pupil began to serve as a literal window on brain function. In her 1958 dissertation paper dealing primarily with pupillary dilatation, Loewenfeld (1958) cited nearly 1600 references, including 114 dated prior to 1830; her 1993 book lists over 15,000 references, covering up to about 1985.

Incidental observations of pupillary dilation associated with increased interest or arousal were well known, such as the use of belladonna to enlarge the pupil artificially as a cosmetic effect, and wearing of eyeshades to obscure any sudden dilatation for the poker player who might otherwise give away his hand.

The re-emergence of pupillary studies among psychologists is related to a series of reports from several different laboratories in the early 1960s in the areas of experimental psychology and experimental psychopathology. The most polemic approach was generated by the initial papers of Eckhard Hess claiming pupillary dilation to positive affect stimuli and constriction to negative affect (Hess & Polt, 1960), which led to continuing controversies. Sokolov (1963) emphasized the contributions of pupillary changes in defining the orienting reaction to novel environmental stimuli. Hess and Polt also began to report on pupillary dilation during mental activities (Hess & Polt, 1964). More carefully conducted studies began to appear involving threshold discrimination (Hakerem & Sutton, 1966), and work by Kahneman and colleagues (e.g., Kahneman & Beatty, 1966) represented a much stronger commitment to the developing concepts of cognitive psychology.

III. Cognitive Psychophysiology and Pupillography: Psychophysiological Measurement of Processing Effort, Capacity, and Information.

Among those measures for which a correlate of both attentional effort and processing activities have been studied, perhaps the most widely emphasized is the pupillary dilation response (Beatty, 1982; Beatty, 1986; Goldwater, 1972; Janisse, 1977). Pupil diameter enlarges with increasing effort during performance. This can be observed for purely mechanical effort, as when varying weights are picked up (Nunnally, Knott, Duchnowski, & Parker, 1967) or even when a simple finger press occurs, in which both response preparation and execution contribute to the dilation (Richer, Silverman, & Beatty, 1983). Mental effort has been manipulated by a number of means, including arithmetic problems of varying difficulty (often a typical "mental stress" paradigm), language-based tasks (including reading of material forward and backwards; Metalis, Rhoades, Hess, & Petrovich, 1980), and especially the effect of increasing memory load during the digit span task, in which pupil diameter increases as the number of digits stored is increased (Kahneman & Beatty, 1966). Of special interest is that as maximum effective storage (judged by performance) is reached, pupillary dilation reaches a maximum (Peavler, 1974). When memory is overloaded, the pupil may even decrease in diameter, suggesting that it is sensitive to both the extent of processing capacity as well as the breakdown of capacity (Poock, 1973; Granholm et al., 1996). Kahneman (1973) relied heavily on results from pupillary experiments in the development of his treatise dealing with basic components of attention and effort. More recent approaches to information processing models such as neural networks have also ustilized pupillary data (Siegle, 1999a).

Pupillary dilation can also be evoked by tasks in which there is little effort employed in recognizing a stimulus, but for which the "informational value" of the stimulus is high. Thus, simple click patterns show a quick habituation when the subject knows what each subsequent stimulus will be, but a clear dilation occurs to the clicks when the subject is asked to guess what stimulus pattern will occur (Hakerem, 1974). Moreover, when the subject is not certain whether a click will actually occur at a specific point in time, but the absence of a click indicates a particular outcome (e.g., correct or incorrect, different amounts of monetary payoff), the "absence" of the stimulus itself elicits a pupillary dilation (Levine, 1969) which is related to the information conveyed by the stimulus absence. Friedman et al. (1973) observed that the amplitudes of pupillary dilation and the amplitude of the P300 component of the event-related brain potential were inversely related to the subjective probabilities (an interaction of the subject's guessing behavior and the stimulus probabilities). Thus, larger amplitudes were seen for the least likely events. The same paradigm was employed by Bock (1976), who recorded pupillary and ERP data from monozygotic and dizygotic twin pairs, and from non-twin siblings.

In dealing with the complexities of stimulus qualities which affect pupil diameter, it is worthwhile to take a brief look at one of the major controversies in pupillary research -- the statements of Hess and colleagues (Hess & Polt, 1960; Hess, 1964) that positive affect is associated with dilation, while negative affect results in constriction. Though the notion of constriction to aversive stimuli has been widely rejected, responses to arousing viusal stimuli continue to be studied (Aboyoun & Dabbs, 1998; Dabbs, 1997). There have been many critical reviews of this research (e.g., Janisse, 1977), as well as attempts by Hess and his students to justify the work (Hess, Beaver, & Shrout, 1975). Two of the problems involved in using complex visual stimuli, which have usually been overlooked, will be mentioned.

The first consideration involves so-called control slides, which are typically presented before each stimulus slide. The notion in several studies was that the control and stimulus slides should be matched for brightness, so that no differential constriction to the slides could occur, and differences could only be attributable to the content of the target stimulus slide. This approach, however, takes a naive view of the physiology of the optic system, including the afferent pathway even at the level of the retina. When stimuli of either different wavelengths or different intensities strike similar regions of the retina, they differentially stimulate receptors, which evoke pupillary constrictions. This was exquisitely demonstrated over two decades ago by Kohn and Clynes (1969): even matching for overall brightness did not eliminate sensory-related constrictions to the onset of different hues.

A second source of confounding is related to the pupillary constriction produced by the initial presentation of stimuli. This portion of the response was usually ignored by researchers employing pictures, who looked at average diameters over periods as long as ten seconds, rather than the specific dynamic responses to the pictures used. One exception to this was a study by Libby, Lacey and Lacey (1973), whose data clearly showed the initial constriction resulting from stimulus presentations. In their study, pupillary dilation was most often seen to interesting pictures, and the unpleasant stimuli overall yielded larger dilations than pleasant stimuli -- a finding totally at odds with the Hess formulation. Similarly, Steinhauer et al. (1983) examined the responses to a series of pictures varying in emotional content, but covaried out effects of initial diameter and the constriction produced by slide onset: the largest dilations were evoked by stimuli reported as most aversive or most pleasant, with smaller dilations to mildly unpleasant or pleasant stimuli, and the least dilation to neutral pictures. Thus, the best controlled studies indicate that the level of emotional stimulation or interest, regardless of valence, is related to the pupillary dilation response, but the confounding effect of initial physiological reactions to visual stimuli must be carefully eliminated.

Genetic Contributions: One of the more intriguing aspects of psychophysiological data is that there is clear evidence that familial similarity can be observed in tonic activity as well as in time-varying measures of cognitive activity (Boomsma & Gabrielli, 1985). Patterns of pupillary dilation have been examined among twin pairs in two dissertations conducted by students of Hakerem. Bock (1976) compared pupillary dilation in identical twins, fraternal twins, and non-twin siblings during a guessing task. Both objective numerical analyses of similarity, as well as judges' blind matching of pairs, indicated greater similarity of the pupil and ERP data for identical twins than for fraternal twins or non-twin siblings. A more recent dissertation (Gaudreau, 1991) used a forced-choice procedure for matching pupillary waveforms, demonstrating significantly high rates of matching identical twin pairs across two different tasks.

Additional work has been conducted to examine underlying substrates of cognitive performance and pupillary reactions. Beatty (1989) demonstrated that the pupil could respond with extremely small average dilations (.001 mm) to stimuli occurring at up to a rate of 3/sec. Matthews et al. (1991) found that blockade of the sphincter by thymoxamine eliminated the dilation that was produced by an effortful task. Granholm et al. (1996) reexamined the use of processing load, presenting subjects with 5, 9 or 13 digits during a digit span task. As expected, processing load increased as demand increased, but more clearly showed stabilization when nearing maximum processing capacity, but decrease in pupil diameter once capacity was exceeded.

Language function has been examined using the pupil in studies of syntactic anomaly (Schluroff, 1982), lexical ambiguity (Ben-Nun, 1986), and syntactic complexity (Just and Carpenter, 1993).

Attempts to model the contributions of different sources contributing to pupillary movements have included bioengineering models (see the chapter by Stark in Loewenfeld's book). Hoeks and Levelt (1992), and Hoeks and Ellenbroek (1993) have proposed a quantitative neural model, although they did not account for contributions of the sympathetic pathway to dilation processes. Steinhauer has proposed a model in which sympathetic and parasympathetic components contribute differentially to dilation under varying task requirements, with different time courses for the contributions of the sympathetic and parasympathetic pathways (see Steinhauer and Hakerem, 1992).

IV. Psychopathology and Pupillary Motility

During the early years of this century, aberrations in pupillary responsivity were carefully noted in psychotic patients (cf. Hakerem & Lidsky, 1975; Hess, 1972), especially by German psychiatrists such as Bumke (1904) and Bach (1908), and were followed up with studies by Lowenstein and Westphal (1933), Levine and Schilder (1942), and May (1948) in the third and fourth decades. Leonard Rubin, at Eastern Psychiatric Research Institute in Philadelphia, was employing pupillary measurement to develop hypotheses of autonomic imbalance in psychiatric patients (for an overview, see Rubin 1974). While his attempts to define a variety of disorders based on the notions of central adrenergic and/or cholinergic activity as assessed by the pupil attracted some interest for a number of years, this conceptualization has been heavily criticized as being overly simplistic, and has been rejected by most researchers (see discussion by Loewenfeld, 1993).

Hakerem and colleagues at New York York State Psychiatric Institute conducted a number of initial studies which indicated decreased light reactions and abnormal response latencies in schizophrenics (Hakerem & Lidsky, 1969; Hakerem, Sutton, & Zubin, 1964; Lidsky, Hakerem, & Sutton, 1971), as well as difficulties in integrating irregular sequences of light pulses (Hakerem & Lidsky, 1975). Decreased responsivity in schizophrenic patients for auditory and visual pupillary responses during cognitive tasks was reported by Steinhauer, Hakerem, and Spring (1979).

Steinhauer and Zubin (1982) reported decreased dilation, as well as decreased P300 amplitudes for schizophrenics compared to controls, during an auditory task in which infrequent stimuli normally evoke substantial pupillary dilation and P300 amplitudes.

Steinhauer et al. (1992) recorded the averaged light reaction in schizophrenic patients during neuroleptic treatment and subsequent (double-blind) drug free withdrawal. Stabilization on haloperidol resulted in a significant increase in extent of constriction than during a subsequent drug-free period in patients. Thus, neuroleptic treatment appeared to normalize the response slightly, but generally still kept the response measure below the mean for normals. Data during the treatment phase were also found to predict likelihood of subsequent relapse.

There have been few additional studies of patients involving task-related dilation. Straube (1982) reported that schizophrenics exhibited larger dilations than controls during performance of the digit span task, which could be interpreted as an indication that patients employed greater effort than did controls. However, Granholm et al. (1996) reported decreased dilation in schizophrenic patients during the digit span task, a finding that appears to conflict with the report of Straube. Morris et al. (1997) evaluated working memory using pupillary reactivity in schizophrenics. Granholm et al. (1999) have used the pupillary response to probe semantic incongruities during verbal fluency in schizophrenic patients.

Several other types of patient groups have been studied. Patients with toxic exposure to organic solvents exhibit reduced dilations during information processing tasks, but also show abnormal increases in overall diameter when even slightly more complex tasks are presented that are not difficult for normal subjects (Morrow & Steinhauer, 1995). For alcoholic subjects, no differences between semantic and phonemic tasks have been observed (O'Leary et al., 1980). An interesting series of studies by Bitsios and colleagues (1996, 1998a, 1998b) has employed the pupillary light reaction to probe the effects of anxiety and effectiveness of anxiolytics; the light reaction is reduced by anticipation of a fear-evoking event (Bitsios et al, 1996). Patients with anxiety disorders, who show reduced light reactions (Bakes et al., 1990), show increasing light reaction amplitude when anxiolytics are administered (Bitsios et al., 1998). Reduction of dilation to fearful stimuli during desensitization treatment of phobic patients has also been reported (Sturgeon et al, 1989). Effects of rumination indicated by dilation have been examined among depressed patients (Siegle, 1999b).

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