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International Journal of Psychophysiology 52 (2004) 1–6

INTERNATIONAL
JOURNAL OF
PSYCHOPHYSIOLOGYwww.elsevier.com/locate/ijpsycho

Introduction

Pupillometric measures of cognitive and emotional processes

Changes in pupil diameter provide a unique window on brain activity. We would like to thank Dr John Andreassi, editor of the *International Journal of Psychophysiology*, for the opportunity to be guest editors of this special issue on pupillometric studies. This volume is an expansion of the symposium ‘Pupillometry and Cognition in Schizophrenia’ presented at the 11th World Congress of Psychophysiology held in Montreal in 2002, chaired by the first author. A number of additional contributions have been included that survey much of the current state of research involving cognitive and emotional processes, and the relevance of pupillary mechanisms to the elucidation of neuropsychiatric problems. All of the papers were peer-reviewed in accord with *Journal* standards, and we would like to acknowledge and thank all of the reviewers and authors for their contributions.

Pupillometric methods are used to measure variations in the diameter of the pupillary aperture of the eye in response to psychophysical and/or psychological stimuli. In keeping with the focus of *International Journal of Psychophysiology*, this special issue emphasizes pupillometric measures of psychological processes, rather than psychophysical processes, despite the wealth of research on the latter. Pupillary responses can be used to index the extent of central nervous system processing allocated to a task. The extent of pupil dilation evoked by a task reflects activation in processing modules of the brain, regardless of whether those modules contribute information processing (e.g. attentional allocation; stimulus identification; working memory maintenance; semantic elaboration; response

organization; motor output) or emotional processing (e.g. attach or interpret an affective valence). In numerous studies of normal individuals, pupil size has been found to increase in response to increased processing demands. For example, pupil size recorded during a digit span recall task systematically increases following the presentation of each additional to-be-recalled digit and then returns to resting baseline size after the digits are recalled. Increased pupil dilation is also found when the number of multiplicands is increased on mental arithmetic tasks, the syntactic complexity of sentences is increased on sentence comprehension tasks, the difficulty of perceptual discriminations is increased, and when processing pleasant and unpleasant stimuli relative to neutral stimuli. As such, pupillometry can be broadly applied in psychological research to inform normal and abnormal cognitive and emotional functioning. One goal of this special issue is to stimulate the application of pupillometric methods in psychophysiological research.

For over two millennia, changes in pupillary motility have been noted and employed as indicators of both emotional arousal as well as signs of medical state. Activation of the sympathetic system stimulates the radial dilator muscles of the pupil, causing enlargement of the pupil, or decrease in diameter as sympathetic activation decreases. When the parasympathetic system is stimulated, with the efferent pathway originating in the Edinger–Westphal complex of the oculomotor nucleus, the sphincter muscles of the iris (forming a band around the inner margin of the pupil) produce

active constriction of the pupil, as seen in the reflex reaction to light. Inhibition of the parasympathetic system can also result in significant dilation. In the references listed and in many of the papers in this volume, the contributions of cortical and subcortical brain systems are described.

The iris of the pupil is one of the few autonomic physiological effectors that is immediately accessible to the eye. For over a century, use of photographic techniques permitted more exacting assessment of pupil diameter, but were limited in temporal resolution. Beginning in the second half of this century, electronically based systems for imaging of the pupil, including TV-based systems, were interfaced with newer computer technologies to provide more accurate assessment of pupil diameter. Systems commonly employed today can resolve better than 0.025 mm in diameter on individual measurements, at rates of 60 Hz, or even up to 240 Hz. Moreover, the introduction of signal averaging techniques, widely used in the study of event-related potentials, was also applied almost immediately to information processing studies involving pupillary assessment (e.g. Hakerem and Sutton, 1966), so that it is possible to resolve changes on the order of hundredths of a millimeter in the average pupillary response.

The articles in this issue are a non-exhaustive illustration of the breath of application of pupillometric methods to the study of normal psychological processes and their breakdown in psychopathology. We have attempted to provide examples of pupillometric studies that address important questions about normal and abnormal cognitive and emotional processes, as well as manuscripts that inform the underlying neurophysiology of the pupillary response, itself. Questions addressed in this issue include the following, but there are many other possible applications:

- What are the relative sympathetic and parasympathetic contributions to pupil dilation during cognitive processing?
- Can the pupil be used to index activation in specific brain areas (e.g. prefrontal cortex)?
- Do people with greater general cognitive ability

(e.g. higher IQ) process information with greater neural efficiency?

- Does top-down control over attention under competing task demands continue to mature through childhood and adolescence?
- Are cognitive deficits in patients with schizophrenia related to attentional allocation problems?
- Are specific psychotic symptoms, like thought disorder, due to information processing overload and cognitive defragmentation?
- Are selective attention deficits in patients with depression related to decreased cognitive control and reduced prefrontal cortex engagement?
- Can a pupillometric alertness level test be used to assist in the diagnosis of sleep disorders and screen for sleepiness in the workforce, e.g. in the transportation industry?
- What can fear-inhibited pupillary light reflexes tell us about the relationships between fear conditioning, arousal and anxiety?

The studies by Karatekin and Verney illustrate how pupil dilation during cognitive tasks can be used to inform normal cognition. The development of attentional control in children was examined in the Karatekin study. In a dual-task paradigm, 10-year-old children and adults divided their attention between a digit recall task and a simple reaction time task. Both groups showed increased dilation in response to each digit to be recalled, but children showed less dilation during longer spans (six- and eight-digits) relative to adults, especially in dual-task conditions. The children's ability to recruit sufficient working memory resources at higher loads was not yet fully mature.

In the Verney study, pupillary responses were recorded during an early visual processing task, the backward masking task, which is commonly used to measure the efficiency of early visual information processing. As in evoked potential research, signal averaging and component extraction techniques (e.g. peak picking; principal component analysis or PCA) were applied to the pupil response data. A PCA of pupillary response waveforms identified a component that was attributed

to processing of relevant target stimuli and a second component was attributed to wasteful processing of task-irrelevant stimuli (masks). College students who had higher SAT scores showed smaller pupillary responses on the irrelevant stimulus (mask) component. That is, brighter students showed more efficient processing by allocating less processing to irrelevant task stimuli than did students with lower SAT scores. The Karatekin and Verney studies illustrate how pupillary responses can be used to test hypotheses about normal cognition and how familiar psychophysiological data reduction techniques can be applied to pupillary response data.

The three papers by Granholm, Minassian and Siegle all examined the breakdown of cognitive processes in patients with psychiatric disorders. Using the backward masking paradigm from the Verney study described above, the Granholm study examined attentional control problems in patients with schizophrenia. Relative to healthy controls, patients with schizophrenia showed greater dilation on the mask component and less dilation on the target component of the pupillary response waveforms. This was interpreted as a breakdown of attentional control functions that determine the relative amount of processing allocated to relevant (targets) and irrelevant (mask) stimuli. This study shows how pupillary response measures of specific cognitive mechanisms can be developed and validated in studies of healthy participants and then applied to studies of the breakdown of cognitive processes in psychopathology.

In the Minassian study, pupillary responses were recorded while patients with schizophrenia and healthy controls named simple line drawings (low processing load) and generated responses to Rorschach Inkblots (high load). Both groups showed greater dilation during the more complex Rorschach problem-solving task than during the naming task, but the schizophrenia patients showed less dilation than controls during the high load Rorschach task. Further, patients who were more overloaded by the demands of the Rorschach task (showed less dilation) had more severe thought disorder. This study is an example of how simul-

taneous recording of pupil responses during performance of a familiar psychological test can inform the mechanisms underlying disturbed performance on the test.

Siegle et al. examined processing on the Stroop task in normal and depressed individuals. While responses to incongruent stimuli (words written in a color to be named, but spelling a different color) showed the typical delayed reaction time and initially higher pupillary dilations to incongruent words, the depressed individuals displayed significantly decreased diameter several seconds later. Siegle demonstrated how a variety of different analytic approaches could be used to explain these effects, including computational neural network modeling. The modeled data are consistent with the notion that decreased activation of frontal cortical activity could be associated with decreased cognitive control in depressed individuals.

In pupillometric studies that use visual stimuli, experimental conditions must carefully control psychophysical aspects of stimuli. For example, the amount of light or hue in visual stimuli can alter dilation and constriction responses. The reverse is also true. The amount of brain activation can alter components (e.g. amplitude and latency) of specific psychophysical pupillary responses, such as the pupillary light reflex. The articles by Steinhauer and by Bitsios illustrate this interplay between cognitive and emotional brain activation and the psychophysical responses of the pupil. The Bitsios study showed that the amplitude of the pupillary light reflex is decreased by anticipation of an electric shock. Further, specific components of the light reflex waveform were differentially related to subjective feelings of alertness and anxiety. An increase in initial (baseline) pupil diameter was related to alertness associated with the anticipation of any stimulus, whereas light reflex amplitude was decreased only by fear of an approaching aversive stimulus. Different components of pupillary responses can be linked to different psychological processes.

A great deal is known regarding central brain mechanisms that activate and inhibit the sympathetic and parasympathetic pathways that control

pupillary changes. The paper by Steinhauer and colleagues examines two approaches for dissociating these contributions. Subjects performed either an easy or difficult mathematical task involving sustained activity, in which they verbalized the results of each operation during the recording period. In the first experiment, recordings obtained during darkness were compared to recordings obtained under lighted room conditions. In darkness, parasympathetic tone is minimized, but in light, the pupil is more constricted, so that any effects of central inhibition due to mental processes are reflected as decreased parasympathetic activity, leading to increased dilation. Enhanced dilation was seen to the more difficult task, especially under the light condition. In the second series of experiments, the dilator and sphincter muscles were temporarily blocked by administering pharmacological agents to the eye in separate sessions, and the experiment was repeated. This procedure permitted isolation of activity in the pathway that had not been blocked to be compared with the dark- and light-recorded data. General sustained activity was present in both the sympathetic and parasympathetic pathways, but differential activation to the difficult task was present only in the parasympathetic pathway, suggesting additional recruitment of frontal cortical regions during greater task demands.

In addition to indexing cognitive and emotional processes, the pupil, like other autonomic systems, also reflects arousal state. Changes in resting pupil diameter over time can be used to index tonic arousal state or fatigue. An important distinction here is between *tonic* pupil size, which can reflect arousal state, and *phasic* changes in pupil size in response to task stimuli, which are used to index cognitive and emotional processes but are less sensitive to arousal state. The article by Merritt illustrates how changes in pupil size recorded over a 15-min period (pupillometric Alertness Level Test) can be used to stage sleepiness and fatigue in participants with sleep problems. This convenient pupil test was validated against EEG/polysomnography testing and self-report sleepiness measures. Pupillometric alertness measures may have future

applications in the diagnosis of sleep disorders and screening for sleepiness in industry.

For more than a century, it has been known that pupillometry can provide psychophysiological researchers with a sensitive and reliable index to examine cognitive and emotional processes. Pupillometric methods are also much more convenient and less expensive than other measures that have been used as correlates of cognitive and emotional brain activation (e.g. fMRI and electrophysiology). It is, therefore, surprising that few psychophysiologicalists take advantage of this method. Beatty and Lucero-Wagoner (2000) speculated that pupillometry is not widely used because, unlike electrophysiology and fMRI, the pupillary response lacks face validity as a measure of brain function. This is changing as pupillary responses are increasingly being recorded during fMRI to validate the neural system activations involved in producing pupil responses. We hope that this special issue on pupillometry will encourage other researchers to apply this powerful and convenient method in their research programs.

One of the objectives in preparing this issue was to provide a guide for those seeking more information on background and methodology for undertaking studies of pupillary motility. An introduction and expanded reference list is available online (Steinhauer, 2002) for the interested reader. Previous journal or book chapters which review pupillary data in relation to psychology include Beatty (1982, 1986, 1989), Beatty and Lucero-Wagoner (2000), Goldwater (1972), Hakerem (1967, 1974), Hess (1972, 1975), Hess and Petrovich (1987) and Kahneman (1973), as well as a brief paper by Tryon (1975). 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) and 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). Much of the literature dealing with psychopathol-

ogy has been related to studies of schizophrenia. Reviews of pupillary reactions in schizophrenia have been provided by Zahn et al. (1991) and by Steinhauer and Hakerem (1992), following earlier reviews of psychophysiology and psychopathology by Spohn and Patterson (1979) and Zahn (1986). More recent findings related to relatives of schizophrenic subjects have been summarized by Steinhauer and Friedman (1995). Relevant information on the physiology of the pupillary response can be found in Loewenfeld (1958, 1993) and Lowenstein and Loewenfeld (1962) and in the Alexandridis (1985) and Zinn (1972) books dealing with neuro-ophthalmology.

In addition to the meetings and journals of the International Organization of Psychophysiology and the Society for Psychophysiological Research, we also encourage interested readers to visit the 'Pupil Page' (<http://www.jiscmail.ac.uk/files/pupil/index.html>) for general links to other pupil sites. Information is also provided on the Pupil Page regarding the International Colloquium on the Pupil, meeting biennially since 1963, at which researchers from diverse backgrounds including psychology, psychiatry, neurology, physiology and ophthalmology meet to share recent findings on the pupil of the eye.

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