

THE PUPILLARY SYSTEM

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The pupil is the opening through which light enters the eye and begins the process of visual perception. The diameter of that opening is determined by the relative contraction of two opposing sets of muscles within the iris, the sphincter and dilator pupillae, and is determined primarily by the light and accommodation reflexes. But in addition to reflexive control of pupillary size there are also tiny, cognitively related, visually insignificant fluctuations in pupillary diameter that appear to serve no functional purpose whatsoever. These miniature pupillary movements – usually less than 0.5 mm in extent – appear to be attenuated reflections of changes in brain activation systems that underlie human cognition.

Fortunately for cognitive psychophysicists, these exceedingly tiny pupillary movements are too small to be of visual consequence. Perhaps because they have no evolutionary cost, they have been spared removal by the sure knife of evolution. These small but ubiquitous pupillary fluctuations form the basis of *cognitive pupillometry*, providing a unique psychophysiological index of dynamic brain activity in human cognition.

We begin by summarizing the brief history of cognitive pupillometry. Next we introduce the concept of pupillary movements as a psychological reporter variable, directly analogous to the reporter genes used with great benefit in molecular biology. We then summarize the anatomy, physiology, and pharmacology of pupillary movements, followed by an overview of the methods by which they are measured.

The heart of the chapter consists of a systematic review of the empirical literature utilizing task-evoked pupillary responses in the study of human cognitive processes. A common graphic format is used in presenting these results so that diverse experimental findings may be directly compared. The result is a consistent depiction of intensity variations in human cognitive processing as reflected

by task-evoked pupillary responses. We conclude with a few small suggestions for future pupillometric studies and the role that they may play in cognitive neuroscience more generally.

Historical Background

LARGE-SCALE PUPILLARY MOVEMENTS IN CLINICAL NEUROLOGY

Large-scale changes in pupillary diameter have played a useful role in the daily practice of clinical neurology since the inception of this medical specialty. Large-scale changes of the pupil are conveniently defined as being apparent to a trained observer without the need for specialized measurement or recording apparatus. Large-scale abnormalities in pupillary diameter are usually either static or slowly changing and are indicative of peripheral or central nervous system (CNS) lesions or the use of psychopharmacologically active substances.

Chronic pupillary constriction is indicative of interruption to the sympathetic pathway leading to the sympathetically innervated dilator muscles of the iris (Bickerstaff & Spillane 1989). Such lesions may occur in the hypothalamus, the brainstem, the lateral upper thoracic spinal cord, the sympathetic ganglia, or the peripheral sympathetic fibers leading to the eye. Extremely constricted, pinpoint pupils are also produced by opiate narcotics such as morphine (Jaffe & Martin 1985).

In contrast, chronic pupillary dilation is produced by disruption of the parasympathetic input that ultimately activates the sphincter pupillae, which constrict the pupil. Disruption may occur anywhere from the pretectal nuclei and the nucleus Edinger–Westphal of the midbrain, through the pathway of the oculomotor (III) nerve to the ciliary ganglion of the orbit. The most common lesions

are produced by vascular accidents of the midbrain, herniation produced by space-occupying tumors, or carotid artery aneurysm (Bickerstaff & Spillane 1989). Pupillary dilation is also produced by ingestion of neuroactive compounds such as atropine.

SMALL-SCALE PUPILLARY MOVEMENTS IN COGNITIVE PSYCHOPHYSIOLOGY

Unlike neurology, cognitive psychophysiology is concerned not with localizing neural lesions in clinical patients but rather with understanding the cognitive functions of the human brain. For this purpose, the examination of large-scale pupillary movements is uninformative. However, there are small-scale, rapid fluctuations in pupillary diameter that are reflective of the dynamic CNS changes that underlie human cognition. The largest of these cognitively driven movements are about 0.5 mm in pupillary diameter, making them difficult to detect by unaided observation. Instead, precise pupillometric recording methods are employed to study the small-scale dynamic pupillary movements that reflect the cognitive activity of the human brain (Beatty 1982a,b; Goldwater 1972).

The fact that pupillary dilation accompanies cognitive processing was suggested in neurology well over a hundred years ago. Schiff (1875; Schiff & Foa 1874) documented that pupillary dilations are evoked by a variety of nonvisual stimuli. Shortly thereafter, W. Heinrich (1896) measured pupillary dilations evoked by cognitive processing in a study of pupillary movements evoked in mental multiplication tasks.

By the turn of the century (1911), Oswald Bumke could assert with confidence that "every active intellectual process, every psychical effort, every exertion of attention, every active mental image, regardless of content, particularly every affect just as truly produces pupil enlargement as does every sensory stimulus" (translated in Hess 1975, pp. 23–4).

However, for reasons that are not at all clear, this body of pupillometric knowledge remained confined to the German neurological literature. American psychophysiology was not aware of this phenomenon until the 1960s, when Hess and Polt (1964) published essentially a reconfirmation of Heinrich's earlier finding of pupillary dilations produced by mental arithmetic. This publication in *Science* was the impetus for the subsequent body of work that is the subject of this chapter.

PSYCHOPHYSIOLOGICAL REPORTER VARIABLES

Pupillary movements have had a curious status in psychophysiological research: they appear to reflect peripheral autonomic factors that are unrelated in any obvious way to central cognitive processes, yet they nonetheless empirically

reflect variations in central processing load with extraordinary precision (Beatty 1982b, 1986; Goldwater 1972). "The implication," wrote Just and Carpenter (1993, p. 312), "is that the pupillary response is only a correlate of cognitive intensity, hence the marker is indirect and not causally linked" – a conclusion with which we agree completely.

But is noncausality a problem? How can a measure with so little apparent face validity be useful in psychophysiological research? We believe that noncausality is in no sense a problem. Rather, the use of pupillary movements in cognitive psychophysiology is analogous in several important ways to the use of reporter genes in molecular biology, where correlational measurement has speeded the study of the genome and its regulation (Alberts et al. 1998; Wood 1995). We suggest that explicit recognition of the properties of task-evoked pupillary response as a reporter variable in psychophysiology might facilitate the study of the biological basis of human cognition. Similar arguments have been made previously by Cacioppo and Tassinari (1990) in their discussion of the psychophysiological inference problem.

In molecular cell biology, reporter genes are DNA sequences that encode proteins of no intrinsic interest *except that* the reporter proteins are easily detected when expressed. Reporter genes are attached to the genome in the immediate vicinity of a gene of interest and thus provide an easily measured correlate of the gene being studied (Alberts et al. 1998).

A number of reporter gene sequences and their associated proteins are routinely employed in molecular biology. In a particularly dramatic example of reporter gene technology, Okabe and colleagues (1997) inserted the DNA sequence for an enhanced version of the green fluorescent protein, which produces bioluminescence in the *Victoria* jellyfish, into the mouse genome in a position that assures its expression throughout the whole body of the mouse, from embryonic stages through adulthood. The result is an extraordinarily vivid marker for use in genetic studies: wherever and whenever this reporter gene is expressed, the mouse glows bright green.

In psychophysiology, we rarely have the luxury of inserting markers of any sort into the human brain to study human cognitive function. Yet we should learn from the molecular biologists and openly exploit any naturally occurring psychophysiological reporter variables that are reliably correlated with central nervous system events of interest to cognitive neuroscience. It is our belief that task-evoked pupillary responses are important psychophysiological reporter variables deserving of further study.

Physical Context

Pupillary movements are determined by the state of the iridic musculature under the direct control of both the sympathetic and parasympathetic branches of the autonomic nervous system. The coupling of pupillary movements to

cognitive processes, however, must occur at much higher levels within the human nervous system.

PUPILLARY ANATOMY

The general structure of the eye is often compared to a camera: each has a lens to refract and focus incoming light rays as well as an adjustable aperture that serves to regulate the amount of light admitted. In the eye, the aperture is the pupil – the opening in a pigmented structure called the iris, which contains two antagonistic smooth muscle groups, the sphincter and dilator muscles. Each of these muscles is innervated by a different component of the autonomic nervous system. The sphincter muscles, which constrict the iris, are under sympathetic control; the dilator muscles, which serve to open the iris, receive input from the sympathetic nervous system. At any moment in time, the size of the pupil is the integrated result of the ratio of activity occurring in the pathways innervating these two muscle groups, as seen in Figure 1.

As early as 1911, the illustrious physiologist C. S. Sherrington described the reciprocal nature of the muscles of the iris: as the agonistic dilator muscles are activated, motor output to the antagonistic sphincter muscles is reduced. In Sherrington's words, "the inhibition is not peripheral but central, that is, it has its seat not in the muscle but in the nervous centre about the starting point of the final common path. The muscle relaxes because the motor discharge from that centre is abated" (quoted in Loewenfeld 1993).

The mechanics of this reciprocal system is complex. Until Loewenfeld's elegant series of experiments on a single macaca mullata monkey (Loewenfeld 1958), it had been believed that parasympathetic inhibition was simply the consequence of activity along the adrenergic sympa-

thetic pathway via the cervical sympathetic or other nerves. Loewenfeld demonstrated that parasympathetic inhibition persists after the sympathetic nerve is cut and that stimulation of the cervical sympathetic chain is insufficient to block the light reflex, whereas low-intensity electrical stimulation of the thalamus or hypothalamus readily prevents its occurrence. The inhibitory influences on the postganglionic parasympathetic neurons thus come not from the periphery but from suppression of the parasympathetic motor nucleus in the midbrain, which is then unable to send constricting impulses to the periphery. This result follows what Sherrington had postulated more than fifty years earlier in his law of reciprocal innervation.

The electrophysiological research of Bonvallet and Zbrozna (1963) directly demonstrated the two opposing systems. When the sympathetic agonist is activated, the motor nucleus of the antagonist is inhibited. These investigators recorded electrical activity in the cortex, the sympathetic chain, and the short parasympathetic ciliary nerves in a flaxidil-immobilized cat with a thoracic-level transection of the spinal cord. Immediately following stimulation of the pontine-mesencephalic reticular formation, several events occurred: cortical arousal, activity along the cervical sympathetic nerve to the dilator muscles, and inhibition of parasympathetic activity in the postganglionic ciliary nerve serving the constrictor muscles. Stimulation of sensory nerves entering above the level of the transection had identical effects.

PUPILLARY MOVEMENTS

Some pupillary movements are primarily optical in nature. For example, the pupillary light reflex serves to regulate the amount of light entering the eye. The accommodation response, or near reflex, involves a series of movements that result in changes in the curvature of the lens to control the depth of field. In addition, there are pupillary movements that are not related to luminance levels or to the distance between a visual image and the fovea of the retina; instead, they are related to sensory, mental, and emotional events. Of special interest to psychophysicists are those changes in pupil diameter that are the systematic indicators of attention and mental effort (Kahneman 1973). These small but reliable changes in pupil diameter are superimposed on the diameter of the pupil, which is determined by the two optical reflexes and the organism's tonic state of arousal. These types of pupillary movements are described next.

Pupillary Hippus

Clinical neurologists and ophthalmologists often comment on the phenomenon of pupillary hippus or pupillary unrest – the rhythmic but irregular (usually < 0.04-Hz) constrictions and dilations of the pupil that occur

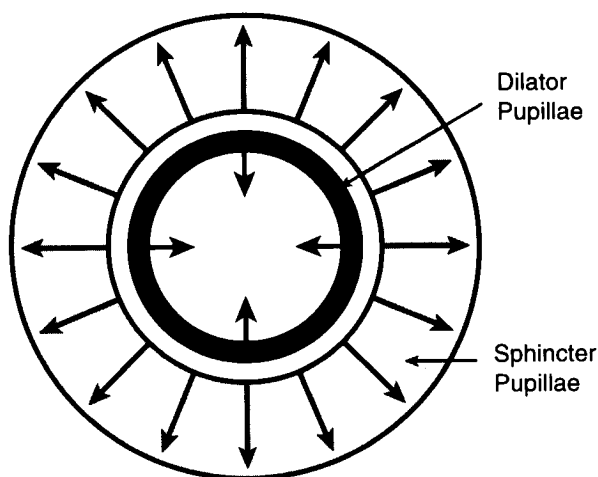


Figure 1. Muscles of the iris. Two opposing muscle groups within the iris of the human eye determine the aperture of the pupil. The sphincter muscles of the iris constrict the pupil when they contract, whereas constriction of the dilator muscles increases pupillary diameter.

independently of eye movements or changes in illumination (McLaren, Erie, & Brubaker 1992). These movements are called pupillary hippus, after the Greek *hippos* meaning horse; the term was probably chosen to convey the notion of a galloping horse's gait. Hippus is a normal condition of the human pupil, although pathological hippus does occur. Pupillary hippus must be the result of central rather than peripheral muscular factors, since these rhythmic movements are always consensual. It has been suggested that hippus may actually reflect the brain processes that underlie task-evoked pupillary responses but are triggered by spontaneous, otherwise unobserved thought.

Pupillary Light Reflex

The pupil is a dynamic structure that changes in diameter in response to luminance levels. In bright light the pupil is small and constricted, whereas in dim light it is dilated and relaxed. The amount of light that enters the eye is proportional to the diameter of the pupil, which changes in size to accommodate variations in luminance at a ratio of approximately 16 to 1. The range of these pupillary movements is quite broad and varies from species to species. In humans, pupil diameter can vary from less than 1 mm to more than 9 mm; in the cat, the range extends from 0.5 mm to more than 13 mm.

The pupillary light reflex can serve as an important diagnostic indicator of neurological status. Under normal circumstances, presentation of a bright light produces consensual constriction of the pupil. These constrictions can occur within 0.2 sec, with peak response occurring from 0.5 to 1.0 sec later. Since it is sensitive also to reductions in luminance levels, the pupil correspondingly dilates in darkness. Either absence of the light reflex or nonconsensual light reflexes may be indicative of lesions in subcortical structures.

The parasympathetic neural pathway subserving the pupillary light reflex is relatively simple and involves a six-neuron arc (Loewy 1990). Three of the cells in this arc are located in the retina itself: the retinal photoreceptors (rods and cones), which synapse on bipolar cells that in turn send their output to third-order neurons, the ganglion cells. Ganglion cell axons form the optic nerve, which carries visual information to both cortical and subcortical projection sites. The optic nerve fibers associated with the light reflex are conveying information from a subset of W-type retinal ganglion cells that are responsive to luminance levels. Cells in homonymous hemiretinae project to the olivary, medial, and posterior pretectal nuclei located at the juncture of the diencephalon and the midbrain (Barlow & Levick 1969). Cells in the olivary pretectal nucleus have been characterized as luminance detectors and are associated with pupilloconstriction. Olivary pretectal cells project to the lateral visceral cell column of the Edinger-Westphal nucleus, from which preganglionic fibers project to the ciliary ganglion via the III cranial nerve, the

oculomotor (Kourouyan & Horton 1997). Postganglionic fibers are then distributed to the sphincter muscles via the short fibers of the ciliary nerve to produce pupillary constriction (Loewenfeld 1993). Clarke and Ikeda (1985) averred that the pupilloconstrictions of the light reflex are almost entirely reliant upon parasympathetic control, because superior cervical sympathectomy has little effect on the nature or occurrence of the light reflex. The cells that produce the dilations observed in dark settings are located in the posterior pretectal nucleus (Clarke & Ikeda 1985). These darkness-sensitive cells follow a similar path to the ciliary ganglion via the oculomotor (III) nerve and are thought to produce the pupillary dilations observed in low luminance.

The Accommodation Response

An unfocused foveal image and binocular disparity are the stimuli that elicit the accommodation response (Cumming & Judge 1986). Loewy (1990) described the accommodation response as requiring three muscular adjustments: contraction of the ciliary muscle and release of tension on the zonule fibers to increase the curvature of the lens; constriction of the iris sphincter to produce pupillary constriction; and contraction of the medial rectus muscle, controlled by the oculomotor (III) nerve, to converge the eyes. The *afferent* pathways involved in accommodation are not known. Jampel (1960) provided evidence of involvement of the Y-retinal ganglion cell pathway that has a series of cortico-cortico projections from Brodmann's area 17 to the middle temporal region located along the surface of the superior temporal sulcus near the anterior limit of the occipital lobe. Although this cortical area lacks direct connections with the oculomotor complex, stimulation of cells in this region produces all three aspects of the accommodation response, and animals with middle temporal lesions show deficits in detecting and grasping near objects (Ungerleider et al. 1984).

The *efferent* pathways concerned with the accommodation response are similar to those involved in the light reflex. There is some evidence that the accommodation fibers, which leave the Edinger-Westphal nucleus via the oculomotor nerve, innervate the eye directly and without synapse in the ciliary ganglion (Jaeger & Benevento 1980; Ruskell & Griffiths 1979; Westheimer & Blair 1973).

PUPILLARY REFLEX DILATIONS

All somatic and visceral afferents and all central connections associated with arousal responses may serve as afferents for the pupillary reflex dilation, which is also called the psychosensory reflex (Loewenfeld 1993). Any sensory occurrence – whether tactile, auditory, gustatory, olfactory, or noxious – evokes a pupillary reflex dilation. Exceptions to this are light stimuli and accommodations to near visual stimuli, both of which produce pupil

constrictions. However, one should not assume that pupillary reflex dilations occur only to external sensory events, because emotions, mental processes, increases in intentional efforts, and motor output also produce systematic changes in pupillary diameter. It is thus not surprising that there is no single, dedicated afferent path subserving pupillary reflex dilations. Several factors determine the magnitude of these pupillary dilations – for example, the individual's tonic state of arousal, the emotional effect of the stimulus, and luminance levels.

The pupillary (or psychosensory) reflex is subserved by both sympathetic and parasympathetic inputs. Loewenstein and Loewenfeld (1969) have written that the efferent sympathetic fibers that innervate all visceral organs arise in the hypothalamic motor regions of the diencephalon. The radially oriented and sympathetically innervated dilator muscles of the iris are but one aspect of this complex sympathetic system. The first-order neurons of the pupillary dilator path descend from the posterior and lateral hypothalamus and travel through the brainstem to the cervico-thoracic spinal cord. These discrete, first-order neurons synapse on preganglionic cells in the grey matter of the cord known as the cilio-spinal center of Budge.

Preganglionic second-order neurons then take an afferent course and exit the ciliospinal center via the ventral roots, primarily at T2 but also at T1. These fibers continue without synapse to the superior cervical ganglion, where they synapse on the third-order neurons. There are species differences in the course of fibers from this point, but in humans it is thought that these fibers extend rostrally in the internal carotid nerve for a short distance from the

superior cervical ganglion, at which point they deviate into the middle ear with the carotico-tympanic fibers and cross the tympanic plexus. After emerging from the middle ear, the fibers pass into the cranium, enter the cavernous plexus, and approach the Gasserian ganglion without synapse to enter the ophthalmic branch of the trigeminal nerve. The pupillary dilator fibers then pass into the nasociliary nerve to reach the iris muscles via the long ciliary fibers; see Figure 2.

Cell bodies for the parasympathetic constricting fibers of the pupil reside in the Edinger–Westphal nucleus of the oculomotor complex located in the mesencephalon. Fibers of these cell bodies course rostrally to the ciliary ganglion as part of the oculomotor (III) nerve. Postganglionic fibers are then distributed to the annular constricting muscles of the iris via the short ciliary fibers.

PUPILLARY PHARMACOLOGY

The fibers of the iris sphincter muscle, like other sphincters, are arranged concentrically. These muscle fibers receive cholinergic input from the parasympathetic nervous system and produce constriction of the pupil. Cholinergic agonists and antagonists have predictable effects on the sphincter pupillae; compounds that are acetylcholine (ACh) agonists produce miosis or pupillary constrictions, whereas ACh antagonists produce mydriasis or pupil dilation. For example, pilocarpine, which has a molecular structure similar to ACh, produces miosis by depolarizing the effector cells directly. Carbachol, another ACh agonist, evokes pupillary constrictions by initiating spontaneous release of ACh at preganglionic cholinergic nerve endings. In contrast, ACh antagonists reduce activity along the parasympathetic pathways innervating the iris and decrease the activity of the constrictor muscles, which reduces opposition of the dilator muscles. Under these circumstances, the dilator muscles contract and open the iris, resulting in mydriasis (Thompson 1996). Atropine, which reduces cholinergic activity by competing with the neural transmitter at the effector sites, and botulinum toxin, whose mechanism of action is to prevent release of ACh, both result in mydriasis.

The dilator pupillae are arranged radially, like the spokes of a bicycle wheel. Contraction of these muscle fibers serves to enlarge the diameter of the pupil and necessarily reduce the size of the iris. Although there is some evidence for inhibitory cholinergic input to the dilator muscles (Ehinger 1967; Paulson & Kapp 1967), they are traditionally thought to be activated primarily via alpha-adrenergic input from the sympathetic nervous system. Thus, noradrenergic agonists and antagonists will produce dilation or constriction of the pupil respectively. Ephedrine, an adrenergic agonist, causes spontaneous release of norepinephrine from the synaptic endfoot and directly stimulates the receptor. With increased activity at

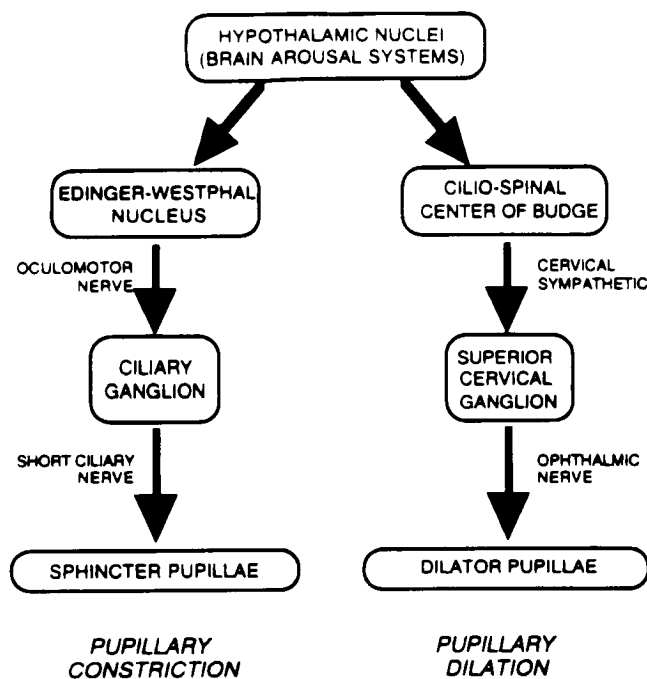


Figure 2. Neural structures and pathways that control pupillary diameter.

the effector site, the pupil dilates. Cocaine, a topical anesthetic for the conjunctiva and a powerful uptake blocker, also produces mydriasis as norepinephrine accumulates in the synaptic cleft. Adrenergic antagonists like thymoxamine (a noradrenergic receptor blocker) reduce activity at the neuromuscular junction, so that the sphincter muscle incurs reduced opposition and miosis results.

Inferential Context: Task-Evoked Pupillary Responses Are Reporter Variables

Nonreflexive phasic pupillary movements are of interest to cognitive psychophysiology for one and only one reason: they function as empirically based reporter indicators for brain processes that underlie the dynamic, intensive aspects of human cognition. In order to understand the use of task-evoked pupillary responses in cognitive psychophysiology, it is necessary to review the methods by which they are measured and analyzed.

BIOMETRICS: MEASURING PUPILLARY MOVEMENTS

Historically, pupil diameter was measured by employing motion picture photography (Hess & Polt 1964; Kahneman & Beatty 1966). This methodology requires photographing the pupil with a macrofocusing motion picture camera and preferably infrared film that allows recording at low luminance levels. Either 16 mm or 35 mm film may be employed; the former is less costly but the latter provides greater resolution. Filming begins with photographing a millimeter rule placed at a distance from the camera that corresponds to the distance at which the pupil will be photographed. The iris is then centered in the frame and the pupil is photographed at a 0.5–1.0-sec rate. Pupillometric measures are obtained by projecting the image of the iris onto a large surface, and measures are extracted with an ordinary ruler. These measures are scaled according to the standard rule appearing at the start of the film.

Infrared motion picture measurement is both labor- and time-intensive for the experimenter. Janisse (1977) reported that 20,000 measurements would not be unusual, citing an instance in which more than 100,000 separate measurements were taken. More recent technologies employ high-resolution infrared-sensitive video cameras that allow continuous monitoring of the dynamic changes in pupil diameter. Most video pupillometers employ a headrest to stabilize the image of the pupil with respect to the camera, although complex devices are also available that provide eye- and head-tracking systems that allow free movement of the head. For both simple and complex devices, the output of the video camera is sent to a hardware interface that contains pattern recognition circuits that automatically determine the boundary of the pupil in the video image. Pupil area or vertical pupil diameter is then

computed electronically. The output of the pattern recognition hardware can be sent to a strip chart recorder, or (preferably) the analog signal is digitized and stored on computer for later analysis. A number of these devices are available commercially and have been described elsewhere (Alexandridis, Leendertz, & Barbur 1991; Nguyen & Stark 1993). Nguyen and Stark (1993) described an economical pupillometric system whose essential feature is a computer with a "frame grabber" to process the output of an infrared-sensitive video camera. In conjunction with the hardware, they describe a set of algorithms that allow precise measurement of pupil size and eye position in real time.

Once the data are acquired and stored on disk, they should be inspected for eye blink, movement artifacts, or accommodation responses. All artifact detection should be conducted blind with respect to experimental condition, response, and behavioral outcome. Artifacts typically appear as either discontinuities or constrictions in the pupil record. If small anomalies are detected in noncritical portions of the trial then it is reasonable to correct them by linear interpolation, a process that does not substantially alter the data. When large artifacts appear, or when small artifacts occur in critical areas of the pupillometric record, it is best to eliminate that trial from further analysis. Data that have been edited and are artifact-free may then be analyzed by single trial or averaged. Trials may be averaged conventionally – that is, averaged with respect to a temporal event – or backward-averaged by realigning trials using the occurrence of a behavioral response as the temporal reference (Richer, Silverman, & Beatty 1983).

The technologies described here are equally useful for the measurement of changes in pupil diameter that are elicited by the light reflex, accommodation response, or task-evoked pupillary responses. Because the light reflex and accommodation responses are quite large in magnitude relative to the changes that are evoked by mental or sensory events, precautions must be taken to avoid masking the small task-evoked pupillary responses (TEPRs) with responses produced by optic reflexes. To do so, care should be taken to equate the luminance levels of all visual stimuli. Accommodation responses can be minimized by providing participants with a distant fixation point. Under all circumstances, participant-initiated trials are preferred because they minimize the occurrence of blinks in the record.

PSYCHOMETRICS: COMPUTING TEPRs

After the data have been edited according to the principles just described, all artifact-free pupil records may then be averaged. The pupillometric data are then analyzed similarly to event-related potentials recorded from the scalp. Usually, baseline pupil diameter is established at trial onset or at some other relevant premeasurement interval. The

baseline value is then subtracted from the peak dilation or average pupil diameter in the trial epoch of interest. The pupil values obtained reflect changes in pupil diameter evoked by the events that served as stimuli.

There are three measures that are typically extracted from each interval of interest: mean pupil dilation, peak dilation, and latency to peak. The methods for extracting summary values, described here, are applicable when the data have been digitized and stored on computer. *Mean pupil dilation* is calculated by first establishing the baseline interval. Assuming a typical sampling rate of 50 Hz (20 points per second) and a baseline period of 500 msec, the first ten data points in the record would be summed and averaged to obtain the average pupil diameter in the 500-msec baseline interval. Mean pupil dilation in the measurement epoch is obtained by averaging the relevant number of data points in the measurement interval and subtracting the mean diameter obtained in the baseline period. There are several sources of bias to consider when using mean pupil diameter, including trials that vary in length across participants. For example, pupil dilations may be measured during a maximum memory span task. In this case, trial durations will vary as a function of the size of an individual participant's span. Thus, the number of data points contributing to a mean will vary across participants. A second source of bias arises when the mean dilations are computed for overlapping intervals of interest. When such sources of bias are present, it is best to employ peak dilation as the index of amplitude.

Peak dilation is defined as the maximal dilation obtained in the measurement interval of interest. It is calculated similarly to mean dilation: first, mean diameter in the baseline interval is established. Baseline diameter is then subtracted from the single maximum value in the measurement interval. Because this measure is based on a single value, it is more vulnerable to random variations than is the measure of mean diameter. It is, however, independent of the number of data points occurring in the measurement interval. *Latency to peak* reflects the amount of time elapsed between start of the measurement interval and emergence of the peak dilation.

TEPRs AS A GENERAL MEASURE OF PROCESSING LOAD

The idea that task-evoked pupillary responses may provide a dynamic neurophysiological index of momentary information processing load was first suggested to American psychophysiology by Hess and Polt (1964) in a small but widely read research report. Hess and Polt photo-

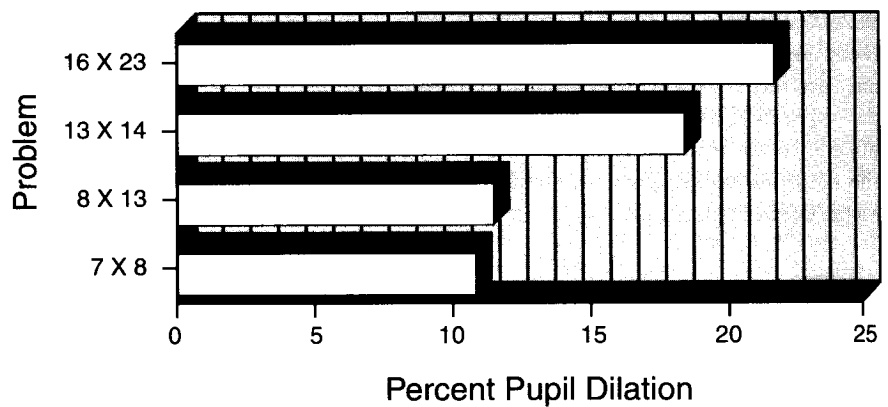


Figure 3. Pupillary dilations during mental multiplication: the original Hess and Polt (1964) finding. A simple but convincing demonstration that pupillary movements reflect an essential physiological aspect of cognitive processing was provided by Hess and Polt, who measured pupillary dilations as subjects mentally calculated the product of two numbers provided by the experimenter. They reported their results as percent pupillary dilation. Today, pupillary movements are conventionally reported as changes in diameter (in millimeters), since this measure appears to be independent of baseline pupillary diameter for a wide range of baseline values (Beatty 1982b).

graphically measured pupil size in five people who were mentally calculating the product of two small numbers in four problems of varying difficulty. Thus, the entire experiment consisted of twenty experimental trials. Yet their results were extraordinarily clear. Each subject's pupils dilated as each product was mentally calculated. Further, the extent of the observed dilation was nearly perfectly monotonically related to the difficulty of the calculation. These results are shown in Figure 3.

The robust nature of even very small TEPR has been repeatedly established in subsequent experiments (e.g. Beatty & Wagoner 1978). The specific finding of pupillary dilations varying directly with problem difficulty in a mental multiplication task has also been replicated by Ahern and Beatty (1979, 1981) in the context of studying individual differences in pupillary responding as a function of intelligence (see Figure 4).

It should be noted that Hess and Polt reported their findings in units of percent dilation over baseline pupillary diameter, but the baseline diameters themselves were not reported. Subsequent investigators have adopted a different convention in quantifying the TEPR, reporting both baseline diameter and pupillary dilation in millimeters. This convention is not only more complete, it is also more appropriate since all available evidence indicates that the extent of the pupillary dilation evoked by cognitive processing is independent of baseline pupillary diameter over a wide range of baseline values. Thus, if the baseline diameter is small – as it probably was in the Hess and Polt experiment, given the conditions of illumination they employed – then the pupil response expressed as a percentage

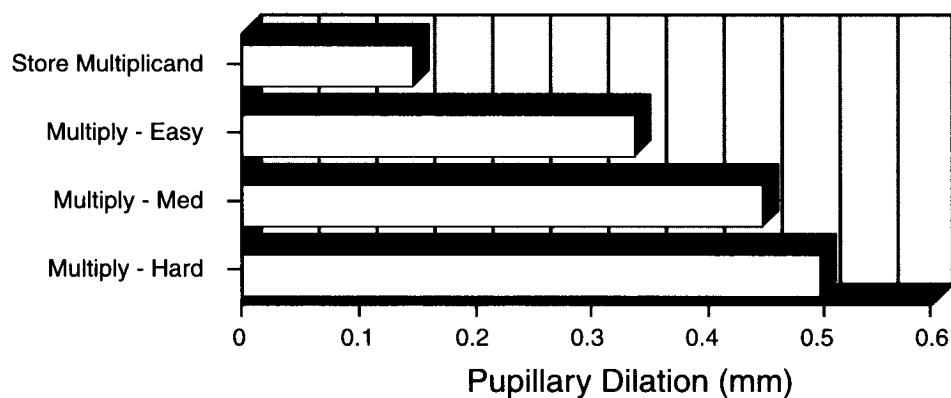


Figure 4. TEPR amplitude in mental multiplication as a function of problem difficulty. Ahern and Beatty replicated the original Hess and Polt finding as part of a larger study of individual differences in intelligence and pupillary movements. (See Beatty 1982b for these data.)

will be much larger than would be measured in percentage units at lower illumination with a large baseline diameter.

This conclusion is supported strongly by the findings of Bradshaw (1969). Bradshaw measured TEPR in seven subjects using a simple reaction task with either a long or short warned foreperiod under two levels of illumination (25 or 0.56 ftL at the fixation screen) to manipulate baseline pupillary diameter. Pupillary diameter was larger by 33% with the darker screen illumination, nearly doubling pupillary area. Yet there was "little evidence of any change in peak (TEPR) amplitude or shape" (Bradshaw 1969, p. 271) for responses at either of the two warning conditions. Similarly, administration of amphetamine in this same task produced a small increase in baseline pupillary diameter (from 3.8 to 4.2 mm) but no change in either the TEPR or reaction time (Bradshaw 1970).

Because TEPR amplitude appears to be independent of baseline pupillary diameter, it is possible to directly compare the amplitude of TEPRs obtained in different laboratories with varying conditions of illumination using absolute dilation amplitude as a common metric. This idea was first suggested by Kahneman (1973) in his influential monograph *Attention and Effort*. Kahneman argued that task-evoked pupillary dilations could serve psychology as a converging psychophysiological measure of mental effort, an idea later refined by Norman and Bobrow (1975) in their concept of a unitary central processing resource.

Beatty (1982b) tested this idea in a meta-analysis of the cognitive pupillometry literature and found that the results of this literature as a whole were coherent. Across a variety of qualitatively different cognitive domains, TEPR amplitude appeared to provide a consistent index of the presumed cognitive demands of each task. It appeared to be empirically demonstrable that TEPR amplitude acts as a psychophysiological reporter variable or psychophysiological marker for task-evoked cognitive activation.

Finally, it has been suggested that the pupil dilates to pleasant and constricts to unpleasant stimuli and thus might serve as a psychophysiological measure of emotional valence. This hypothesis stemmed from the widely cited early report by Hess and Polt (1960) that seemed to demonstrate a bidirectional pupillary response to affectively loaded photographs. This conclusion has not been supported by subsequent, carefully controlled pupillometric studies (e.g. White & Maltzman 1978). Further, the pleasantness hypothesis has been criticized on a variety of methodological grounds by a number of reviewers of the pupillometric literature, who have marshalled strong support for the cognitive activation hypothesis instead (Beatty 1982b; Goldwater 1972; Janisse 1977).

TEPRs and Perception

Among the most basic of all cognitive tasks is the detection of weak sensory signals. Once conceived as a threshold problem, the process of signal detection is now widely recognized to be probabilistic in nature and has been well described by statistical decision theory (Green & Swets 1966). In this formulation, a weak sensory signal generates some amount of evidence of its presence. This evidence is compared with a criterion and a decision is then made. The value of the criterion is determined by nonsensory factors, such as the a priori probability of a signal and the various rewards and costs of the various decision outcomes (e.g., correct detection of a signal, correct report of signal absence, incorrect report of a signal in its absence, or incorrect missing of a signal).

The first pupillometric treatment of this problem was reported by Hakerem and Sutton (1966), who studied detection using an increment in the duration of a pulse illumination in a monocularly viewed *Ganzfeld*. They report the presence of a stimulus-evoked pupillary dilation on trials in which the stimulus was detected that was absent on trials in which the same stimulus was not "seen," as shown in Figure 5.

Beatty and Lucero-Wagoner (1975) explicitly employed a decision-theoretic framework in their pupillometric analysis of the signal detection task. They studied a standard

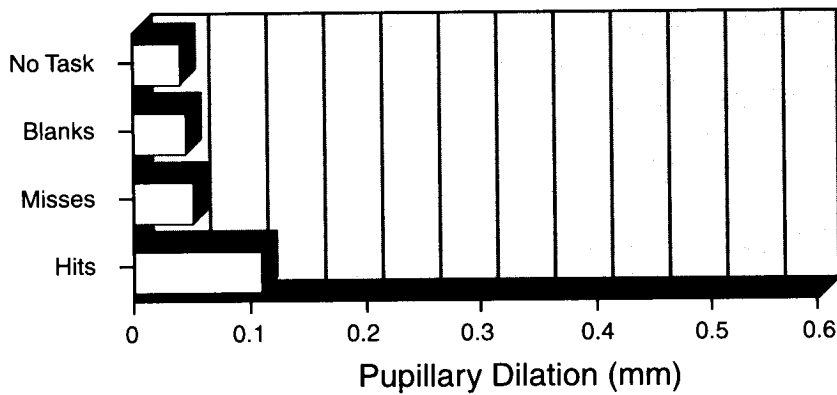


Figure 5. TEPR amplitude in a signal detection task. Hakerem and Sutton (1966) provided the first analysis of pupillary movements in sensory signal detection, reporting their data within the theoretical framework of the threshold model of perception.

auditory signal detection task (cf. Green & Swets 1966) with a 100-msec, 1-kHz sinusoid against a background of white noise. The use of auditory rather than visual stimuli prevented contamination of the TEPR by pupillary movements resulting from the light reflex. Beatty and Lucero-Wagoner also employed a four-alternative rating scale of response in order to assess a range of criterion values. They reported that TEPR amplitude varied as a monotonic function of the likelihood ratio across four stimulus-response conditions (certain hits, uncertain hits, uncertain correct rejections, and certain correct rejections). Thus, the largest responses appeared for certain hits and the smallest for certain correct rejections, with the two uncertain categories having intermediate values. Such a result would be expected if the TEPR reflected the processing of varying amounts of weak sensory signals that are present on any given trial. Thus, targets detected with certainty would result from the presence of relatively large amounts of sensory data, and nonsignal trials rejected with certainty would occur when virtually no sensory evidence was available for processing. This interpretation is consistent with Norman and Bobrow's (1975) characterization of signal detection as a data-limited task. These pupil-

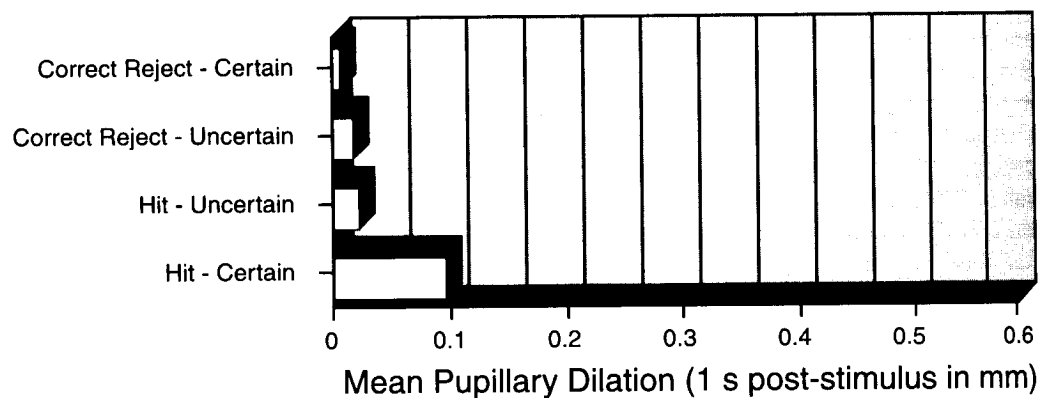
lometric findings also argue against any interpretation of the pupillary response as a reflection of test anxiety or similar emotional reaction to the possibility of error, since TEPR amplitude does not vary directly with subjective uncertainty. See Figure 6.

Signal discrimination is computationally more complex than signal detection and involves additional cognitive processes. In simultaneous discrimination, two sensory signals must be analyzed simultaneously and compared with respect to some underlying dimension. In successive discrimination using the method of constant stimuli, relevant properties of the second (comparison) stimulus must be compared with a stored representation of the first (standard) stimulus. This was the procedure used by Kahneman and Beatty (1967) in their pupillometric analysis of pitch discrimination, which used eleven frequencies of tones that were compared with a 850-Hz standard tone. The comparison stimuli varied between 820 Hz and 880 Hz in 6-Hz steps. In this situation, the amplitude of the TEPR evoked by the comparison stimulus varies monotonically with its similarity to the standard stimulus (or the difficulty of the sequential discrimination), as shown in Figure 7. The additional cognitive demands induced by signal discrimination result in systematically larger task-evoked pupillary responses than occur in signal detection.

TEPRs and Memory

Pupillometric analysis was extended to the study of short-term memory and a long-term memory retrieval in

Figure 6. TEPR amplitude in signal detection as a function of decision category and certainty. Beatty and Lucero-Wagoner (1975) utilized statistical decision theory's signal detection model in a study of the detection of weak auditory signals. Using a four-category rating scale permitted the assessment of pupillary dilations evoked by detection judgments reaching different internal criterion levels. These results suggest that TEPR magnitude in this task reflects the accumulation of sensory evidence leading to a decision of signal present.



the early experiments of Kahneman and Beatty. The Kahneman and Beatty (1966) study was motivated by the striking findings of Hess and Polt (1964) on mental multiplication and pupillary dilation. In the first of a series of pupillometric studies, Kahneman and Beatty (1966) tested subjects with three paced auditory serial recall tasks. In the first, pupillary dilations were measured in the common digit span task for digit strings of three, four, five, six, and seven items presented and repeated at the rate of one item per second. Pupillary diameter systematically dilated as each stimulus digit was presented, reached a maximum between presentation and reporting, and declined to baseline after the last item was reported from short-term memory. Peak pupillary dilation varied as a function of the number of digits in the target string, as shown in Figure 8.

Kahneman and Beatty also examined the effect of item difficulty on pupillary dilation and performance using two additional serial tasks. The first was a four-item word span in which a string of high-frequency monosyllabic nouns were presented instead of digits. The second was a digit transformation task in which the subject heard a string of four digits (as in the four-item digit span) but was required to add 1 to each digit heard and report the transformed digit string. These three four-item tasks differed markedly from each other in difficulty, as indicated by mean span for correct performance in each task (digit span, 7.8 correct items; word span, 5.7 items; digit transformation, 4.5 items). These differences in task-induced processing load were also reflected in the amplitude of the task-evoked pupillary responses, as shown in Figure 9.

In one of the first applications of dual-task methodology in the measurement of mental processing load (see also Gopher & Donchin 1986; Norman & Bobrow 1975), Kahneman, Beatty, and Pollack (1967) examined the effects of the four-item digit transformation task on concurrent performance of a visual target detection task and the task-evoked pupillary response. The top half of Figure 10 presents pupillary dilation in the digit transformation task as a function of time. As in Kahneman and Beatty (1966), pupillary diameter increases as each digit is presented, reaching a maximum as the first transformed item of the string is reported. Pupillary diameter then decreases, returning to baseline after completion of report.

Performance on the visual target detection task mirrors these results, providing converging evidence that the amplitude of the task-evoked pupillary response is a reporter

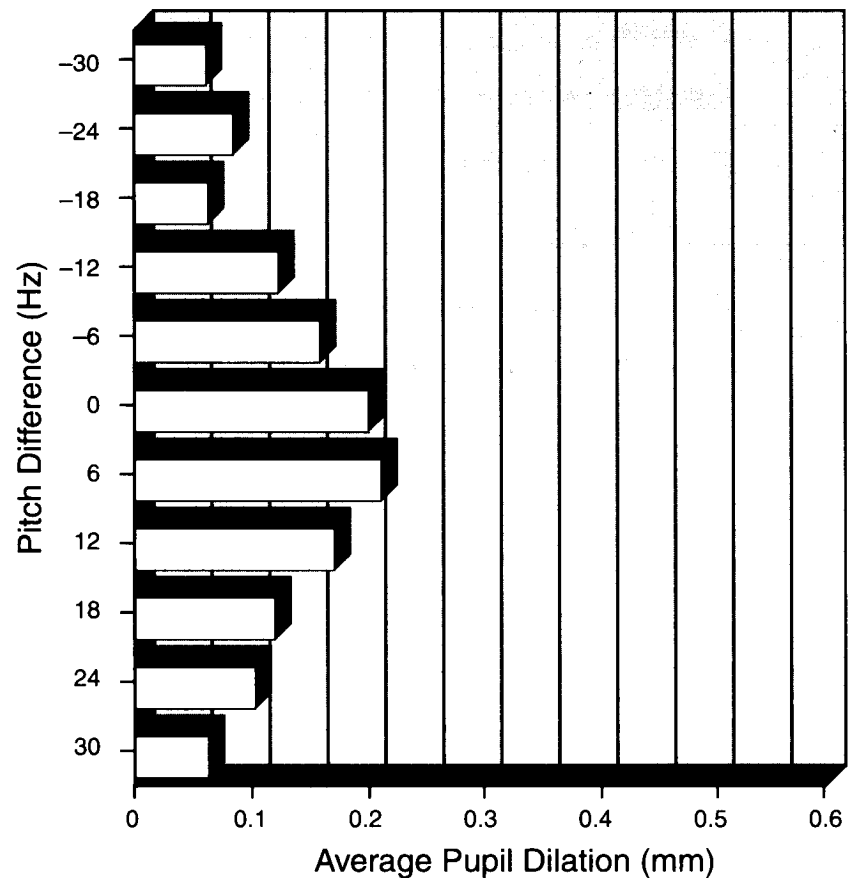


Figure 7. TEPR amplitude in signal discrimination. Kahneman and Beatty (1967) examined pupillary dilations evoked in a successive auditory discrimination task. The magnitude of the task-evoked pupillary response during the decision period of each trial varied with the similarity between the standard and comparison stimuli.

index of central information processing load. Errors in the target detection task follow the curve of the TEPR, reaching a peak at the beginning of transformation report. These results are shown in the bottom half of Figure 10.

If the task-evoked pupillary response is in fact a reporter of central processing load or processing intensity, then what would happen if central processing resources are fully saturated? Peavler (1974) examined this question by presenting subjects with strings of five, nine, or thirteen digits for immediate paced recall, the task previously employed by Kahneman and Beatty (1966). The three string lengths were randomly intermixed, so that subjects could not anticipate string length on any given trial. Under these conditions, pupillary diameter increased with each digit present until the maximum digit span (about seven or eight items) was reached. At this point, the task-evoked pupillary response reached an asymptotic value for the task. Peavler's results provide evidence that overloading the capacity of the human short-term memory system does not result in any additional pupillary dilation. These results are shown in Figure 11.

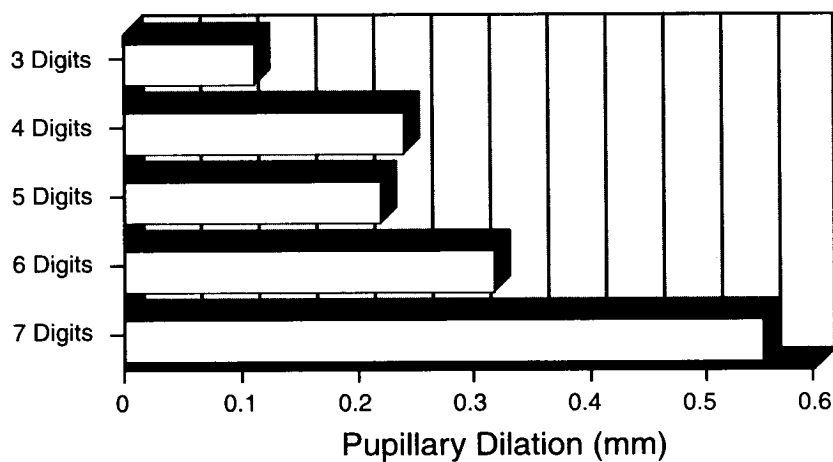


Figure 8. TEPR amplitude in a short-term memory task. In a paced auditory digit-span task, pupillary diameter increases as each successive digit is presented to the subject and reaches maximum dilation between the end of digit presentation and the beginning of digit report. Peak pupillary dilation varies directly with the number of digits held in short-term memory for immediate report. During the report itself, pupillary diameter decreases with each digit spoken, returning to baseline diameter at the completion of the trial. (Data from Kahneman & Beatty 1966.)

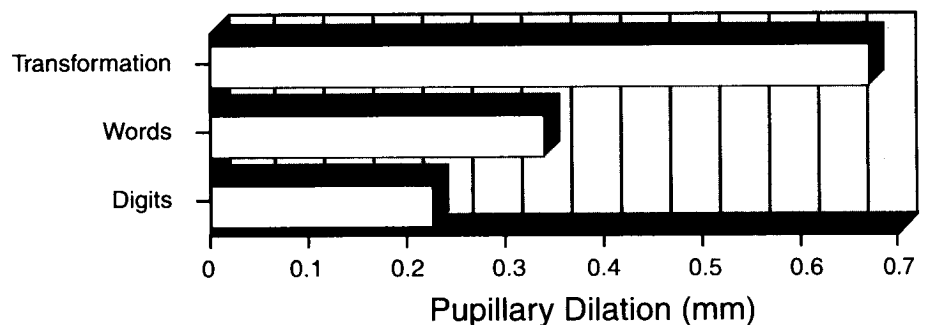
It should be mentioned in passing that Peavler's data also provide strong evidence against the idea that TEPRs in cognitive tasks index emotional, anxiety-related variables commonly associated with the autonomic nervous system. Emotional activation (if any) produced by performance failure should peak after digit span overload, but this is precisely the point in the task at which no additional dilation is present.

More recently, Granholm and colleagues (1997) reported a replication and extension of Peavler's original overload study. Like Peavler, Granholm et al. reported that the amplitude of the TEPR increases as each digit is presented, up to the span of digit memory (about 7 ± 2 digits). But unlike Peavler's finding that the pupil reached an asymptote in the 13-digit condition, pupillary diameter in Granholm's data decreased from maximum as the subject became overloaded. Granholm et al. attributed this discrepancy to a difference in instructions in the two experiments, not-

ing that Peavler explicitly told his subjects that some strings would be too long to remember perfectly (but to try nonetheless to reproduce as many digits as possible on every trial). Thus, Peavler's subjects may have adopted a "strategy of maintaining active rehearsal of the maximum number of digits possible [i.e., 7 ± 2] and ignoring further input" (Granholm et al. 1997, p. 460). Thus, the asymptote of the TEPR that Peavler observed may reflect a continued constant engagement in the memory task on the part of his subjects.

Finally, the same type of pupillary responses that reflect processing load in the storage and recall of digit strings in short-term memory (STM) occur in long-term memory (LTM) as well. We have all had the experience of dialing a telephone number from the fleeting short-term memory established by a telephone information operator or automated system, an action that seems subjectively to be much more difficult than simply dialing an already well-known number. Beatty and Kahneman (1966) measured TEPRs in a close analog of this familiar situation; their subjects verbally produced the seven-digit number in response to hearing an unfamiliar string or a one-word cue for a number that each knew well. Perhaps surprisingly, a larger TEPR was evoked when the telephone number was recalled from the subject's own long-term memory than when it was supplied by the experimenter, as shown in Figure 12. This finding suggests that TEPR in the LTM task reflects the load imposed by LTM retrieval in addition to that imposed by the processes of response organization and production, which is common to both the LTM and STM conditions.

Figure 9. TEPR amplitude for differing item types and memory tasks. Maximum pupillary dilation in the short-term memory task depends upon the types of information being processed and the nature of that processing. Kahneman and Beatty (1966) found that TEPR amplitude for four words was greater than for four digits. The largest dilations were produced by the four-item digit transformation task, which required recoding of the output string and not simply repetition. In these tasks, TEPR amplitude varied inversely with span length.



TEPRs and Responding

Richer, Silverman, and Beatty (1983) recorded pupillary dilations during the performance of simple and disjunctive (Go-No-Go) responses. In the simple reaction task (experiment 1), the foreperiod was either short (1 sec) or long (3 sec). Waveforms for the two conditions showed steady dilations that begin approximately 1.5 sec prior to the imperative stimulus and peak about 1 sec after stimulus presentation. The time course of these preparatory dilations is paralleled in the electrophysiological literature by the contingent negative variation (CNV), a slow negative potential measured from the scalp. Rohrbaugh, Syndulko, and Lindsley (1976) reported that the response-related component of the CNV also precedes movement by approximately 1.5 sec. Rate of dilation was inversely proportional to the length of the foreperiod, but neither peak dilation nor latency to peak differentiated short- and long-foreperiod trials.

Experiment 2 required a disjunctive reaction in which one of two stimuli are presented at S2. The Go stimulus required execution of a speeded response, whereas the No-Go stimulus mandated that no motoric output occur. Participants performed in both an immediate- and a delayed-response condition. In the immediate-response condition, subjects were presented with a warning tone of 860 Hz (S1), which was followed 1.5 sec later by a tone (S2) of either 600 Hz or 1,110 Hz. In the delayed-response condition, participants withheld any responses mandated by S2 until the presentation of S3, an 860-Hz tone. The delayed-response paradigm is especially valuable because it allows the separation of dilations due to response selection and preparation from those due to response execution.

In comparing immediate- and delayed-response conditions, small but reliable dilations are observed following S2 for all four trial types. Dilations to Go trials are greater than dilations to No-Go stimuli in both immediate- and delayed-response conditions. Further inspection of the data show that there are large dilations associated with the immediate No-Go trials and smaller dilations for the delayed No-Go trials. This suggests that there is a response-related process involved in the suppression of a response. This process may reflect either central organization and preparation of the response or peripheral motor adjustments.

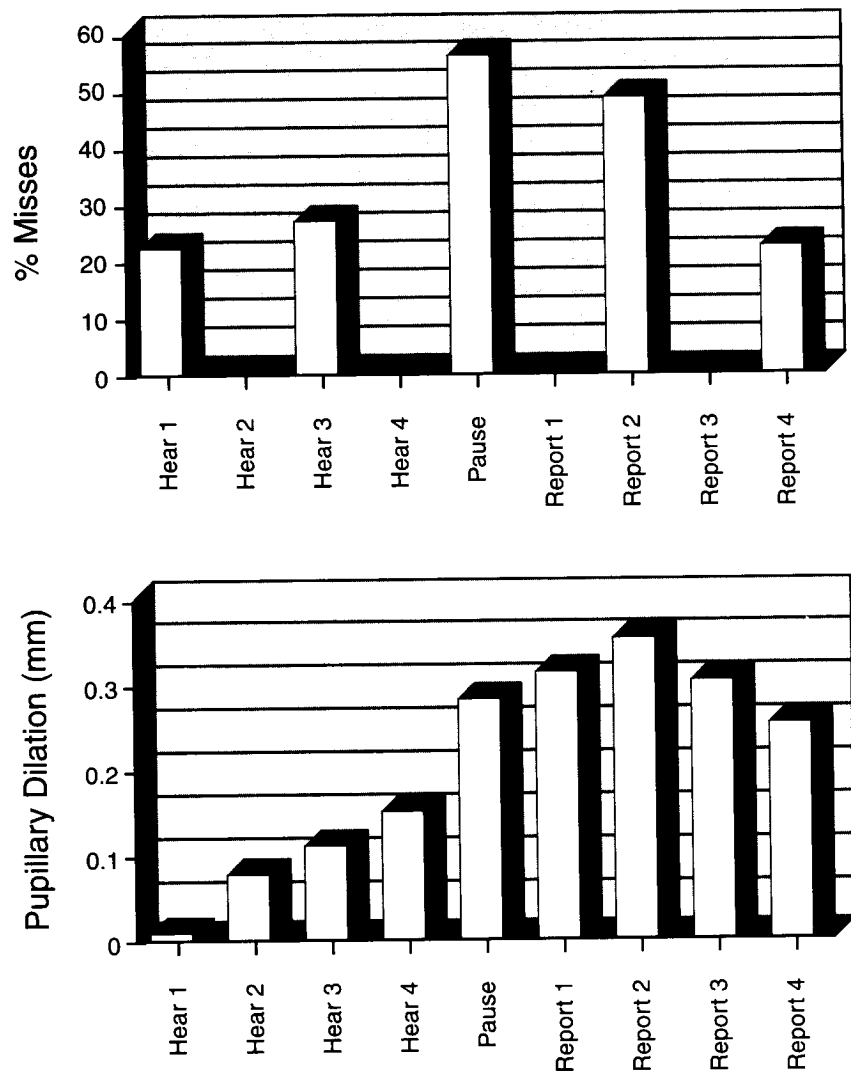


Figure 10. Two measures of processing load in the four-digit transformation task. Kahneman and colleagues (1967) measured both the TEPR and second-task interference produced by the four-digit transformation task. The upper panel presents the percentage of missed detections in a visual target detection task performed simultaneously with the digit transformation task. Targets were presented at one of five temporal positions in the paced trial. The bottom panel shows pupillary dilation during the performance of the two tasks.

To determine whether the dilations seen in the immediate No-Go trials were due to response execution processes, Richer and associates varied the probability of occurrence of Go and No-Go trials. They rationalized that if motor preparation is common to both Go and No-Go trials then the preparatory process should be sensitive to changes in likelihood of the response. Increasing the probability that a response will be required should increase the amplitude of the No-Go dilations, while the dilations associated with Go trials should not be affected because the demand associated with execution of the task has not changed.

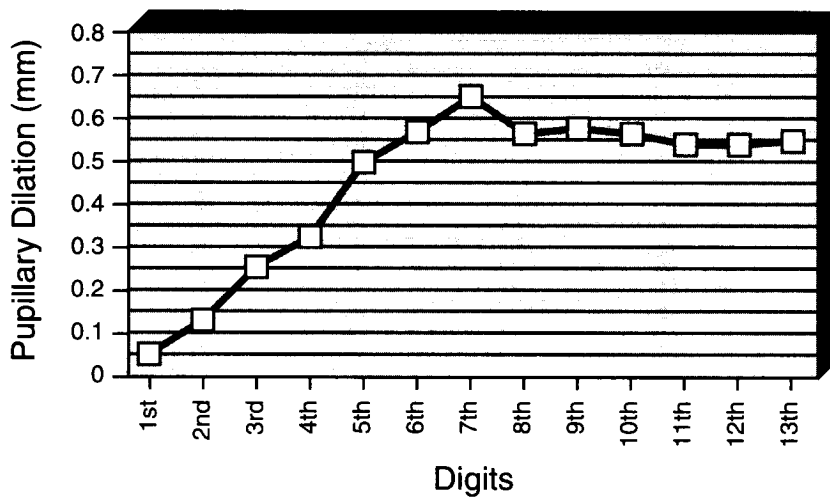


Figure 11. Pupillary response and short-term memory overload. These data from Peavler (1974) show pupillary dilation when the memory span of the subjects is exceeded but the subjects endeavor to report the largest number of sequential digits possible. These data suggest that the amplitude of the TEPR reaches an asymptote that corresponds to the behavioral limit of the short-term memory system.

Participants performed a task identical to the immediate-response paradigm just described, but the probability of occurrence of an overt response was manipulated between 0.33 and 0.66. As predicted, the amplitude of the No-Go trials increased as their likelihood decreased. There was no effect of probability on the pupil dilations generated by the Go trials. The absence of a probability effect in Go trials suggests that these dilations represent the maximum processing demands associated with the task. The nondirectional component of the dilations associated with No-Go trials reflects motor preparation processes, with amplitude of the response reflecting the proportion of preparation completed.

To examine the time course and amplitude of pupil responses that attend the preparation and execution of simple movements, Richer and Beatty (1985) asked participants to execute self-paced finger flexions. Participants produced either a single key press, a double key press with the right index finger, double key presses involving both index fingers, or a sequence of key presses with the index, ring, and middle finger in a counterbalanced order. Both peak pupil diameter and latency to peak were found to vary with

complexity of movement. These dilations began 1.5 sec before response execution and peaked 0.5 sec after the response.

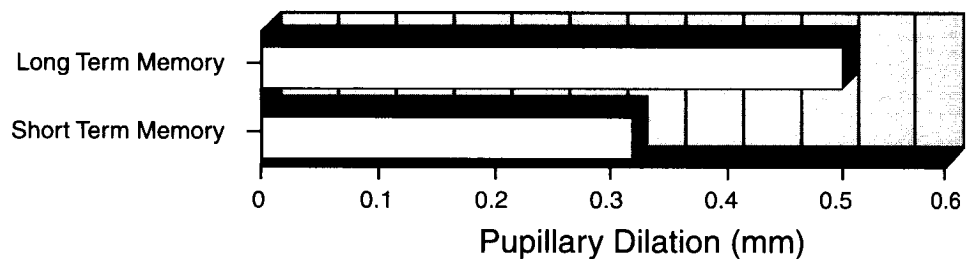
In a second experiment, Richer and Beatty determined that force of movement systematically affects the magnitude of movement-related pupillary responses. When participants pressed a microswitch activated by a 100-g load, average peak pupillary dilations were 0.28 mm. The more forceful movements required to activate a microswitch with a 1,250-g load produced average peak dilations of 0.38 mm.

Readiness potentials recorded from the scalp during similar finger movements have a time course similar to the preparatory dilations seen in Richer and Beatty's first experiment. Like pupillary diameter, these readiness potentials appear approximately 1 sec prior to movement and vary in amplitude with the force of the movement required (Becker et al. 1976; Kutas & Donchin 1974). Slow preparatory responses are also seen in the electromyogram (Brunia & Vingerhoets 1980), and heart rate deceleration has been found to index response preparation (Coles & Strayer 1985). Such parallels between certain event-related potential components and autonomic variables such as the TEPR may be of use in providing an interpretation of the electrophysiological readiness potentials, at least under some conditions.

TEPRs and Probability

The pupil response to probability also has parallels in the electrophysiological event-related potentials recorded from the scalp. These brain potentials consist of a series of positive and negative components that have been associated with certain psychological processes. The components appearing within 100 msec of stimulus presentation are taken to reflect stimulus characteristics. The late-occurring components (evident 100 msec or more poststimulus) have

Figure 12. TEPR amplitude in short- and long-term memory. Beatty and Kahneman (1966) measured TEPR amplitude as subjects produced seven-digit telephone numbers in response to hearing a novel number presented for the first time or hearing a verbal cue for a well-known telephone number that subjects had supplied before the testing session. Larger TEPRs were produced when numbers had to be extracted from long-term memory before they were produced.



been shown to be sensitive to higher-order psychological processes such as attention. Friedman and colleagues (1973) demonstrated that both the P300 component (which appears approximately 300 msec after stimulus presentation) and pupil dilations have inverse relationships to stimulus probability: less-frequent stimuli produce higher-amplitude P300 and pupil responses.

Qiuyuan and associates (1985) conducted a series of three experiments to assess the effects of stimulus probability and task relevance (target vs. nontarget) on task-evoked pupillary responses. In each of the three experiments, participants heard Bernoulli series of 50 tones of 50-msec duration presented at 1.5-sec intervals. For each level of stimulus probability, the participant's task was to count the number of stimuli of a given type (the targets).

In their first experiment, Qiuyuan et al. employed probabilities of 0.2, 0.5, and 0.8. An inverse relationship was found between pupil amplitude and probability. Dilations to both targets and nontargets were found to be larger in amplitude and longer in latency when their probability of occurrence was 0.2 than when their respective probabilities of occurrence were 0.5 or 0.8. For a given level of stimulus probability, TEPRs to targets were similar to nontargets. These results differentiate the task-evoked pupillary response from the P300, which is seemingly insensitive to nontargets (Pritchard 1981).

In the second experiment, the participant's task was once again to count the target tones. In this instance, however, target probabilities were restricted to 0.1, 0.2, and 0.3. A significant effect of probability was seen for targets but not for nontargets for this restricted range of probabilities. Peak amplitude and latency to peak increased as target probability decreased from 0.3 to 0.1. The amplitude and latency for nontargets did not change as a function of their complementary probabilities of 0.7, 0.8, and 0.9.

In a third experiment, Qiuyuan et al. established that the TEPR need not be stimulus driven. For this experiment, tones were either presented or omitted with target probabilities of either 0.1 or 0.3. As in the second experiment, probability affected peak dilations to targets but not nontargets; greater amplitudes to targets were elicited by a probability of 0.1 than by a probability of 0.3. More interestingly, the magnitude of the pupillary response was greater for trials in which the tone was omitted than for those trials in which the tone was presented. This effect of target type (omitted vs. tonal) interacted with probability in such a way that dilations to omitted targets were greater when the probability of target occurrence was 0.1 than when the probability of target occurrence was 0.3. These results suggest that pupil dilations are elicited not only by external stimuli but also by an orienting response or a stimulus mismatch, as described by Sokolov (1960). Thus, the P300 and the TEPR may be complementary reflections of central processes associated with orientation to a task-important stimulus.

TEPRs and Language

Pupillometric studies of language processing have been both plentiful and productive, perhaps in part because language (and its symbolism) is the essential distinguishing feature of the human brain (Deacon 1997) and because there are well-developed linguistic models of the human language system (Pinker 1994). Task-evoked pupillary responses have been employed to investigate language processing dynamics from the levels of letter perception, syntax, and processing of semantic content – all with compelling findings.

Beatty and Wagoner (1978) built upon the seminal reaction time studies of Michael Posner (see e.g. Posner 1978) to examine the processing dynamics of visual letter matching. In a pair of related experiments, Beatty and Wagoner measured TEPRs as subjects viewed pairs of visually presented letters and were required to make Same-Different judgments about the pair presented. In the first experiment, subjects were requested to render a judgment of Same if the two letters shared the same name. Thus, the letter pairs *AA*, *aa*, and *Aa* are all examples of Same pairs (whereas *Ae* would be categorized as Different). Following Posner's logic, a Same judgment could be reached for the examples *AA* and *aa* after processing only the physical attributes of the printed letters, whereas judging the example *Aa* as Same requires an additional computational step – the extraction of each symbol's name code – an inferred processing step that increases reaction time (Posner 1978). Beatty and Wagoner reported that physically identical letter pairs evoke a smaller TEPR than do letter pairs identical only at the level of naming.

In a second experiment, subjects were requested to render Same or Different judgments using a category rule: determining whether the phoneme represented by the printed letters were vowels or consonants. In this experiment, there were three types of pairs that should be judged as Same: *AA* (visually identical), *Aa* (phonetically identical), and *Ae* (categorically identical). As before, the amplitude of the TEPR clearly reflects the extent of processing required to reach a correct decision of Same, as shown in Figure 13. Task-evoked pupillary response amplitude is indeed a sensitive and reliable reporter of even very small (but well-specified) differences in the structure of cortical language processing and decision.

Schluroff (1982) presented a striking set of data relating TEPR amplitude to syntactic complexity of English sentences. Schluroff asked his subjects to rate the comprehensibility of a series of auditorily presented sentences, and TEPRs were measured during sentence presentation. All sentences were parsed using Syntako, a transformational grammar of English, and from these derivations a quantitative measure of Yngve (1960) sentence depth or complexity was calculated. Schluroff reported that mean pupillary dilation during sentence presentation correlated

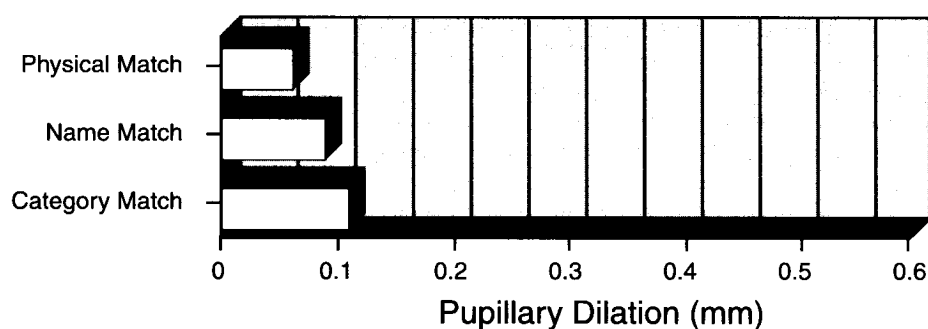


Figure 13. TEPR amplitudes vary with level of language processing. Here, subjects performed category judgments for letter pairs that could be identical at the orthographic, phonemic, or category level. The amplitude of the TEPR varied with the complexity of the processing required by each judgment.

+0.82 with Yngve syntactic complexity, accounting for 67% of the variance in TEPR amplitude. This correlation was not significantly reduced by covariation with sentence length. Schluroff's seminal investigation provides a strong demonstration of the close relation between quantitative aspects of syntactic sentence structure and the computational demands imposed by the language processing system of the normal human brain.

Schluroff and colleagues (1986) extended this pupillometric analysis of syntax in an ingenious study of syntactic ambiguity, presenting subjects with sentences (such as "Peter chased the man on the motor bike") that are ambiguous in the active voice but are disambiguated when transformed into the passive voice (as either "The man was chased by Peter on the motor bike" or "The man on the motor bike was chased by Peter"). The first rendering is verb-oriented (since the relative clause refers to the action denoted by the verb) whereas the second interpretation is object-oriented, with the phrase referring to the object of the sentence. Object-oriented readings of such ambiguous sentences are syntactically simpler than verb-oriented readings (Schluroff et al. 1986), which leads to a prediction concerning ambiguity resolution and TEPR amplitude.

In the foregoing example, both the verb-oriented and object-oriented resolutions of the syntactic ambiguity are sensible; thus, this example is not strongly biased toward object- or verb-oriented resolution. But other examples of syntactically ambiguous sentences are highly biased toward a single alternative. Schluroff proposed that highly biased syntactically ambiguous sentences are easier to process since they are disambiguated by semantic factors.

Schluroff tested these ideas by visually presenting subjects with a series of syntactically ambiguous sentences of high or low bias and requiring them to transform the ambiguous active form to an unambiguous passive form while changes in pupillary diameter were measured. Principal components analysis was employed to identify three main factors contributing to the TEPR: factor 1 loaded on pupil-

lary diameter as subjects transformed the sentence into the passive voice; factor 2 covered the period of the task in which the sentence is read; and factor 3 was related to baseline pupillary diameter.

Pupillary dilation during the actual transformation of the sentence from active to passive voice, as reflected in factor 1, indicates that verb-oriented transformations impose a greater cognitive load than do the simpler, object-oriented transformations. Furthermore, low-bias sentences produced larger-amplitude pupillary responses than did high-bias sentences, as Schluroff predicted, suggesting mediation of syntactic complexity by semantic interpretation.

Just and Carpenter (1993) also used pupillometric methods to study the cognitive load imposed by syntactic structure in sentence processing. They examined sentences with center-embedded relative clauses, which impose significant demands on short-term memory.

The sentence "The reporter that the senator attacked admitted the error" is an example of an object-relative center-embedded clause because the leading noun of the sentence, "reporter," is the object of the clause. This particular construction imposes a large load on short-term memory. In contrast, subject-relative center-embedded clauses such as "The reporter that attacked the senator admitted the error" are much easier to process, since (i) the leading noun of the sentence is near the beginning of the relative clause and (ii) the agent of the sentence and agent of the clause is the same. This is evident from previous experiments of word-by-word sentence reading times in which subjects take 25 msec longer to make a lexical decision about the verb in object-relative versus subject-relative clauses (Ford 1983).

Just and Carpenter presented subjects with a series of sentences similar to the preceding example – intermixed with other superficially similar filler sentences – and required them to judge the truth of a comprehension probe that followed presentation of the sentence. They found that the TEPR amplitude was greater for the sentences with object-relative (versus subject-relative) center-embedded relative clauses, as shown in Figure 14. Further, the peak of the TEPR was delayed by 116 msec in the object-relative as compared with the subject-relative clause items. Thus, increased syntactic complexity results not only in more

errors of comprehension and longer processing times but also in increased central processing demands, as indicated by larger-amplitude task-evoked pupillary responses.

Increases in the semantic demands of sentence processing also result in increases of the TEPR. Hyönä, Tommola, and Alaja (1995) reported two experiments measuring pupillary responses in simultaneous interpretation and translation of semantic content between Finnish and English. The first experiment measured averaged pupillary diameter for large passages of text as Finnish subjects passively listened to English text, shadowed English text, or simultaneously translated English text into their native Finnish. They report mean pupillary diameters for the three conditions of 4.20 mm (listening), 4.72 mm (shadowing), and 5.22 mm (interpreting).

In a second experiment, Hyönä, Tommola, and Alaja modified their tasks for single words (rather than long passages of text), permitting the computation of TEPRs. Stimulus words were also scaled for ease of translation using data from a preliminary experiment. Hyönä et al. confirmed and extended the findings of their first experiment, as shown in Figure 15. Increasing semantic processing of single words by variations in task demands produced an orderly increase in TEPR amplitude. The smallest dilations were produced by word listening. Shadowing produced intermediate dilations, and the largest dilations were evoked by simultaneous translation. Further, words that were more difficult produced larger TEPRs in each of the three task conditions.

Taken as a whole, the experimental literature relating task-evoked pupillary responses to theory-based measures of linguistic processing is remarkably robust and reliable. Indeed, TEPRs appear to provide an exquisitely sensitive measure for assessing processing demands imposed in human language processing tasks.

Figure 14. TEPR amplitude for sentences of differing syntactic structures. Sentences with syntactically more complex object-relative clauses evoked larger task-evoked pupillary responses than did sentences with simpler subject-relative clauses.

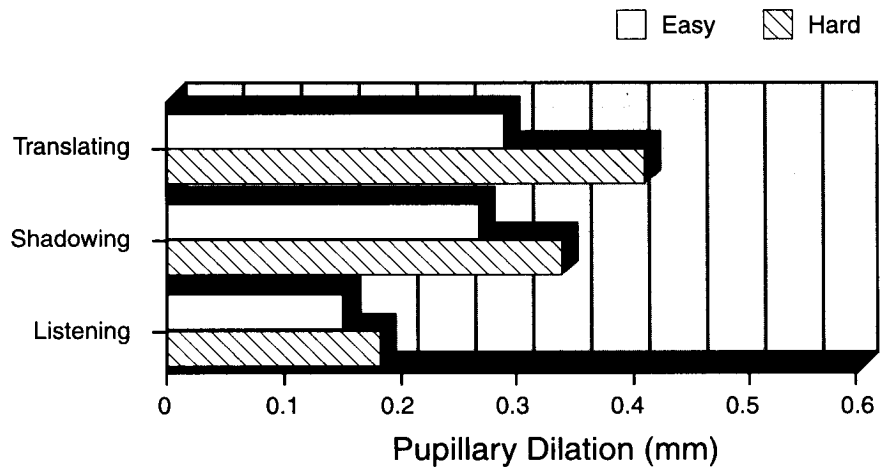


Figure 15. TEPR amplitude in bilingual language tasks. Here, subjects were required to listen passively to single English words, shadow English words, or translate English words into the listener's native Finnish. TEPR amplitude reflected the complexity of the processing task. For each task, the more difficult words elicited the larger responses.

TEPRs and Attention

Perhaps one of the slipperiest fundamental concepts in all of cognitive psychophysiology is that of *attention*. William James's century-old definition of attention still holds well today. He viewed attention as "the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence" (James 1890, pp. 403-4).

Two studies have used pupillometric methods to explicitly examine human attention. Beatty (1988) looked for pupillometric evidence of selective attentional processes as subjects monitored one of two channels (a series of 800-Hz tone bursts presented to one ear or 1,500-Hz tone bursts presented to the other) for targets (tone bursts of 860 or 1,575 Hz, respectively). Interstimulus intervals (ISIs) were randomly generated to produce an average ISI of 333 msec and average of one target every 10 sec. Subjects were required to detect targets on either the high- or low-pitch channel on different blocks of trials.

These conditions generated some of the smallest task-evoked pupillary responses ever published, which are shown in Figure 16. There were no visible TEPRs for nontarget

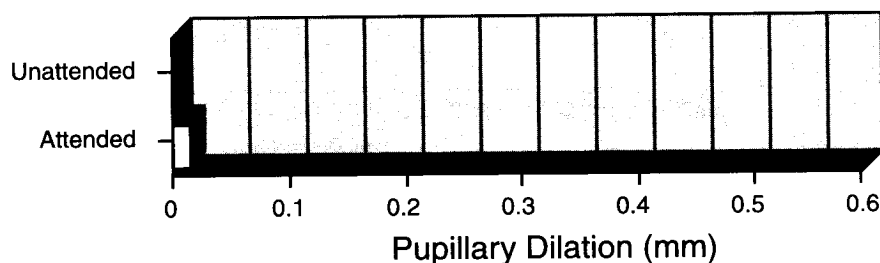


Figure 16. Amplitude of the TEPR in auditory selective attention. When subjects selectively monitor one of two auditory channels to detect slightly deviant target stimuli, an exceedingly small but reliable TEPR is evident for nontarget stimuli on the attended channel. No pupillary response is observed for nontargets on the unattended channel.

stimuli in the unattended channel while 0.015-mm peak TEPRs were present for nontarget stimuli in the attended channel. (Signal stimuli, naturally, generated large TEPRs as well as overt behavioral responses.) These results are similar to those previously reported by Hink, Van Voorhis, and Hillyard (1977) for event-related potentials.

Task-evoked pupillary responses in a sustained attention or vigilance task have also been reported. Beatty (1982a) measured pupillary movements as students monitored a series of 1-kHz 50-msec tone bursts presented at 3.2-sec intervals for a period of 48 min. Their task was to detect infrequent targets (tone bursts at -3 dB). These conditions produced a classic vigilance decrement. Signal detection analysis revealed that subjects became both decreasingly sensitive and increasingly conservative in their judgment criteria as a function of time in the task. Amplitude of the TEPR mirrored this change in sensitivity as it also decreased with time in the task.

Taken with the literature just summarized, TEPR amplitude appears to quantitatively reflect the state of central attentional processes. It is our opinion that pupillometry provides a unique and powerful methodology for the study of human attention that has yet to be fully exploited.

TEPRs and Individual Differences

The question of individual differences in cognitive abilities has also received attention in the pupillometric literature. Ahern (see Ahern & Beatty 1979, 1981) asked if college students of differing psychometric intelligence would exhibit differences in the amplitude of TEPRs during cognitive processing. They examined a group of 43 UCLA students with (combined verbal and quantitative) Scholastic Aptitude Test scores of either below 950 (low-intelligence group) or above 1350 (high-intelligence group). Four cognitive tests were used to search for between-group TEPR differences: mental multiplication, digit span, vocabulary, and sentence comprehension. In all but the vocabulary test, increasing task difficulty resulted in increased TEPR amplitude, confirming that these tests were in accord with previously published results.

Between-group intelligence differences in TEPR amplitude emerged in the tests for mental multiplication, digit span, and sentence comprehension. Task-evoked pupillary responses were smaller for subjects in the high-intelligence group than for their counterparts in the low-intelligence group. (Pupillary responses were essentially

identical for both groups in the vocabulary test.) These results suggest that the cognitive processes of individuals with high psychometric intelligence are more efficient and less demanding of attention or resources. Whether this presumed heightened efficiency is innate or the product of practice and overlearning is a question not addressed by the pupillometric data.

RELATION BETWEEN TEPRs AND OTHER PSYCHOPHYSIOLOGICAL VARIABLES

Kahneman and associates (1969) provided comparative data concerning task-evoked pupillary responses and co-occurring changes in heart rate and skin resistance. Investigators measured the pupillary diameter, heart rate, and skin resistance of ten subjects performing a four-item digit task at three levels of difficulty: add 0, 1, or 3 to each digit. The results are shown in Figure 17.

Kahneman et al. reported similar changes in all three psychophysiological systems, suggesting that the common origin of these effects is relatively high within the central nervous system. But of the three response systems, the responses of the pupillary system were most reliable and significant for the size of the observed data sample. This finding is in accord with the frequent observation of high statistical reliability with very small sample sizes common in pupillometric research (cf. the highly systematic and significant data obtained from only twenty experimental trials by Kahneman & Beatty 1966). These and other data indicate that the pupillary system is a very sensitive, low-noise system for psychophysiological measurement.

RELATION BETWEEN TEPRs AND BRAIN ACTIVITY

Perhaps even more interesting than the concordance of task-evoked pupillary responses with other autonomic psychophysiological indicators is evidence that TEPR amplitude also covaries with cortical activation. Just et al. (1996) described an elegant experiment using positron emission tomography (PET) to measure the extent of activation in Broca's and Wernicke's areas of the left cerebral hemisphere in a sentence comprehension task similar to that studied pupillometrically by Just and Carpenter (1993). Just et al. (1996) presented subjects with superficially similar sentences of equal length that differed

in syntactic construction and short-term memory load. In the least demanding syntactic structure, two related active clauses were conjoined (e.g., "The reporter attacked the senator and admitted the error"). More demanding were sentences with a subjective-relative clause ("The reporter that attacked the senator admitted the error"). The most demanding syntactic structure contained an object-relative clause ("The reporter that the senator attacked admitted the error"). As in the earlier study, the subject's comprehension of each sentence was tested with a true-false comprehension probe ("The reporter attacked the senator; true or false?"). These conditions had been shown previously to yield increasingly large task-evoked pupillary responses.

The PET data revealed that increasing syntactic complexity in this sentence comprehension task increased the area of task-evoked cortical activation most prominently in Wernicke's area, but also in Broca's area as well as homologous regions of the right cerebral hemisphere (Figure 18). In all cases, the additional activation appeared as expansion of the regions activated by the simplest sentences. Additional, new areas were never recruited as syntactic complexity increased.

These data of Just et al. (1996) are particularly important for the purposes of this chapter in that they provide a unique, parallel evaluation of specific regional cortical activation patterns in a task previously characterized more generally using pupillometry. Their results are clear and conclusive elaboration of the task-evoked specific cortical events that occur concomitantly with the task-evoked pupillary response in a behaviorally well-controlled and linguistically well-defined high-level cognitive task. Such data speak directly to the importance of pupillometric methods in the psychophysiological study of human cognitive processes.

Epilogue

Pupillometry has served psychophysiology well in the study of the dynamics of human cognitive processing. This literature is remarkably consistent and without significant contradictions. The TEPR meets Kahneman's three criteria for a psychophysiological measure of processing load. Task-evoked pupillary responses have been shown to index accurately the within-task variations in task demands that result from changes in task parameters. Further,

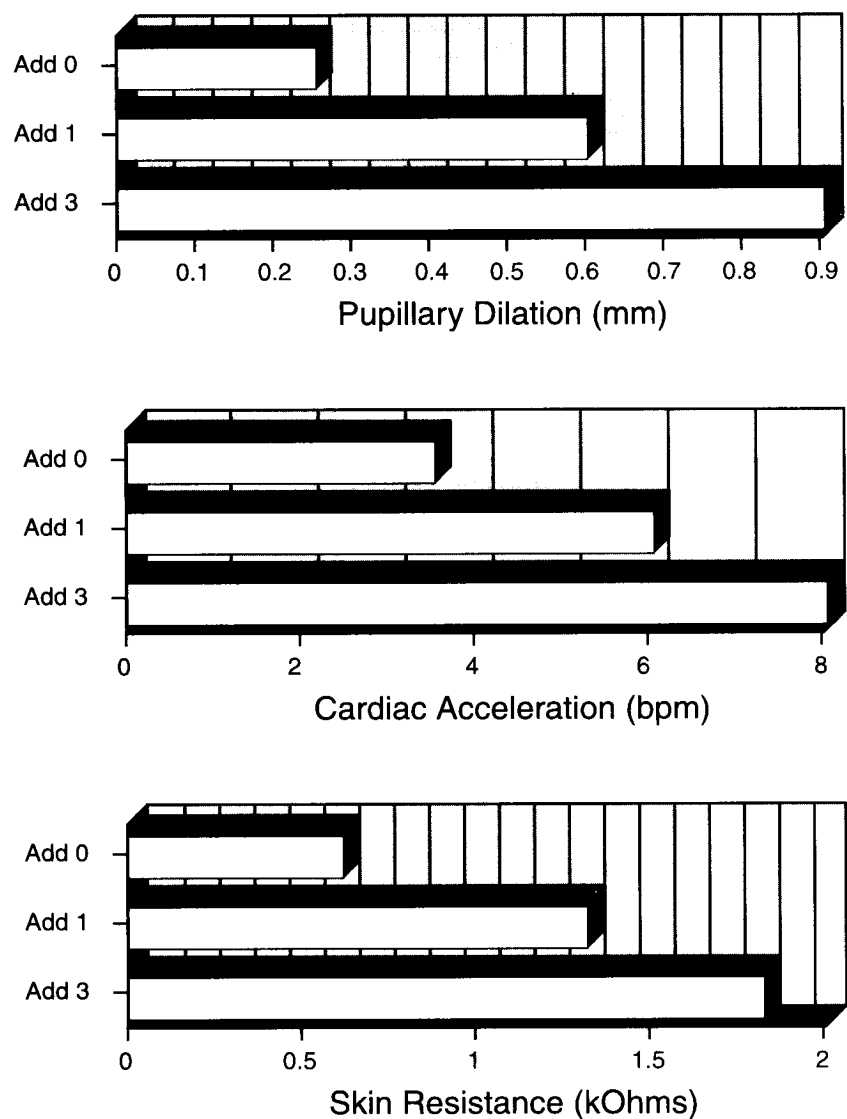


Figure 17. Concordant responses in three psychophysiological systems. Similar patterns of results of varying the difficulty of the digit repetition/transformation task are seen in pupillary dilation, cardiac acceleration, and skin resistance, arguing for the high-level central nervous system origin of these psychophysiological responses.

they relate between-task differences in processing load evoked by qualitatively different mental tasks in a reasonable and consistent fashion. Finally, TEPR amplitude is responsive to individual differences in cognitive abilities, as reflected in studies of intelligence and processing load.

Given the sensitivity, reliability, and consistency of TEPRs as a measure of cognitive load, it is somewhat surprising that the pupillometric psychophysiological literature is not large. We suspect that pupillometry is not widely employed in cognitive psychophysiology because the pupil lacks face validity as a measure of brain function. If a similar pattern of findings were produced by an electrophysiological indicator of cortical origin, we suspect that

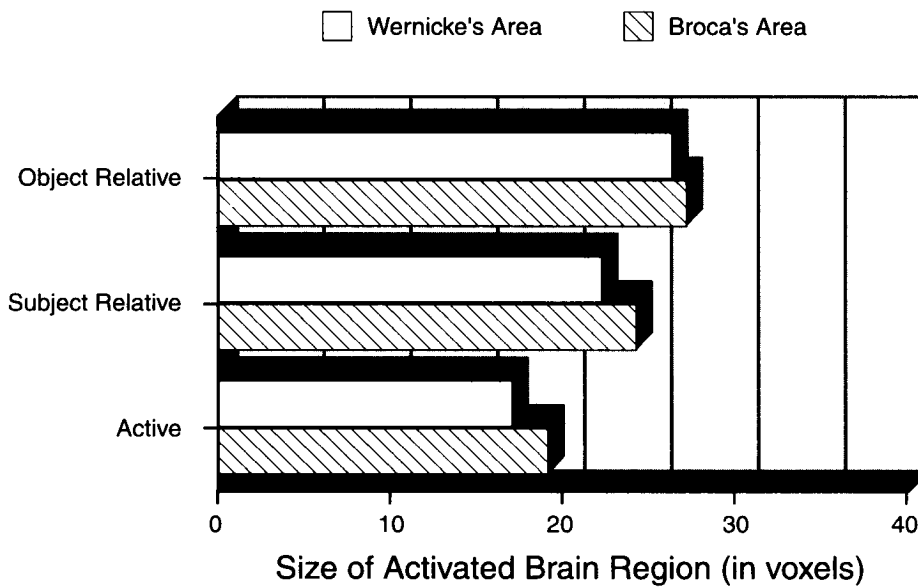


Figure 18. Brain activation responses mirror prior pupillary response data. The extent of activation in two language-related regions of the dominant cerebral hemisphere, Broca's and Wernicke's areas, directly reflects the processing load imposed by auditorily presented sentences that differ in syntactic structure. This pattern of results (Just et al. 1996) is predictable from previous pupillometric findings (Just & Carpenter 1993).

it would be widely pursued as a chosen methodology in cognitive psychophysiological research.

For this reason, in this chapter we offer the argument that the TEPR should be viewed as a reporter variable for human cognitive processes in much the same way as reporter genes are used in studying the molecular biology of the cell. In both cases, correlation is quite sufficient and the lack of causality is irrelevant. We hope that this reasoning will encourage others to join in the pupillometric study of cognitive processes.

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