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Pupillary Dilations in Movement Preparation and Execution

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ABSTRACT

Movement-related pupillary responses (MRPRs) were examined during self-triggered finger flexions to determine the time course and extent of response-related effects on this measure of general processing demands. MRPRs to self-triggered finger movements began about 1.5 s before the response and peaked 0.5 s post-response for simple movements. This dilation increased in amplitude and latency with the complexity of the movement as determined by the number of flexions executed. Peak pupillary amplitude was also sensitive to the force of the movement. The data establish the very large contribution of motoric processing demands to the pupillary response both before and after the onset of the movement.

DESCRIPTORS: Pupil, Response processes, Movement, Autonomic nervous system.

The task-related pupillary response (TRPR) functions as a continuous index of the general processing load imposed on the subject by most aspects of a cognitive task. Beatty (1982) has summarized the evidence for this in perceptual, memory, and problem solving aspects of numerous tasks. However, the usefulness of this index in human performance with respect to motor processing has not been carefully examined.

Since the first modern reports of pupillary dilations to central nervous system activity (e.g. Hess & Polt, 1964; Kahneman & Beatty, 1966), very few studies of the effects of motor activity on the pupillary measure have appeared in this literature. Bernick and Oberlander (1968) demonstrated that pupillary dilations are observable during tasks involving manual and verbal responses. Nunnally, Knott, Duchnowski, and Parker (1967) reported that pupillary diameter increased with the weight of objects lifted in a test of tonic motor effects on the pupil.

The purpose of the present investigations was to examine quantitatively the effects of preparing and executing simple manual responses upon the time course and amplitude of pupillary responses. Movement-related pupillary responses (MRPRs) were obtained during self-paced finger flexions. Averaged MRPRs were computed across trials using the movement as a temporal reference. These experiments also examined the relationship between the MRPR and two parameters of the movement: its complexity and its force.

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EXPERIMENT 1

Method

Subjects

Eight right-handed college students (4 men, 4 women), aged 18–40 yrs, participated in Experiment 1.

Apparatus

The subject sat at a table with his or her head supported by a Bausch & Lomb head rest. The subject's right hand was positioned over a membrane keyboard (RCA model VP606) from which responses were recorded. Key presses on this keyboard required only minimal finger displacement.

All aspects of stimulation and recording were controlled by a DEC PDP-11/34 computer. Pupil size was recorded using a Gulf + Western 1050S video pupillometer. The output of the pupillometer was digitized at 12 bits with a sampling frequency of 40 Hz, and individual pupil traces were stored on disk. The experimental trials began and ended with auditory prompts of digitized speech presented to the subject through a loudspeaker.

Procedure

The experiment was divided into four blocks in which one of four different responses was produced. Each block was composed of four 60-s response periods initiated by the subject. Each period was begun with the 'READY' prompt, following which the subject was to initiate the response period by pressing a key on the keyboard. The subject was then to make the designated response for that particular block approximately every 5 to 10 s without keeping count of his responses or trying to respond at regular intervals. The subject was also instructed to try to refrain from blinking during the 60-s period and to fixate a point at a 2 m distance. The response period ended with the presentation of the 'REST' prompt.

Experimental blocks were preceded by four 1-min practice periods in which the subject was asked to produce single key presses with the right index finger. In the four experimental blocks the subject was instructed to respond with either single key presses, double key presses with the right index, double key presses involving the two index fingers (right index followed by left index), or triple key presses in which the index, the ring finger and the middle finger sequentially pressed keys on which they rested. The order in which the response blocks were presented was balanced across subjects.

One subject was given an additional block of single key presses during which the EMG from the index flexor was recorded in addition to the key press to compare the effect of these two timing signals on the average MRPR. The EMG was recorded using Ag-AgCl electrodes and a Grass amplifier with a bandpass of 5 to 70 Hz and a sampling rate of 100 Hz. In this block, pupillary data were also sampled at 100 Hz with a bandpass of 0.1 to 35 Hz.

For each response period, individual pupil records were obtained beginning at the onset of the period. Before further processing, the pupillary data were segmented by a response-locked realignment procedure. Using the recorded onset of the manual response as a temporal marker, the pupil traces were aligned to reveal the pupillary dilation associated with the movement. The obtained traces included data for the 2 s preceding and following recorded onset of the movement.

All 4-s traces were visually inspected for blink or accommodation artifacts. Trials containing such artifacts (approximately 10% in all conditions) were discarded. The artifact-free records were then averaged separately for each subject in each response condition. Approximately 18 individual traces were included in each of the average waveforms for each subject.

Results

Figure 1 contrasts the key-press and EMG time-locking on the pupillary response. The two waveforms are virtually identical, the EMG-locked waveforms leading the other waveform by 30 ms, which is the average latency between the onset of the EMG and the recorded key press in this block. These data indicate that there is very little difference between the two measures of response time as far as the MRPR is concerned. This is in line with the rather long time constant generally associated with pupillary responses in other situations (see Beatty, 1982).

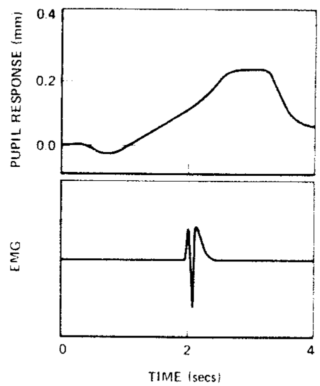

Figure 1. Averaged movement-related pupillary response to a self-triggered finger movement time-locked to the flexor EMG and to the activation of the key. The two pupil traces were virtually indistinguishable so that they appear as one trace in the figure. The lower trace is the average EMG. All traces are averages from one subject.

Figure 2 presents the group average MRPR waveforms obtained for the entire subject sample in the four response conditions. During single responses, the dilation began an average of 1.5 s (SD = 0.3 s) before the response. This dilation peaked an average of 530 ms (SD = 70 ms) post-reponse.

The peak amplitude of the dilation increased from .21 mm (SD = .07 mm) in single responses to an average of .36 mm (SD = .15 mm) in the two types of double responses, to .58 mm (SD = .27 mm) in triple responses. Amplitude was significantly affected by the number of responses ($F(3/21) = 15.4$, $p<.001$), but there was no difference between the peak amplitudes in the two double response conditions by the Newman-Keuls test ($Q(2/21) = .81$, NS).

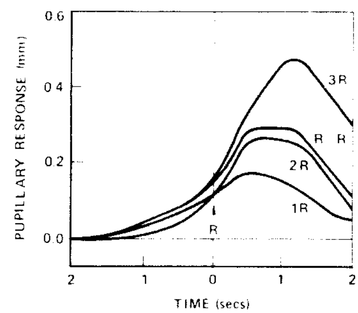

Figure 2. Averaged movement-related pupillary responses in the four response conditions including single keypresses (1R), double keypresses from the same finger (2R), double keypresses involving two different fingers (R-R), and triple keypresses (3R). The waveforms are group averages from 8 subjects.

The latency of the peak of the MRPR also increased to 750 ms (SD = 250 ms) in double response conditions and to 1000 ms (SD = 270 ms) in triple responses. This increase in latency with the complexity of the response was statistically significant ($F(3/21) = 15.6$, $p<.001$). As with the amplitude measure, the difference between the latencies of the two double response conditions was not significant ($Q(2/21) = .79$, NS).

The complexity of the response did not affect the tonic baseline level of pupillary aperture ($F(3/21)<1$) nor did it affect the time at which the dilation began ($F(3/21) = 1.4$, NS).

EXPERIMENT 2

The second experiment examined the relationship between the amplitude of the MRPR and the force of the required movement.

Method

Subjects

Ten right-handed college students (5 men, 5 women) participated in Experiment 2.

Procedure

The experimental procedure used was similar to that of the first experiment, except that two microswitches separated by 5 cm were placed in front of the subject's right arm. The levers on the microswitches were mounted with springs of different caliber so that one switch was activated by a load of 100 g and the other by a load of 1250 g.

In this experiment, the session was composed of two blocks of 24 trials. On each 9-s trial the subject was asked to activate one of the two microswitches with a rapid movement a few seconds after the beginning of the trial. Half the subjects were asked to depress the lightly loaded (Easy) switch on trials of the first block and the heavily loaded (Difficult) switch on trials of the second block; the reverse was true for the remaining subjects. Each subject received extensive practice on the assigned microswitch before the beginning of each block.

Individual pupil records were processed and averaged in the same manner as in Experiment 1. Separate response-locked average waveforms were obtained for Easy and Difficult conditions for each subject. Approximately 16 traces were included in the averaged waveforms of individual subjects.

Results

The group waveforms for the two force conditions are shown in Figure 3. The average peak dilation associated with depressing the Easy switch was 0.28 mm (SD = 0.1 mm), compared to 0.38 mm (SD = 0.1 mm) for the Difficult switch. The difference between these two amplitudes was significant ($F(1/9) = 59.78$, $p<.001$); depressing the switch requiring a more forceful movement was associated with a larger dilation than was the less demanding movement.

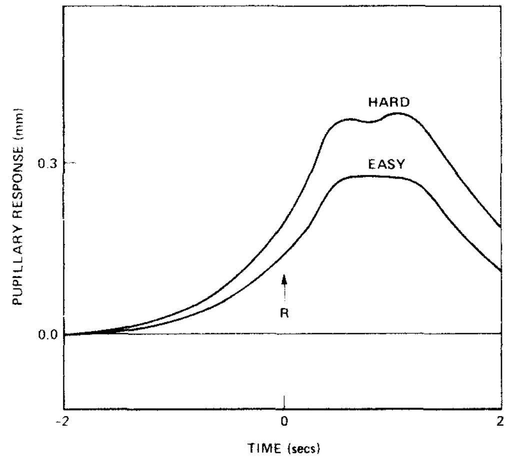

Figure 3. Averaged movement-related pupillary responses under two load conditions. The waveforms are group averages from 10 subjects.

The dilation peaked 827 ms (SD = 229 ms) after the response in the Easy condition and 845 ms (SD = 247 ms) after the response in the Difficult condition. These values did not differ significantly ($F(1/9)<1$).

DISCUSSION

These results provide strong suppport for the existence of orderly effects of response factors on the pupillary response. MRPRs were found to occur in the absence of stimulation, they began 1.5 s before the response and varied in amplitude with the complexity and the force of the movement. The peak of the dilation to simple responses occurred about .5 s after the movement, which corresponds to the latency-to-peak of dilations evoked by sensory events. This appears to be a general feature of pupillary dilations but its physiological basis is presently unknown. However, the time course of the MRPR suggests that all aspects of responding, including preparation, execution, and proprioceptive feedback, can affect the autonomic response.

These findings shed light on the pattern of autonomic activation observed in reaction time tasks (Bradshaw, 1968, 1969; Richer, Silverman, & Beatty, 1983). In such tasks a preparatory pupillary dilation occurs before the imperative stimulus. This dilation is most probably response-related and should, according to the present data, be sensitive to the parameters of the overt reaction.

The pupillary responses obtained in the present study can also be compared to those obtained in qualitatively different tasks involving CNS activity. Beatty (1982) has analyzed the peak amplitudes obtained in perceptual and cognitive tasks in the pupillometric literature; the dilations obtained in the execution of simple finger movements in the present experiment are comparable to those observed during difficult auditory discrimination or during the storage of about five digits in memory for immediate recall. This suggests that responding is one of the activities that entails large and widespread increases in nervous system activation.

The preparatory dilation of the MRPR shows some similarities with other physiological processes. During self-triggered responding, the slow readiness potential (RP) recorded on the scalp has been reported to appear a little over one second before finger movements (Becker, Iwase, Jurgens, & Kornhuber, 1976). The RP has also been shown to vary in amplitude with the force of the movement (Kutas & Donchin, 1974). Slowly developing response preparation components have also been observed in the EMG (Brunia & Vingerhoets, 1980) and in changes in the excitability of spinal reflexes (Brunia & Vuister, 1979). Finally, autonomic changes such as heart-rate deceleration during response preparation have also been interpreted as peripheral manifestations of central processes (e.g. Obrist, Webb, Sutterer, & Howard, 1970). All these measures converge to indicate that the presetting of CNS structures is an important part of responding.

One striking fact emerges from these data: the preparation and execution of simple responses have a widespread effect on the peripheral nervous system as indexed by the pupillary response. Why this occurs remains an open question. But the answer to this question may provide critical information to understanding the nature of preparatory and attentional processes of the human brain.

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