国家自然科学基金重大项目

视觉信息加工研究

（一九八八年十月——一九九二年十月）

论 文 集

下 册

项目学术领导小组

一九九二年十月

前　言

国家自然科学基金重大项目《视觉信息加工研究》经过全体参加者四年的努力，已经按计划并超额完成，取得了一系列基础理论成果和一些有实际应用前景的成果。据初步统计，在此项基金的支持下，在国内外学术刊物和学术会议上共发表／撰写研究论文 267篇。获中国科学院自然科学二等奖二项、三等奖一项、省级自然科学一等奖二项及本单位奖多项、获国家专利二项。另有待申报国家自然科学成果奖二项、院级奖一项及国家专利二项。这批成果达到了国际水平或为国际领先，为了解视觉信息加工的神经基础和理论描述提供了丰富的资料，受到国内外同行的高度评价和重视。

本研究工作总结包括四部分内容分五册出版。第一部分在简述本项目研究的主要成绩之后，依次说明各个子课题研究所取得的进展，并列出研究论文目录；第二部分是 176篇论文的摘要，它们是我们研究工作的缩影；第三部分是获奖成果简介；第四部分是分上、下二册出版的论文集。承担此项研究的全体同事谨以此献给予我们以有力支持的国家自然科学基金委员会及其生命科学部，献给各位参与评审的专家和所有关心、支持我们的同事和朋友。

项目学术领导小组

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一九九二年十月

项目负责人：王 书 荣

中国科学院生物物理研究所

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视觉图象识别中眼动对图象特征提取作用的研究

Human Pupillary Response to Ramp Changes in Light Intensity

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The dynamic behavior of the pupillary system was explored using different velocity ramp changes in light intensity. Ramp stimuli ranged in velocity from 0.02 to 8.00 log units/s and the responses were recorded from three subjects. For ramp velocity below 0.066 log units/s, the responses were mainly ramps. Above 1.0 log units/s ramp velocity, the responses were mostly steps. In the stimulus velocity range of 0.066 to 1.0 log units/s, the primary responses were step-ramps. The amplitudes of the initial step movement in step-ramp responses were found to be proportional to stimulus ramp velocity. Thus the pupillary system appears either to convert the total energy in a time interval or the rate of change of intensity of the ramp stimulus into a step signal for driving the pupillary plant output. © 1988 Academic Press, Inc.

INTRODUCTION

The pupillary response to light stimulus has been used extensively in the clinic to assess central nervous system function and in the laboratory to examine the fundamental behavior of the pupillary system. Static and dynamic anomalies of pupillary responses, such as those seen in Argyll Robertson's pupil, Adie's pupil, and Horner's syndrome, have been used to differentially diagnose central nervous system diseases (14, 16). Normal pupillary light responses parallel many functions found in visual psychophysics. For exam-

ple, incremental thresholds were found to be proportional to background illumination (Weber's law); responses were proportional to the product of stimulus flash intensity and duration for durations less than 100 ms. (Bloch's law); and responses were equal to the time average of the intermittent stimuli above the flicker fusion frequency (Talbot's law) (18). A variety of stimuli have been used to probe the pupillary system in the study of its control properties. Different amplitude step inputs showed responses that were faster for on-step than off-step of light (8), and also revealed the pupillary escape (7) and capture (15) phenomena. Pulse inputs of opposite directions showed the dominance of the faster on-response relative to the off-response (3). Pulse stimuli at different pupil sizes showed a range nonlinearity with the highest responsiveness at midrange (9, 12, 13). Small-amplitude sinusoidal stimulation showed responses corresponding to a system with a third-order lag element with a cutoff frequency of 1 Hz. Other investigators used double-pulse (2) and band-limited noise (17, 6) to examine the nonlinear properties of the pupillary system. We describe here an investigation using different velocity ramp changes in light intensity. The majority of pupillary responses found were step-ramps, with the initial step amplitude proportional to the stimulus ramp velocity. The implication of the control process converting the ramp velocity to step output is discussed.

METHODS

Instrumentation. Pupil area was measured dynamically using an infrared camera pupillometer system (PUP1). An infrared source was directed at the subject's eye to provide infrared reflected light to an infrared camera. The infrared television camera was mounted on a movable stage, which allowed forward and sideways horizontal movement. A screw ring allowed vertical camera adjustment. The degree of focus of the eye was monitored on a (625 lines) television monitor. The video signal was then processed by a pupillometer electronic module. This specially designed pupillometer circuit allowed the experimenter to control the size and location of a circular window surrounding the television image of the pupil. Thus, most of the lid, eyelash, and scleral reflection artifacts could be eliminated in this way. A trigger level adjustment was used to select the pupil as the dark central circular area for signal processing. The pupillometer output was a voltage signal proportional to pupil diameter.

The light stimulus system used continuous gradient neutral density wedges in which the density of the wedges changed logarithmically with linear change in wedge position. One wedge (Barr and Stroud, Ltd., WGN2) was mounted on the pen drive of an X–Y servo-controlled plotter. The weight of the wedge was counterbalanced by a dead weight via a pulley system. An-

other wedge, with oppositely directed density gradient complementing the first wedge, was fixed on the plotter itself. Thus at any particular relative displacement of the two wedges, the density throughout the intersected region was the same. The X–Y plotter was mounted on its side, so that actual movement of the first wedge was in the vertical direction. Thus, if one views a light stimulus through the fixed wedge, movement of the first wedge yielded a uniform change in luminance. The light source was a tungsten bulb driven by a constant current source circuit. A diffuser was placed in front of the light bulb to provide a uniform luminance light source at a fixed focal distance. A 10 diopter lens was positioned in front of the diffuser to give a collimated light output. A 2-cm^2 aperture stop gave a sharp delineation of the source boundary. This entire light source system was enclosed in a black case so that only the output light could be seen by the subject.

As the initial stimulus light level for all patterns of stimuli was 0.33 lux (7900 Trol), this level was used as the reference for calculation of values of log light intensity. A photometer (United Detector Technology, Inc., Model 11A Photometer/Radiometer) was used to calibrate both the static and dynamic light signal outputs.

A PDP 11/23 Plus computer was used to drive the light source and record the pupil responses. The computer A/D board limited the recorded response resolution to 0.03 mm^2. A stimulus program allowed the experimenter to configure a variety of stimulus intensity time courses such as different velocity ramps or different amplitude steps. The computer was also used for editing the data, calculating velocity curves from amplitude records, and averaging the responses. The computer terminal could also be used as a graphics screen. Figures on the screen could be selected for plotting on an HP 7470A plotter.

Subjects. Subjects included two graduate students from the Shanghai Institute of Physiology and one of the authors (G.H.). They all gave prior consent to serve as subjects in the experiments. The subjects have normal oculomotor function and 20/20 vision based on standard optometric tests (except one, but whose refractive error was corrected in the stimulated eye).

Experimental protocol. The stimulating light source was presented to the subject's left eye as a collimated light source 2 cm in diameter. Thus the experiments were conducted under closed-loop conditions to approximate normal pupil operating conditions. Note, however, that because the pupillary system feedback loop has low gain, the responses would be nearly the same whether the system is open or closed-loop (Webster). The consensual pupil response in the right eye was monitored by the infrared TV camera. A partition was placed at the subject's midline so as to prevent vergence stimulation. The subject was instructed to view the diffusing source with well-marked contours and maintain constant clarity, thus keeping accom-

modation constant. After the right eye's image was focused on the TV screen and the pupillometer window and trigger level were adjusted to give a sharp image of the pupil, the experimental room light was turned off. The subject then adapted to the stimulus background light for at least 2 min. Initial pupil diameter was about 6.2 mm for all responses. Before each stimulus presentation, the computer sent three "beep" sounds to warn the subject. Two seconds later, the light stimulus was presented to the subject; the stimuli were presented in random order. Ramp stimulus velocity ranged from 0.02 to 8.0 log units/s. The maximum amplitude was 2 log units. Step stimuli ranged in amplitude from 0.4 to 2.0 log units. After the stimulus presentation, the computer emitted another "beep" sound to signal the end of the stimulus presentation record. The interstimulus interval varied from 5 to 20 s. depending on the light level reached in the previous presentation. This allowed the subject to adapt to the background light level and prepare for the next stimulation presentation. Record lengths were 10 s for steps and ramps above 0.25 log units/s, and 20 s for slower ramp stimuli. After about 20 presentations, the subject was allowed to rest 5 min outside the experimental room. Then the setup process was repeated, but generally this was much faster than the first setup.

Data analysis. The numerous data record curves were visually inspected on the computer graphics terminal to determine which of the four types of response patterns each response belonged to. For example, a step response could be seen in the amplitude trace as a fast downward movement followed by a flattening of the response. The corresponding velocity trace has the shape of a pulse. A ramp response was characterized by a constant slope movement in the amplitude trace and a flat velocity trace. Combination responses such as step-ramp and multiple-step were similarly analyzed. In this manner, responses were categorized as ramp, step-ramp, multiple-step, or step. Due to inherent noise in the pupillary system (11, 15), the responses to a particular velocity ramp (or step) stimulus and belonging to a particular type of response were averaged. In the response selection process, the beginning of the response was marked by a movable cursor on the computer graphics terminal and the delay was recorded but removed before averaging was performed. If the beginning was slightly ambiguous, a small range of the plot could be expanded both in time and amplitude to help mark the beginning of the response. Flattening or distinct change in curvature of the corresponding velocity curve also helped to define the beginning of the response movement. The average time delay for a particular set of responses was first adjusted for mechanical delay of the stimulus source, which was empirically determined to be 100 ms. The net delay was then added to the average of that set of responses. Individual and averaged curves and the corresponding velocity curves were plotted on the HP-7470A plotter.

TABLE I

Frequency Distribution of Response Types in Percentage[a]

Ramp velocity	R	SR	MS	S	N
8.0		39		61	38
4.0		36		64	22
1.0		58	5	37	19
0.66		78	9	13	23
0.50		74	11	15	38
0.33		72	23	5	44
0.25	14	60	12	14	35
0.20	5	95			38
0.13	26	70	4		51
0.066	17	83			42
0.020	77	23			22

[a] Pupillary responses are categorized as ramp (R), step-ramp (SR), multiple-step (MS), and step (S). Stimulus ramp velocities (in log units/s) are shown in the left column. The total number of responses at each stimulus ramp velocity is listed in the right column. Values are the percentage of occurrence of each type of response for a particular stimulus ramp velocity.

RESULTS

Percentage of different types of responses. Responses to various stimuli for the three subjects were similar. For clarity of presentation, data for only one subject (G.H.) are presented. Individual responses to a particular ramp velocity light stimulus are categorized as ramp, step-ramp, multiple-step, or step. The percentage of occurrence of different types of responses at each ramp velocity are tabulated in Table 1. The total number of responses to each ramp velocity stimulus are tabulated in the right column. The center of the distribution of responses shifted from ramp to step-ramp, then to mainly steps as stimulus ramp velocity increased. This provided a general overview of the control strategy used by the pupillary system in response to ramps at different velocities. For ramp velocity below 0.066 log units/s, the responses are mainly ramps. In the stimulus ramp velocity range of 0.066 to 1.0 log units/s, the primary responses were step-ramps. Above 1.0 log units/s ramp velocity, the responses consisted mostly of steps.

Representative curves: initial step amplitude vs stimulus velocity. Using an arbitrary criterion of greater than 50% occurrence of a response type as representative of the response to a particular ramp velocity stimulus, the averaged curve for that response type was selected for display. The representative average curves at each stimulus ramp velocity are plotted as a composite plot in Fig. 1A; the corresponding velocity curves are plotted in Fig. 1B. The
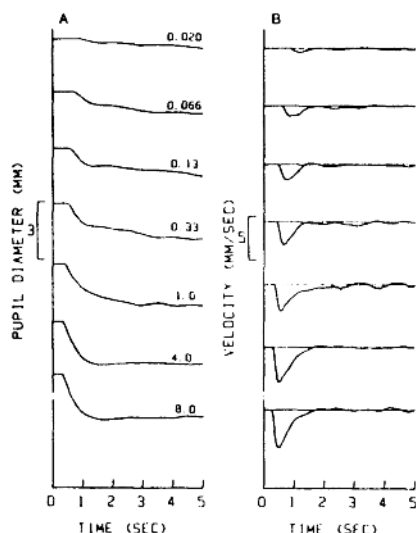
FIG. 1. A (left)—averaged representative curves for ramp stimuli ranging from 0.2 to 8.0 log units/s. Criterion for choice as representative curve was based on > 50% occurrence of a response type for a particular ramp velocity stimulus (see Table 1). Stimulus velocity (in log units/s) is shown next to the representative curve. Subject, G.H. B (right)—velocity curves corresponding to averaged curves of A.

progression of increased initial step amplitude in the responses to increasing stimulus ramp velocity can be seen in the curves in Fig. 1A. This is more explicitly plotted in Fig. 2.

Step responses: comparison of amplitude–velocity characteristics. In order to be certain that the initial step in step-ramp responses as well as secondary steps in multiple-step responses seen for ramp stimuli are the same as actual step responses, we conducted a series of step stimuli experiments at different stimulus amplitudes. Averaged step responses are shown in Fig. 3A; the corresponding velocity traces are shown in Fig. 3B. The amplitude–velocity relationship over a range of amplitudes and velocities represented the characteristic dynamic behavior of the pupillary system. The relationships for step movement in response to ramp stimuli and for actual step responses are shown in Fig. 4. As the data for initial step, multiple-step, and step responses to ramp stimuli were very close to those for actual step stimuli, all the step movements most likely came from the same control process. The amplitude–velocity relationship for saccades has been called the "main sequence"

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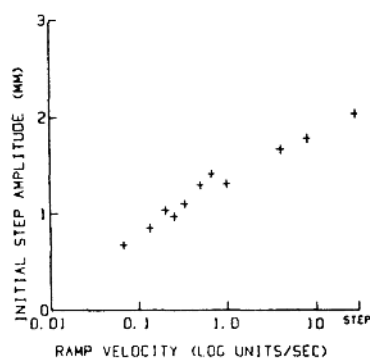FIG. 2. Semilog plot of initial step amplitude vs ramp stimulus velocity derived from the averaged curves of Fig. 1A. Subject, G.H.
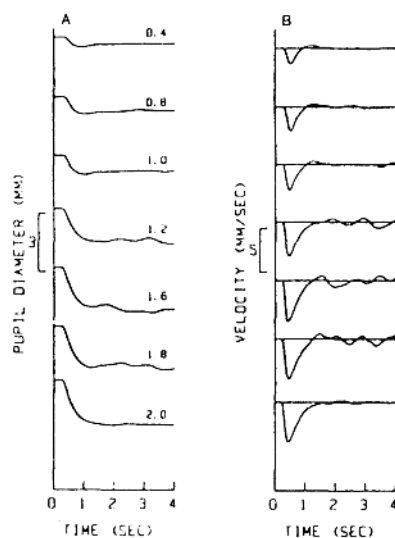

FIG. 3. A (left)—averaged responses to pure step stimuli ranging in amplitude from 0.4 to 2.0 log units. The stimulus step amplitude values are shown next to each curve. B (right)—velocity curves corresponding to the averaged response curves of A. Subject G.H.
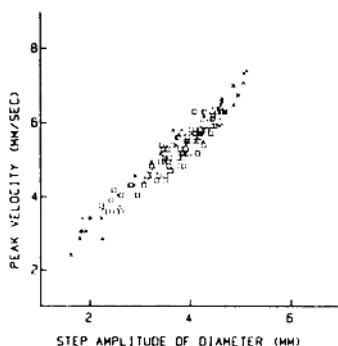
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FIG. 4. Peak velocity vs initial step amplitude obtained from individual responses. This relationship may be called the "main sequence" for pupillary responses. It can be seen that this relationship is similar for responses to actual step stimuli (×), initial steps in step-ramp and multiple-step responses to ramp stimuli (□), step responses to ramp stimuli (△), and step following the initial step in multiple-step responses to ramp stimuli (○). Subject G.H.

for saccades (1) as it describes the dynamic relationship over a wide range of amplitudes and velocities. Thus, Fig. 4 may be called the "main sequence" for pupil light response.

DISCUSSION

Pupillary responses to different light stimuli reveal the basic control properties of the pupillary system. The initial movement to ramp stimuli shows amplitude vs velocity characteristics which occur on the main sequence for actual pupillary step responses. This indicates that the initial part of the ramp response has the same dynamic characteristics as step responses and this may be called a step movement. The fact that the amplitude of the initial step movement is proportional to the stimulus ramp velocity suggests that either the rate of change of light intensity or the total amount of light accumulated during a time interval is converted to an effective neural step command signal. Perhaps part of this signal is due to a manifestation of Block's law, which states that responses are proportional to the stimulus energy within a 100-ms interval. Thus the faster the stimulus ramp velocity the greater the amount of energy that is accumulated in the 100-ms interval. However, this does not explain how the pupillary system would respond to the continued increase in stimulus light intensity of a ramp stimulus. Perhaps a rate-sensitive mechanism in the pupillary system converts the rate of change of light to an effective step signal which drives the pupillary plant. Evidence for a rate-sensitive

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mechanism is found in the unidirectional rate sensitivity of the pupillary system proposed by Clynes (3), in which positive rate of change of light intensity produces a faster response than that for negative velocity stimulus.

The use of ramp stimuli adds to the repertoire of stimuli available to vision research scientists and clinicians for probing the pupillary system. The basic control properties of the pupil are revealed in the responses to ramp stimuli as discussed above. Additional experiments, for example, using different velocity ramp intensity inputs to the two eyes, may be used to determine whether the site for synthesis of the ramp information is before or after the motor controller. Clinically, pupillary responses to ramp stimuli may be a more sensitive indicator of pupillary system function than other stimuli which involve large changes in velocity, such as pulses and steps. Pupillary pathway abnormalities that involve gradual degradation of pupillary responsiveness may be more easily seen in ramp responses than in pulse or step responses, as the latter two tend to overwhelm the system and obscure the response deficit.

Ramp stimuli have also been used in other oculomotor systems and have revealed important control properties of those systems. Ramp changes in stimulus disparity resulted in vergence eye movement that show step-ramp and multiple-step responses (10, 5). The accuracy of the vergence step movements in matching the stimulus led Hung et al. (5) to suggest a preprogramming mechanism in the vergence eye movement system. Similar results were found for the accommodation system (4). Although the mechanism for generating step-ramp responses to ramp stimuli in these systems may be quite different from that in the pupillary system, it is interesting to note the parallel in response patterns to ramp stimuli for all three systems.

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