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A Pupillometric Correlate of Scotopic Visual Acuity

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While not easily fit into the classic descriptions of the pupillary light reflex, previous studies reported that changes in the spatial composition of the retinal image can evoke a pupillary response. The present study extends this observation by showing that the pupil constricts in response to scotopic as well as photopic spatial patterns. Moreover, the amplitude of the scotopic response decreases with increasing spatial frequencies suggesting a pupillary spatial acuity of about 3 c/deg. The scotopic pupil acuity is similar to the scotopic perceptual visual acuity measured in the same observers.

Pupillary light reflex   Scotopic vision   Visual acuity

INTRODUCTION

It is well known that the pupil, the aperture stop of the eye, constricts in response to luminance increments in the stimulus field. Less appreciated is the observation that the pupil also constricts in response to changes in the spatial frequency composition of the stimulus (e.g. Slooter & van Norren, 1980; Ukai, 1985). At first glance, one might attribute the latter response to luminance increments either in spatially local areas or across the entire stimulus field. But three kinds of studies over the past 15 yr suggest a somewhat different explanation.

One study concerned the spatial resolution limit of the pupillary response. Slooter and van Norren (1980) were among the first to observe that the amplitude of the pattern-evoked pupillary response depends on the spatial frequency of the pattern. They suggested that because the amplitude is extinguished as the spatial frequency is increased, the underlying visual mechanism has a spatial resolution limit, or as they termed, a visual acuity. Investigating the pupil acuity in a group of normal observers, however, they found a somewhat surprising result. At a photopic luminance, the pupil acuity not only correlated with but was as high as the perceptual acuity of the observers. Subsequently, several studies substantiated this conclusion (e.g. Barbur & Thomson, 1987; Cocker & Mosely, 1992), and most recently Cocker, Mosely, Bissenden, and Fielder (1994) demonstrated that the pupil acuity is even similar to the Teller visual acuity in infants older than 1 month.

A second study dealt with the effects of a lesion in the geniculo-striate pathway on the pupillary responses evoked by luminance and by spatial patterns. Barbur and Forsyth (1986) found that whereas the luminance-evoked response was normal, the pattern-evoked pupillary response was almost completely absent. That is, the pattern-evoked response depended on the geniculo-striate pathway, whereas the luminance-evoked response did not. This observation suggests that the visual signals required for the pattern- and luminance-evoked pupillary constrictions do not travel through identical visual pathways.

A third study reported on the pupillary response evoked when a uniform luminance field is replaced by a sinewave grating whose peak luminance is identical to the uniform luminance. Young and Kennish (1993, their Fig. 8) found that the pupil constricts. This observation is interesting because the spatial grating was formed only by luminance decrements. In the absence of any luminance increments, the implication is that spatial changes *per se* can cause a pupillary constriction.

In summary, the results from the three studies do not support the idea that the pattern-evoked pupillary response originates solely from temporal luminance increments in the stimulus field. Rather, the results lend support to the notions that the pattern-evoked responses somehow reflect aspects of spatial vision processing and that such pupillary responses may provide an objective method of assessing spatial visual function in humans (or at least a method that yields a different visual assessment from the classical luminance-evoked pupillary responses). However, the studies mentioned above focused on responses evoked by photopic spatial patterns and left a number of questions unanswered. For example, do scotopic spatial patterns evoke a pupillary constriction? Do the scotopic, like photopic, responses

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exhibit a high spatial frequency cut-off? Are the scotopic pupil and perceptual visual acuities similar? The objective of the present study was to examine the pupillary responses evoked by scotopic spatial patterns and address some of these questions.

METHODS

The subjects were healthy adults with 20/20 visual acuity or better. All were emmetropic and were not on medication during the testing period. Subjects A, F, L, and M were men, ages 37, 32, 27, and 28 yr respectively. Subject J was a woman, 31 yr old. All subjects participated in our previous study of pattern-evoked pupillary responses in photopic luminance (Young & Kennish, 1993); subject A also participated in a study concerned with color exchanges (Young, Han & Wu, 1993). Complete sets of pupillary responses were obtained for three of the subjects. Complete sets of psychophysical results were obtained for two subjects. The tenets of the Declaration of Helsinki were followed and informed consent from participants was obtained after the procedures had been fully explained to them. Institutional human experimentation committee approval was obtained prior to the start of the investigation.

Subjects were dark-adapted for at least 30 min prior to the pupil recording. During the recording, subjects sat with their heads held in position by a chin and forehead rest and monocularly viewed the stimulus (a Macintosh II color monitor) from a distance of about 700 mm. The pupil diameter of the right eye was recorded using an infrared video pupil tracking system (ISCAN model 416), while the left eye viewed the stimulus. The subject could not see the stimulus field with the right eye, as the viewing surface of the monitor was encased in a pyramid-like occluder. The apex of the pyramid was positioned next to the subject's left eye and its base was mounted flush against the monitor. Neutral density filters of 3.0 or greater were placed at the apex of the pyramid. Otherwise, the recording procedure and apparatus were similar to those described previously (Young & Kennish, 1993). The digital resolution of the recording system was about 32 μm.

The appearance and disappearance of sinewave gratings were produced in a similar fashion as in a previous study by Young and Kennish (1993); however, the stimulus field was produced by exciting only the blue phosphor. The spectral power distribution of the blue phosphor is maximal at about 450 nm and has a half-band width of about 75 nm. The blue phosphor was chosen to increase the luminance range over which rod vision could be isolated from cone vision. The stimulus field was displayed with a video frame rate of 67 Hz. The field subtended about 18.5 deg horizontally and 14.5 deg vertically. Temporal changes in the stimulus were calibrated using a PIN-10SB photodiode. The luminance was calibrated with a Minolta Color TV analyzer. A stimulus trial consisted of an initial delay period of about 450 msec, a change in the stimulus field for 6 sec, followed by a change back to the original field. Each stimulus condition was tested 30 times. As in our previous study (Young & Kennish, 1993), the space-averaged luminance of the stimulus field was monitored occasionally using a Spectral Spot Photometer. The spot photometer can measure the space-averaged luminance of a video display if one selects the appropriate measuring aperture and viewing distance of the photometer so as to cover the display. No significant luminance change was found during the grating appearance and disappearance.

To determine the luminance range over which the sinewave gratings could be seen only by rods, we psychophysically determined each subject's dark-adaptation curve. The stimulus was a pattern of blue square-wave stripes, each of 4.6 deg width. The rationale for the square-wave pattern was to introduce high spatial frequency components that would preferentially stimulate the cone visual system and, hence, yield a conservative estimate of the upper luminance range over which rod thresholds could be isolated. The pattern was presented periodically every 2 sec. In the dark adapting procedure, the subject's eye was first exposed for 3 min to an intense bleaching field. Then thresholds were determined in the dark. The dark-adaptation curve was tracked by setting the stimulus at a fixed luminance and recording the time required for the subject to detect the stripes. Once the stripes were detected, the stimulus luminance was lowered and the procedure repeated. Our results show that in the present apparatus the psychophysical cone threshold was about -1.36 log scot cd/m^2, or in terms of the retinal illuminance, about 0.48 scot td (the mean pupil diameter for our subjects being about 7.5 mm).

In an ancillary experiment, we also determined the psychophysical contrast sensitivities under similar stimulus conditions used for the pupillary recordings, except that the spatial frequencies tested were chosen to lie on the high frequency roll-off of their contrast sensitivity function and the stimulus duration was 225 msec. The stimulus duration was chosen to be longer than the estimated critical flash duration for detection in the dark-adapted eye (100–200 msec) but short enough that the stimulus could be presented well within the temporal interval of a psychophysical trial. The method for determining the contrast sensitivity was a three-alternative forced-choice procedure. The subject's task was to determine the temporal interval on which the spatial grating appeared. The stimulus grating was presented in one of three randomly selected temporal intervals. A brief auditory tone signaled the start of each interval. For each spatial frequency tested, the percentage of the correctly identified trials was determined for different contrast levels. Each condition was tested 30 times in a pseudorandom fashion. The psychometric functions obtained were then fitted to the following equation,

$$\% \text{ correct} = 100\% - (66.67\%) \times 2^{-(c/t)^{\gamma}}$$

where c is the grating contrast and γ is a parameter controlling the steepness of the psychometric function which varies from subject to subject. The γ parameter is fixed for different spatial frequency conditions.

Psychophysical contrast threshold, *t*, is defined as the contrast level for which the subject correctly identified the temporal interval containing the grating for 66.67% of the trials.

RESULTS

Response waveforms for representative spatial frequencies illustrate two main findings (Figs 1 and 2). First, the appearance of very dim (0.12 and 0.0048 scot td) gratings produces minute—but measurable—pupillary constrictions. In some subjects (e.g. subject J) there is also a small transient constriction following the disappearance of the 0.27 c/deg grating. Second, the amplitude of the constriction varies with the spatial frequency of the grating. The amplitude is largest for the lowest spatial frequencies tested and generally decreases as the spatial frequency is increased.

The amplitude of the initial transient constriction varies systematically as a function of the contrast and retinal illuminance of the spatial gratings [Fig. 3(a)]. Amplitude is measured as the difference between the pupil diameter just prior to the onset of the grating and at the peak of the constriction. The amplitude generally decreases as the retinal illuminance of the grating is lowered. The shape of the amplitude–contrast function also seems to change with illuminance. The function for the highest illuminance (adapted from Young & Kennish, 1993) is nonlinear. As the illuminance is decreased, the function becomes progressively more linear.

To compare the pupillary responsiveness at photopic and scotopic retinal illuminances, we computed the contrast gain of the pupillary response. Contrast gain is a measure used in electrophysiological studies to describe how responsive visual neurons are to low contrast stimuli (e.g. Purpura, Kaplan & Shapley, 1988). Contrast gain is operationally defined as the initial slope of the amplitude–contrast function. Figure 3(a) illustrates how we fitted straight lines to the low contrast portions of the function. For the two lowest illumination conditions, the amplitude–contrast function is approximately linear; so, the gain for different illuminances and spatial frequencies was simply derived from the slope of the best-fitted line.

The magnitude of the pupil contrast gain for a representative spatial frequency (0.27 c/deg) is plotted as a function of different retinal illuminances [Fig. 3(b)], along with our estimate of the psychophysical cone threshold. The results show that the pupil is responsive to spatial patterns presented at retinal illuminances below cone threshold, but its responsiveness is dropping steadily as the retinal illuminance of the pattern is reduced. The pupil contrast gain for other spatial frequencies has a similar function, but its value is lower.

The amplitude–contrast functions for the pupil vary systematically with different spatial frequencies (Fig. 4). At scotopic illuminances, all the functions can be

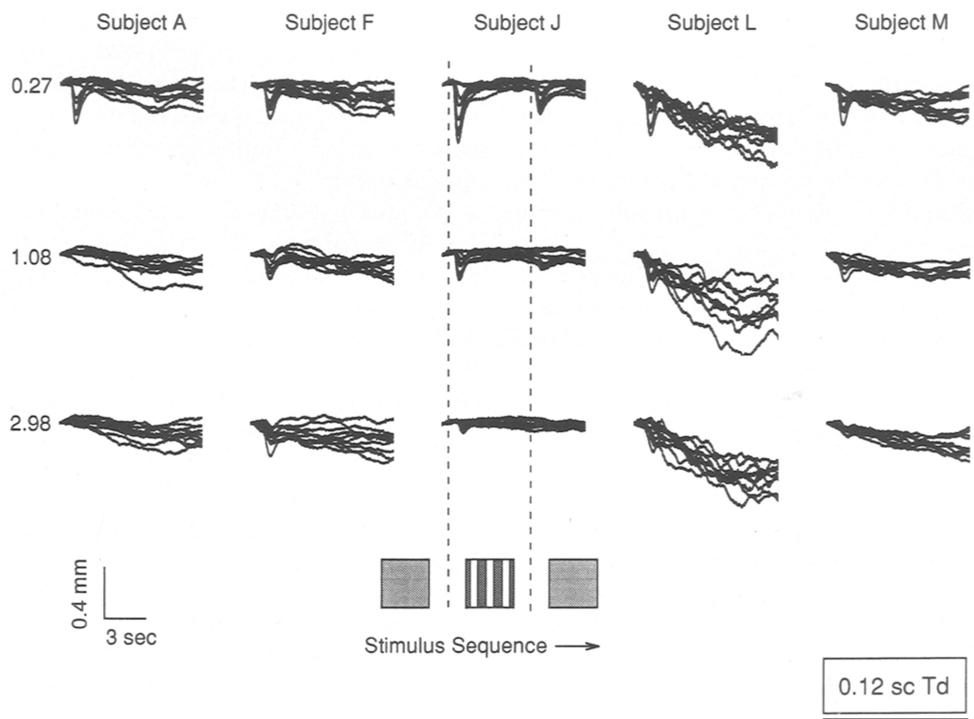

FIGURE 1. Pupillary responses evoked by the appearance of sinewave gratings presented at 0.12 scot td. The spatial frequencies are described by the numbers to the left in c/deg. The superimposed waveforms are responses evoked by different contrast levels. A downward deflection indicates pupillary constriction. The waveforms show an initial transient in response to the grating appearance and then, in some of the subjects, a second smaller transient constriction in response to the grating disappearance. The steady-state diameter of the pupil for the different subjects ranged from about 6.9–7.8 mm just prior to the start of the stimulus. The stimulus used in the experiment is illustrated at the bottom of the figure along with the calibrations for the amplitude and latency.

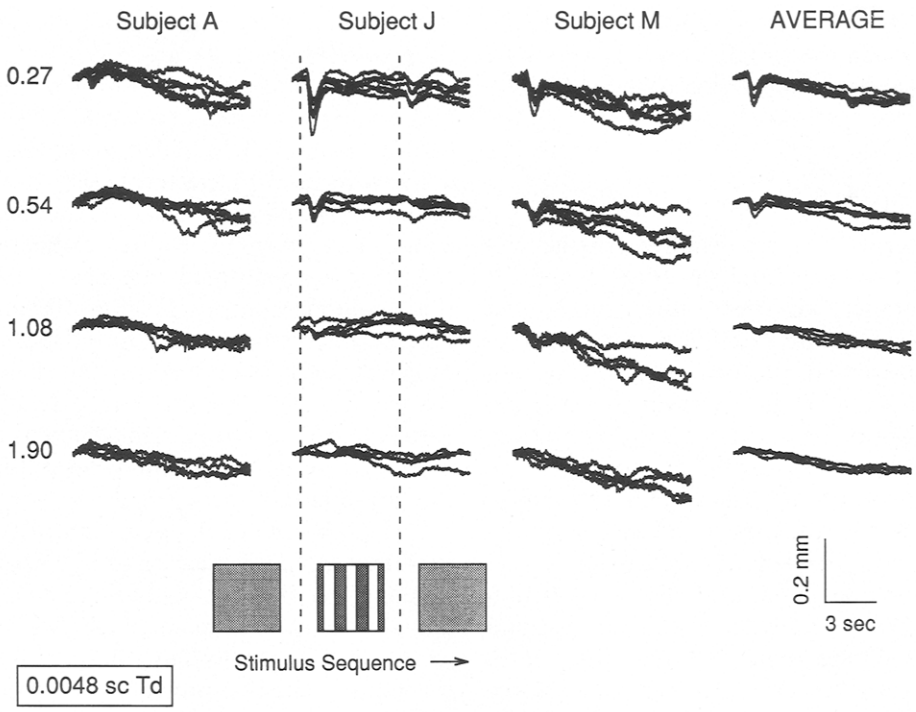

FIGURE 2. Pupillary responses evoked by the appearance of sinewave gratings presented at 0.0048 scot td. Responses for individual subjects and the averaged response for the three subjects are shown. The latter illustrates the general trend that the amplitude of the responses is reduced as the spatial frequency of the gratings is increased. The steady-state diameter of the pupil ranged from 7.5 to 8.0 mm. The figure is organized similarly to Fig. 1 except that the amplitude scale for this figure is different.

described by straight lines. The slopes of regression equations computed on the data were significantly different from zero at the $P < 0.01$ level for all spatial frequency conditions at 0.12 scot td and significantly different from zero at the $P < 0.05$ level for the 0.27 and 0.54 c/deg conditions at 0.0048 scot td. The slopes (pupil contrast gain) generally decreased with increasing spatial frequencies. With slightly higher spatial frequencies, one may anticipate that the pupil contrast gain will drop to zero.

To investigate whether the scotopic visual acuity for the pupil is similar to that for perception, we searched for a way in which our pupil data could be compared with psychophysical data published in the literature or obtained in our laboratory. The approach selected is based on the empirical observation that the pupil contrast gain and log psychophysical contrast sensitivity can both be described, to a first approximation, by a linear function of the logarithm of spatial frequency (Fig. 5). On such a graph, the pupil and perceptual visual acuities can be compared side-by-side because the pupil acuity can be estimated by extrapolating the pupil data down to a contrast gain of zero, whereas the perceptual acuity can be estimated by extrapolating the psychophysical data down to a contrast sensitivity of unity.

The pupil visual acuity was found to be 5.73 and 2.15 c/deg for the 0.12 and 0.0048 scot td illuminances respectively. Comparable psychophysical estimates from the literature for the 0.12 scot td level were 3.88 c/deg, derived from D'Zmura and Lennie (1986); and 4.77 c/deg derived from Hess, Nordby and Pointer (1987). A comparable psychophysical estimate for the 0.0048 scot td level was 3.08 c/deg; derived from Daitch and Green (1969). It should be noted that the results from D'Zmura and Lennie (1986) are based on the high frequency roll-off of their best-fitted theoretical curve, as the psychophysical results obtained at this low illuminance provide insufficient information for estimating spatial acuity.

We also investigated the psychophysical contrast sensitivity performance for two of our subjects. Most sets of data provided sufficient information from which we could derive an estimate of the contrast sensitivity for different retinal illuminances and spatial frequencies. However, the data obtained for 7.32 c/deg at 0.12 scot td (subject M) and for 1.90 and 2.98 c/deg at 0.0048 scot td (subject J) were not informative as the percentage correct at all contrast levels hovered around chance performance level (i.e. 33.33%).

The perceptual scotopic visual acuities for our subjects were based on their psychophysical contrast sensitivity functions (Fig. 5). The visual acuities for the 0.12 and 0.0048 scot td illuminances are, for subject M, 5.05 and 2.86 c/deg, respectively; and for subject J, 3.00 and 1.96 c/deg respectively.

DISCUSSION

The present results document that the pupil constricts in response to the appearance of scotopic (in addition to photopic) spatial patterns (Figs 1–3). In general, the amplitude of constriction decreases as the mean illuminance of the spatial pattern is reduced, but minute pupillary constrictions can still be measured at illuminances below the psychophysical cone threshold. Pattern-evoked responses may be recorded at even lower luminances, although our results make clear that such recording will require a greater amplitude resolution than available on our present system and a greater number of trials per stimulus condition to offset the relatively large spontaneous pupillary fluctuations.

Moreover, the present results document that scotopic, like photopic, pattern-evoked responses exhibit a spatial frequency dependent property. However, the high spatial frequency limit, or in Slooter and van Norren's terminology the visual acuity, is much lower for scotopic (Fig. 5) than for photopic (e.g. Slooter & van Norren, 1980; Barbur & Thompson, 1987; Cocker & Mosely, 1992) stimuli. The reduction of the pupil acuity with decreasing luminance parallels the reduction of perceptual visual acuity with luminance. Our estimate of the scotopic pupil visual acuity is similar to perceptual scotopic visual acuity in two of our observers and similar

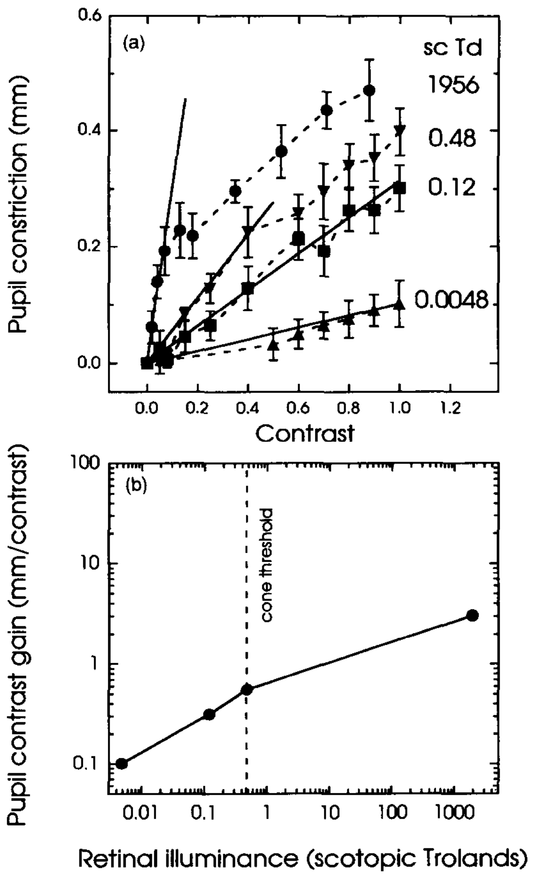

FIGURE 3. Contrast gain as a function of different retinal illumination levels. The grating spatial frequency is 0.27 c/deg. (a) Mean amplitude (± 1 SEM) of the averaged pupillary constriction obtained across all subjects plotted as a function of the grating contrast for four retinal illumination levels. Contrast gain is graphically illustrated by the initial slope of amplitude–contrast functions (solid lines). Data for the 1956 scot td level was adapted from a previous study (Young & Kennish, 1993) which used the same subjects. (b) Plot of pupil contrast gain derived from the top graph. The dashed lines indicates the mean psychophysical cone threshold for five subjects.

to the estimates derived from published psychophysical results (Daitch & Green, 1969; D'Zmura & Lennie, 1986; Hess *et al.*, 1987). Thus, we conclude that the similarity between the pupillary and perceptual visual acuity is not specific to photopic illuminance levels but, rather, is general to a wide range of levels, including scotopic illuminances.

The observation that spatial acuity can be assessed using the pupillary responses implies that the appropriate visual information must somehow reach the pupillomotor center. While little, if any, is known about the exact anatomical pathway through which such information passes, we speculate on two general possibilities. One possibility is directly from neurons dedicated to the processing of visual information. That is, the pupillary constriction is driven, for example, by signals from the visual cortex. A second possibility is that the pupillary constriction is driven by signals from another visuomotor center which received and processed the spatial visual information. For example, in cat, there is evidence that pupillary constriction nuclei receives input from areas of the cortex that are specialized in coordinating intraocular muscular movements such as in the near-reflex when lens accommodation is accompanied by pupillary constriction (Bando, Toda & Awaji, 1988). The present results do not discriminate between these two possibilities.

Pupillary studies in humans, however, do provide a few clues about the nature of the incoming visual information. The results of Barbur and Forsyth (1986) suggest that the pattern-evoked pupillary responses depend greatly on the geniculo-striate pathway. The results of Young and Kennish (1993) suggest that such pupillary responses are composed of functionally separable components. The main components include one with a temporally transient response waveform and a low-pass spatial filter property and a second with a temporally sustained waveform and a band-pass spatial filter property. Young and Kennish (1993) speculated that the components may reflect visual signals of neurons functionally similar to phasic (M-) and tonic (P-) cells.

The present results contribute information about the duplicity of the visual mechanism underlying the pattern-evoked pupillary responses. As is currently understood, mammalian retinal ganglion cells can be classified into those through which only cone signals travel and those through which both rod and cone signals travel (Daw, Jensen & Brunken, 1990). There are no ganglion cells through which only rod signals pass. Our results lead us to reject the possibility that the underlying visual mechanism has access to signals originating solely from ganglion cells that carry cone signals, as would have been supported if the pupillary and perceptual visual acuities were similar only at photopic illuminances.

Finally, the present results are relevant to the objective assessment of scotopic visual acuity for which few, if any, methods are currently available. While a study by Wu and Armington (1989) demonstrated the existence of scotopic pattern-evoked ERG and a study by Benedek, Janaky, Adamkovich, Rubicsek and Sary (1993)

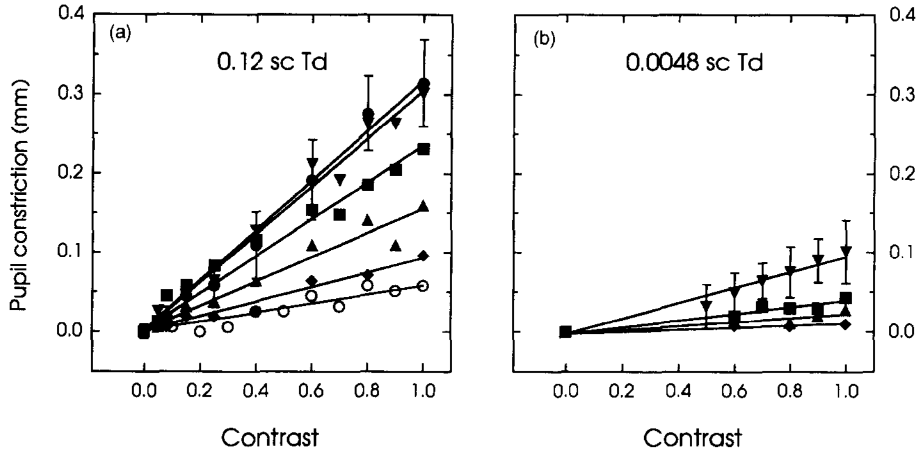

FIGURE 4. Mean amplitude of the averaged pupillary constriction obtained across all subjects as a function of grating contrast for several spatial frequencies at two retinal illumination levels, 0.12 scot td (a) and 0.0048 scot td (b). For the sake of clarity, error bars (±1 SEM) are only shown for the lowest spatial frequency condition. Solid lines graphically illustrate our computation of the contrast gain from the slope of the amplitude–contrast functions. The spatial frequencies are 0.14 c/deg (●), 0.27 c/deg (▼), 0.54 c/deg (■), 1.08 c/deg (▲), 1.90 c/deg (◆), and 2.98 c/deg (○).

demonstrated the existence of scotopic pattern-reversal VECP, neither study investigated the high spatial frequency limits of these scotopic responses. So there is little information indicating whether the pattern-evoked ERG or VECP provides an acuity estimate that is similar or dissimilar to perceptual scotopic visual acuity. Our results suggest the pupillary measure as a candidate method for assessing scotopic visual acuity because the pupil and perceptual visual acuities are similar. However, our support for the pupillary measure is balanced with two practical considerations. First, our success in recording responses from cooperative, college-age subjects may not be indicative of the testability of subjects from the optometric and ophthalmic patient population. Second, the pupillary response amplitudes evoked by scotopic patterns are minute in comparison to spontaneous pupillary fluctuations; thus, the recording procedure will likely require time-consuming repeated measurements.

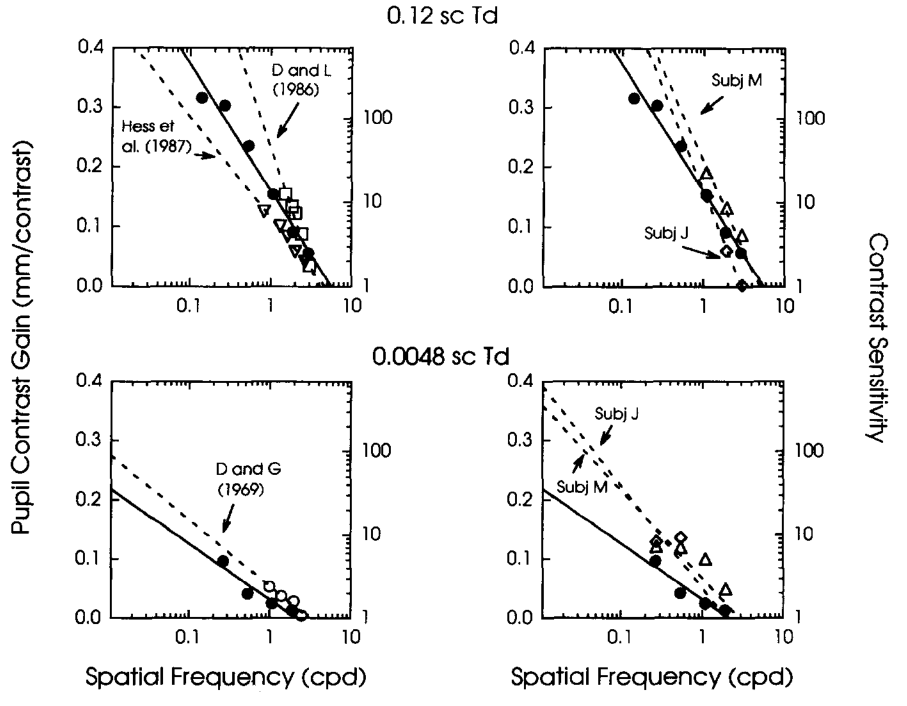

FIGURE 5. Comparison between pupillary (solid symbols) and perceptual (open symbols) scotopic spatial acuities obtained at about 0.12 scot td (top row) and 0.0048 scot td (bottom row). Pupil results are compared with published psychophysical results (left column) and psychophysical results obtained from subjects J and M (right column). Pupillary data are expressed as contrast gain (left ordinate), whereas psychophysical data are expressed as contrast sensitivity (right ordinate). Pupillary visual acuity is defined as the spatial frequency at which contrast gain equals zero, whereas psychophysical visual acuity is defined as the spatial frequency at which contrast sensitivity equals unity. Note that several of the psychophysical data points for subjects J and M are coincident with the pupillary data.

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