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13. ABSTRACT *(Maximum 200 words)*

This research project further developed and tested the first-ever practical suprathreshold contrast test chart (SCTS). The SCTS, which measures a family of suprathreshold contrast-matching curves, was found to be a valid and reliable test chart and extends our knowledge about spatial mechanisms in normal and abnormal vision by allowing extensive data collection due to its portability, and ease and speed of administration. Comparison of normative data collected in 336 eyes with data collected on patients having amblyopia, glaucoma and macular degeneration showed that the SCTS may be effectively used as an initial screening tool and for monitoring patients in clinical situations. Individual differences in contrast-matching curves, similar to those seen in contrast sensitivity, were seen in visually normal and clinical patients. The SCTS significantly predicts letter detection and discrimination above the predictive ability of contrast sensitivity by approximately 12%. This test may be used within a battery of tests to aid selection of visually capable individuals for driver's licensing, piloting, athletics and the military.

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(a) Research objectives and significant accomplishments

This Phase II research project entitled "Suprathreshold Contrast Sensitivity Vision Test Chart (SCTS)" further developed and tested a new vision test chart, the SCTS (Vision Sciences Research Corp.). This chart measures individual differences in normal and abnormal suprathreshold contrast perception in an easy, rapid and clinically meaningful manner. This project was centered around five goals:

(1) Optimize the design of the chart. The SCTS has been specifically designed to be fast, easy and inexpensive. A printing technique using a phototypesetter which interprets a Postscript program was found to produce multiple, high-quality contrast charts.

(2) Compare the results found with this new suprathreshold contrast sensitivity test chart to results found with computer-video systems. The first experiment revealed that the SCTS is a valid measure of suprathreshold contrast-matching curves.

(3) Determine the reliability of the vision chart. The second experiment revealed that practice on the task does not significantly alter contrast-matching estimates.

(4) Determine the relationship of suprathreshold contrast-matching estimates and real-world performance. The third experiment revealed that the SCTS generally enhances the prediction of performance in everyday visual tasks beyond the predictive ability of contrast sensitivity.

(5) Derive normal suprathreshold contrast-matching values based on a large population study. The fourth experiment provided normative data for 336 eyes in eight age decades and the data extend the findings of age-related changes in high spatial frequency contrast sensitivity to include low contrast suprathreshold contrast perception.

(6) Examine the diagnostic and assessment potential of the SCTS on clinical populations. The fifth experiment revealed individual differences in contrast-matching estimates in normal and clinical patients. The shape of the contrast-matching function differed in some amblyopes, glaucoma and macular degeneration patients from that obtained from normal control subjects.

(c) List of manuscripts in preparation

Ginsburg, A.P. and Beard, B.L. The validity of the SCTS suprathreshold test chart. Optom & Vis Sci.

Ginsburg, A.P. and Beard, B.L. Suprathreshold contrast test system reliability. Optom & Vis Sci

Ginsburg, A.P. and Beard, B.L. Suprathreshold contrast-matching predicts letter detection and discrimination. Vision Res

Ginsburg, A.P. and Beard, B.L. Large sample norms for contrast-matching using the SCTS. Am J Opt Physiol Opt

Ginsburg, A.P. and Beard, B.L. The screening potential of suprathreshold contrast-matching. Clin Vis Sci

(d) Professional personnel associated with the research effort

Arthur P. Ginsburg, Ph.D. 1980 Biophysics, Thesis title: Visual information processing based on spatial filters contrained by biological data.

Bettina L. Beard, Ph.D. 1988 Experimental Psychology, Thesis title: Crawford masking as a function of mask contrast and spatial frequency.

Martin Eggers, B.S. 1989 Mechanical Engineering

Heleni Korwik, B.A. 1990 Psychology

Bridgette Robinson, B.A. 1990 Psychology

(e) Interactions

(i) Ginsburg, A.P. and Beard, B.L. A novel suprathreshold contrast test chart. Paper to be presented at the Optical Society Meeting in San Jose, CA, November 1991.

(ii) AFHRL - Williams Air Force Base, regarding the pilot study pending.

(f) Patents A patent application is anticipated in the near future.

(g) Additional information

This highly successful SBIR II grant produced a final prototype from which a commercially viable product will be developed and marketed to the clinical and research communities. This unique product will, for the first time, determine suprathreshold contrast-matching estimates in a practical manner to clinicians and researchers.

The rationale, methods, results and discussion of the results for each of the five experiments will now be presented.

EXPERIMENT 1: SCTS TEST CHART VALIDITY

INTRODUCTION

Everyday visual perception requires the processing of complex objects whose important information is comprised of different sizes, or ranges of spatial frequencies, at just visible (threshold) and highly visible (suprathreshold) levels of contrast. Threshold contrast sensitivity measurements to simple patterns, such as sine-waves, have proven to be a powerful tool, greatly increasing the understanding of the function of spatial channels in the visual system and their role in visual perception. The multiple channels model, first proposed by Campbell and Robson (1968), used psychophysical evidence for the existence of spatial channels in vision, each channel having maximum sensitivity to a range of different sizes or spatial frequencies. More mature models based on visual channels have emerged (DeValois and DeValois, 1988; Ginsburg, 1978, 1986; Graham, 1989).

The contrast sensitivity of a range of different spatial frequency targets, sine-wave gratings, produces a bell-shaped curve called a contrast sensitivity function that describes the envelope of the separate responses of the multiple spatial channels. The psychophysical manipulation of the contrast sensitivity function has provided much understanding of how spatial channels process visual information (e.g., Graham, 1989). Similarly, the contrast sensitivity function has provided the clinician with powerful new information to detect early visual disease, monitor treatment and understand visual dysfunction (Arden, 1978; Bodis-Wollner, 1972; Comeford, 1983; Ginsburg, 1981; Hess and Woo, 1978; Regan, Silver and Murray, 1977). Finally, the contrast sensitivity function has been shown to be related to everyday visibility of objects ranging from letters and faces to complex military targets (Ginsburg, 1978, 1986; Ginsburg, Evans, Sekuler and Harp, 1982; Ginsburg, Easterly and Evans, 1983; Owsley, Sekuler and Boldt, 1981; Shinar and Gilead, 1987; Stager and Hameluck, 1986).

As powerful as the contrast sensitivity function is, it is not a complete description of contrast perception. Much of the contrast of the visual world is above threshold, at suprathreshold. Therefore, a more complete description of contrast perception should include visual sensitivity to spatial frequencies at suprathreshold levels of contrast. While the relationship of spatial frequency and contrast sensitivity is well understood (e.g., Sekuler, 1974; Ginsburg, 1981), the relationship between spatial frequency and suprathreshold contrast perception is less understood. In addition, no research has investigated the relationship between the perception of everyday objects and suprathreshold contrast perception.

Contrast-matching methods are often used to determine the relationship between apparent and physical contrast across spatial frequencies. In a contrast-matching task, observers are asked to match the apparent contrast of different spatial frequency gratings. Specifically, a grating of variable contrast (the comparison) is compared, and the contrast changed, to perceptually match the contrast of a grating of predetermined contrast (the standard).

Early contrast-matching studies (Blakemore, Muncey and Ridley, 1973; Georgeson and Sullivan, 1975; Watanabe, Mori, Nagata and Hiwatashi, 1968) found that a family of curves from just above threshold to high levels of contrast could be created in vision similar to the family of equal loudness curves in hearing (Scharf and Houtsma, 1986). This family of curves, seen in Figure 1, show that contrast-matching curves flatten with increases in contrast, that is, variations in apparent contrast as a function of spatial frequency become less pronounced as stimulus contrast is increased above threshold (Blakemore, Muncey and Ridley, 1973; Bowker, 1983; Bryngdahl, 1966; Georgeson and Sullivan, 1975; Watanabe, Mori, Nagata and Hiwatashi, 1968). The flattening results have been assumed to be due to a stage in the visual system that compensates for contrast sensitivity losses at threshold by increasing the gain of the system to low contrast gratings (Bowker, 1983). Gain increases not only as stimulus contrast increases, but also as the spatial frequency content of the stimulus varies from the most sensitive regions of each observer's contrast sensitivity function. This gain mechanism presumably operates to equate the apparent contrast of a suprathreshold stimulus to correspond more closely to its actual physical contrast.

These suprathreshold contrast-matching curves, revealing well-behaved changes from low to high contrast levels in normal vision, can change quite dramatically in certain cases of abnormal vision, such as amblyopia (Ginsburg, 1978, 1981; Hess, Bradley and Piotrowski, 1983; Loshin and Levi, 1983). The first suprathreshold contrast-matching curves to show abnormal channel behavior at suprathreshold contrast levels are shown in Figure 2 (Ginsburg, 1978). Note that the contrast matches at low spatial frequencies are similar to that of normal observers (compare to Figure 1). These curves demonstrate that at high comparison spatial frequencies, this amblyope matches the standard grating to a lower comparison contrast than do normal observers.

Contrast-matching estimates have been determined using various techniques, such as the method of adjustment and forced-choice procedures. In the method of adjustment the observer adjusts, by turning a dial, the comparison grating's contrast until it perceptually matches the contrast of the standard grating. Although this technique is rapid, it provides little control over an observer's response criterion, which results in large variability in contrast-matching estimates from trial to trial. Forced-choice designs are assumed to help control for response criterion variation (Swets, 1964). In a forced-choice task, the observer is asked to indicate which of two gratings has greater contrast. Using an adaptive forced-choice technique, the contrast of the comparison grating on a particular trial is determined by the observer's responses on previous trials. For example, two gratings of different spatial frequency may be presented either spatially or temporally separated and the observer may indicate which grating had the greater contrast. The contrast of the comparison grating is increased if the observer indicated that the comparison grating was of greater contrast and decreased if the observer indicated that the standard grating was of greater contrast. The contrasts of the comparison grating on different trials form a staircase going up and down around the contrast-matching estimate. Forced-choice methods, although allowing controls for observer response criterion changes, are time-consuming and therefore not convenient to use under clinical or research conditions.

Techniques using a photometric test chart for measuring threshold levels of contrast in a quick, simple and inexpensive manner have existed for several years (Ginsburg, 1984; Ginsburg and Evans, 1981). The Vision Contrast Test System (VCTS; Vistech Consultants, Inc.) has yielded data similar to large sample norms (Ginsburg, Evans, Cannon, Owsley and Mulvanny, 1984) which may be used in clinical settings to evaluate deficits in contrast sensitivity (Ginsburg, Osher, Blauvelt and Blosser, 1987; Rogers, Bremer and Leguire, 1987).

To date, contrast-matching estimates have required time-consuming, complex and expensive CRT displays to generate and control the spatial frequency and contrast of the gratings. No research has been devoted to the development of techniques for the rapid assessment of contrast-matching estimates. Normative contrast-matching curves have not been collected possibly because of the time-consuming methods available. In addition, the time-consuming methods used to generate contrast-matching curves is a major deterrent in routine use of contrast-matching estimates in clinical settings.

The research here investigates the validity of a rapid and inexpensive contrast-matching method which uses a chart format. The chart is called the Suprathreshold Contrast Test System (SCTS; Vision Sciences Research Corp.) and is schematically shown in Figure 3. In this experiment, the SCTS is compared to three contrast-matching estimation methods: the method of adjustment, spatial two-alternative forced-choice and temporal two-alternative forced-choice methods. If the new suprathreshold contrast-matching chart is measuring the same underlying visual mechanisms as those measured using the method of adjustment or forced-choice techniques, then the results should be similar between methods. If, however, the methods do not reveal similar contrast-matching curves, then the techniques could be using different visual processing. The following experiment shows that contrast-matching, similar to that obtained using time-consuming and complex computer video based techniques, may be determined quickly and easily in a chart format.

METHOD

Subjects. Eleven normally-sighted observers participated in this study. Ages ranged from 18 to 39 years (mean age, 21.8 years, SD = 5.6). All had Snellen acuities of at least 20/25 from the distances of 118 cm and 16 inches using Snellen and the Lighthouse Near Visual Acuity Test (ETDRS). The mean acuity of all subjects was 0.89 min arc (SD = 0.15) for the far distance and 0.90 min arc (SD = 0.21) for the near distance.

Procedure. Four contrast-matching methods, discussed below, were evaluated. A single experimental session involved testing only one method. Order of testing was randomized. Experimental sessions lasted no longer than an hour. Observers were allowed to take breaks as needed. All contrast-matching methods measured the contrast for which comparison gratings of 1.5, 3, 6, 12 or 18 c/deg perceptually matched the contrast of a 6 c/deg standard grating. Observers were instructed to match the darkness, or grayness of the bars of the grating and to ignore differences in the size or visibility of the bars. Five standard grating contrast levels were tested: 4%, 8%, 16%, 36% and 50%.

<u>Suprathreshold Chart</u>. The new suprathreshold contrast test system (SCTS) consists of five rows of grating patches, each row having a different comparison frequency (see Figure 3). Each row contains fourteen different contrast patches. The contrast of the comparison grating patches progressively decreases from left to right. The specific contrast values of the grating patches are provided in Table 1. All gratings are vertically oriented and subtend 1.6 degrees of visual angle when viewed from an 18 inch distance. Gratings were created by photographing computer generated sine-wave gratings having different spatial frequencies and contrasts. The mean luminance of the background was 160 cd/m^2, and of the grating patches was 100 cd/m^2.

A set of five standard grating patches could be moved on a fixed linear path beneath or above the row of comparison gratings. The task was to move the 6 c/deg standard gratings along the path until they were next to the comparison grating which appeared to be equal in contrast. These perceptual matches were made for the five standard grating contrast levels at the five comparison grating spatial frequencies in random order specified by the experimenter. A minimum of two measurements were taken for each condition in both eyes. The total measurement time took approximately 40 minutes.

Method of Adjustment. Sinusoidal grating stimuli were generated using the Prisma VR 1000 Grating Generator (Millipede Electronic Graphics) and were displayed on a CRT. The display consisted of two circular openings within a white surround separated by 4 cm. Each opening subtended 2.5 degrees visual angle from a viewing distance of 118 cm. Initially the screen displayed a preview of the grating to be judged. Observers were instructed to let their eyes wander over the screen to minimize the formation of afterimages. A hand-held response box contained a push button and an adjustable dial (10-turn linear potentiometer).

The observer was asked to press the button when ready to begin. Then, either one or two aural tones sounded to indicate that the contrast of either the left or right grating could be changed using the adjustable dial. The comparison grating contrast randomly began either above or below the contrast of the standard grating. When the observer had adjusted the contrast of the comparison grating to perceptually match the contrast of the standard grating, they pushed a button, their contrast match was recorded and a preview of the next condition was then displayed. There were two repetitions of each condition.

Spatial Two-Alternative Forced-Choice (spatial 2AFC). The same apparatus described for the method of adjustment was used for the spatial 2AFC method. A preview of the standard grating was provided to reduce uncertainty about its contrast and spatial frequency. Observers were asked to gaze in the area between the two gratings, not to look directly at either grating. Observers held a response box containing two buttons. To begin the session either button could be pushed. A warning tone signalled the occurrence (500 msec later) of two simultaneously presented grating patterns of 500 msec duration. The task was to determine whether the left or right grating contained the greater contrast by pushing one of the two response buttons. Interstimulus interval was one second in duration. A set of trials consisted of 12 contrast reversals. A reversal in contrast was defined as a change in the direction of a contrast increment or decrement in the comparison grating (50% tracking criterion). The geometric mean of the last 10 reversals determined the contrast match for that condition.

Temporal Two-Alternative Forced-Choice (temporal 2AFC). The same apparatus described for the method of adjustment was used for the temporal forced-choice procedure except that the display contained only one opening. Observers were instructed to let their eyes wander over the screen. The observer pushed a response button to begin the session. Two 500 msec intervals, separated by 500 msec and demarcated by warning tones were then presented. The task was to indicate whether the first or second interval contained the grating of greater contrast. Again 12 reversals in contrast were recorded with the last 10 determining a contrast match for that condition. A 50% tracking criterion was again used.

RESULTS

Although there were individual differences in contrast-matching data that will be discussed later, the overall results for each of eleven observers revealed the same general trends. For this reason Figure 4 displays the combined results of all observers.

Contrast-matching curves across spatial frequency can be seen in Figure 4 for the method of adjustment (panel a), temporal 2AFC (panel b), spatial 2AFC (panel c) and the SCTS chart (panel d). The standard grating was set to five contrast levels: 4% (open squares), 8% (filled triangles), 16% (open triangles), 36% (filled circles) and 50% (open circles). For all methods, at the lower standard contrasts, contrast matches for higher and lower spatial frequencies than the standard grating (6 c/deg) are made for gratings which are of a higher contrast than the standard, consistent with previous findings (e.g., Georgeson and Sullivan, 1975). All methods show a flattening of the contrast-matching functions as the contrast of the standard is increased, also in agreement with other reports in the literature (Blakemore et al., 1973; Bowker, 1983; Bryngdahl, 1966; Georgeson and Sullivan, 1975; Ginsburg, 1978, 1981; Watanabe et al., 1968).

The four methods showed similar contrast-matching estimates at 16%, 36% and 50% standard contrasts. The two forced-choice methods did not show significantly different contrast-matching estimates under any conditions. The method of adjustment showed significantly different contrast-matching thresholds from the two forced-choice methods at 4% and 8% standard contrast at 1.5, 3 and 18 c/deg. Contrast-matching estimates obtained using the SCTS differed from the spatial 2AFC method at 4% standard contrast at 1.5, 6, 12 and 18 c/deg and at 8% at 1.5 and 18 c/deg. The SCTS significantly differed from the temporal 2AFC method at 4% standard contrast at 1.5, 6 and 12 c/deg and at 8% standard contrast at 18 c/deg. Finally, the SCTS differed from the method of adjustment only at 4% standard contrast at 6 and 12 c/deg.

DISCUSSION

This research determined the validity of a new contrast-matching chart, the SCTS, by comparing the chart data to that of three commonly used psychophysical techniques. The SCTS produces contrast-matching curves statistically similar to those obtained using spatial and temporal two-alternative forced-choice methods at 16%, 36% and 50% standard contrasts. The SCTS contrast-matching curves approximate those obtained using the method of adjustment at all standard contrasts.

One possible reason that the low standard contrast SCTS contrast-matching curves are similar to those measured with the method of adjustment but different from the 2AFC methods may relate to the duration of stimulus presentation. Processing time of low and high spatial frequency gratings differ at low contrasts but not at high contrasts (Kulikowski, 1975). The method of adjustment and SCTS chart both allow unconstrained viewing time. The shorter stimulus duration of the 2AFC methods will increase contrast threshold of the low spatial frequencies (Kelly, 1961). This shorter viewing time may differentially affect the lower contrast levels resulting in similar findings at low contrasts for the method of adjustment and SCTS chart while contrast-matching curves obtained at higher standard contrasts are similar between all four methods. A major criticism of the method of adjustment and SCTS could be that free inspection of the gratings could result in large adaptation effects particularly at higher contrasts (Blakemore, Muncey and Ridley, 1971). The results of this study support the findings of Kulikowski (1976) showing that there is little difference between the method of adjustment with unconstrained viewing time and forced-choice methods at high contrast.

At low standard contrasts, SCTS contrast-matching curves showed reduced sensitivity at low spatial frequencies compared to the CRT methods. Some of this difference may be due to the reduced display size of the SCTS. Each grating patch on the SCTS subtended 1.6 degrees of visual angle while CRT display sizes were 2.5 degrees of visual angle. Cannon and Fullencamp (1988) have demonstrated that for contrasts below 6%, sensitivity is reduced with decreases in display size. That the SCTS grating patch size was 1.1 degree VA smaller than the CRT displays may explain the decreased sensitivity found at 5% standard contrast using the SCTS chart.

Some differences seen between the SCTS chart and the CRT methods at low standard contrasts may be due to the use of polaroid film for chart grating generation. Obtaining precise contrast levels was difficult to accomplish using polaroid film at very low contrasts. For this reason, future versions of the chart used better photographic techniques to generate more precise contrast for the gratings.

The SCTS was designed for the rapid testing of contrast-matching estimates. To obtain a single contrast-matching estimate for five comparison spatial frequencies at five standard contrast levels using the method of adjustment, temporal 2AFC, spatial 2AFC and SCTS chart were on average 30 minutes, two hours, 1.5 hours and 40 minutes, respectively. Since the SCTS chart resulted in contrast-matching estimates similar to those of the two criterion-free forced-choice techniques but three times faster, it is clearly a more practical suprathreshold contrast-matching testing instrument. Future research needs to determine and compare the reliability, specificity and sensitivity of each testing method.

Measurement of suprathreshold contrast perception extends our knowledge about spatial mechanisms in the visual system beyond that possible from threshold measures alone. In addition, such a testing chart may be useful for the initial screening and monitoring of patients in clinical situations and will be particularly useful when patients have a limited attention span. Observers found the instructions for the SCTS chart easy to understand and the task easy to perform. The simplicity of the instructions and task should benefit research and clinical settings with patients having cognitive impairment. In summary, the SCTS chart is valid, measures a family of contrast-matching curves rapidly, shows low variability and is simple to administer.

EXPERIMENT 2: SCTS TEST CHART RELIABILITY

INTRODUCTION

The Suprathreshold Contrast Test System (SCTS) is a rapid testing chart which measures a family of suprathreshold contrast-matching curves. The previous experiment has shown that the SCTS is a valid measure of contrast-matching. A critical question regarding the SCTS chart is whether it is reliable and may be used repeatedly to monitor the course of visual disease development as well as normal developmental changes.

Classical Test Theory (Allen and Yen, 1979; Thorndike and Hagen, 1977) requires, among other things, that tests be reliable. Reliability means that repeated measures are stable. The lack of reliability means that a test is insensitive to changes due to the progression of disease. Reliability is needed if changes in visual function are to be meaningfully related to changes in suprathreshold vision. When a test is reliable then systematic differences in time-course changes such as learning or fatigue are absent. It is important to determine it the SCTS is reliable and not subject to changes due to practice effects or to shifts in response strategies. The lack of reliability could disguise deterioration in visual function or improvement due to medical intervention.

To determine the reliability of the chart in repeated applications, it is important that repeated measurements on the SCTS chart be intercorrelated, or systematically correspond. In addition, before inferences can be made about the charts' relationship with visual performance, it is also important to establish the test-retest reliability of the testing method. This experiment tests the reliability of the SCTS suprathreshold chart.

METHODS

Subjects. Seven observers were tested in this experiment whose ages ranged from 22 to 42 years (mean age, 34.4; SD = 7.2). The mean acuity of all observers was 0.91 min arc (SD = 0.10) from the test distance of 18 inches. Observers were free from eye disease as indicated by self-report.

Procedure. Contrast-matching curves were obtained using the SCTS chart. Previous to this investigation the chart format involved circular grating patches (1.6 degrees visual angle) which had a mean luminance of 100 cd/m^2 and background mean luminance of 160 cd/m^2. Thorn (1990) suggested that an aliasing artifact is an inherent part of small field gratings with sharp edges and lower luminance than the surround. This was anticipated as a potential problem by Ginsburg (1982). The aliasing may involve an interaction between the grating with its own edges resulting in low frequency beats. To avoid any potential aliasing problems, the chart was modified by tapering the grating edges in a Gaussian profile and making the grating and background mean luminance the same (50 cd/m^2). This has the advantage that contrast matches may be found for different spatial frequency gratings without varying the mean light level to which the eye is adapted, reducing the effects of negative afterimages. The resulting gratings subtend 1.98 degrees of visual angle from a distance of 18 inches.

The SCTS chart consists of five rows of fourteen vertically oriented comparison grating patches (see Figure 5). The gratings on each row are a different spatial frequency. The contrast of the grating patches on each row decreases from left to right, ranging from 42% to 1.4% on row A (1.5 c/deg), 45.5% to 1.4% on row B (3 c/deg), 65% to 2% on row C (6 c/deg), 65% to 8% on row D (12 c/deg) and 70% to 4% on row E (18 c/deg). The specific contrast values of the grating patches fit the following equations (except for the 14th patch on rows A and B which equal 1.4%):

Rows A-B: C(p) = r - ((10^(m*p+b))/(m * ln(10))) * 0.7
Rows C-E: C(p) = r - ((10^(m*p+b))/(m * ln(10))) * 1.0

where C is the percent contrast, r is a constant, m is the slope, b is the y axis intercept and p is the grating patch number. These equations were based on the results of a pilot experiment which determined the just noticeable difference (JND) in contrast between two gratings of the same spatial frequency using the method of adjustment on a CRT display. Four subjects were asked to adjust the contrast of one grating while the contrast of a second grating was held constant at either 5%, 10%, 20% or 50% contrast. JNDs for each of the four subjects were similar. The best fitting line for the JND data was calculated for the averaged data of the four subjects.

A set of five standard grating patches (6 c/deg) can be moved on a fixed linear path above or below the row of comparison gratings. The five standard grating contrasts are 5%, 9%, 19%, 35% and 56%. The task was to move the standard patterns along the path until they were next to the comparison pattern which appeared to be equal in contrast. These judgments were made for the five standard grating contrast levels at the five comparison spatial frequencies in a random order. A minimum of two measurements were taken for each condition. This procedure was repeated over four nonconsecutive test days.

RESULTS

These data are first analyzed statistically, then graphically to determine the reliability of the SCTS. A common way to estimate reliability is to average all of the correlations in an inter-trial correlational matrix (e.g., Kennedy and Dunlap, 1990). Test-retest correlations were computed between the eight trials, resulting in

28 correlational matrices for the five spatial frequencies and five contrast levels. Each matrix supplied information as to the relationship between trials, or repetitions. The average correlation of each matrix remained the same from r = 0.59 for the correlational matrix relating trials 1 and 2, to r = 0.54 for the correlational matrix relating trials 1 and 8. This result suggests similar, moderate reliability from the first to the eighth trial.

The individual test-retest reliabilities were variable within a matrix suggesting that different test conditions have different reliability. Average test-retest reliabilities of the 28 matrices are shown in Table 2. These reliabilities range from weak (r = 0.25) to strong relationships (r = 0.95). To determine if any one spatial frequency or standard contrast led to less reliable responses, correlations were collapsed across these two variables. These test-retest reliabilities average to $r \geq 0.70$ for all spatial frequencies except 3.0 c/deg; specifically, r = 0.70 for 1.5 c/deg, r = 0.40 for 3 c/deg, r = 0.77 for 6 c/deg, r = 0.71 for 12 c/deg and r = 0.79 for 18 c/deg. Test-retest reliabilities were high for 9% and 19% standard contrasts; r = 0.64 for 5%, r = 0.82 for 9%, r = 0.80 for 19%, r = 0.62 for 35% and r = 0.48 for 56% standard contrast. Thus, the average test-retest reliabilities between 8 trials on the SCTS were high for four of five spatial frequencies ($r \geq 0.70$) and two of five standard contrasts ($r \geq 0.80$). Test-retest reliabilities were average for two of the remaining standard contrasts ($r \geq 0.62$). In summary, except for the 3 c/deg test condition, the average reliabilities were high. One possible explanation for the low test-retest reliabilities at 3 c/deg could be because subjects performed similarly across trials, choosing the same comparison grating patch. These similar responses reduced variability causing between trial correlations to fall to zero.

Minimal practice effects can be seen graphically. Figure 6 shows the average contrast-matching estimates over 8 trials (2 repetitions x 4 test days). Panel a presents the data for a comparison spatial frequency of 1.5 c/deg, Panel b for 3 c/deg, Panel c for 6 c/deg, Panel d for 12 c/deg and Panel e for 18 c/deg. Each panel contains the data for the five standard contrasts tested: 5% (open squares), 9% (filled triangles), 19% (open triangles), 35% (filled circles) and 56% (open circles). Average contrast-matching estimates were extremely reliable over all conditions except over the first trial at the highest standard contrast and comparison spatial frequency (Panel e). This lack of reliability may be explained by the increased task difficulty for most observers at the highest standard contrast and comparison spatial frequency. Initially many observers reported some difficulty ignoring the reduced visibility of the 18 c/deg comparison gratings due to the smaller width of the grating bars, and tended to match the 56% contrast standard grating to the highest contrast comparison. After one repetition, the observers were able to attend only to the comparison grating contrast, ignoring the grating bar width. In general, there are no obvious practice effects over trials in Figure 6.

Reliability can be improved by averaging the repeated measurements within a session. The Spearman-Brown relationship (Allen and Yen, 1979) maintains that the average of the repeated measurements within a session will always have greater reliability than the individual measurements that made up the average. Since an analysis of variance for repeated measures determined that there were no significant differences among the two trials within a session ($F(1,6) = 1.43$, $p > 0.05$) or between the four sessions ($F(3,18) = 1.01$, $p > 0.05$) averaging the data within a session seemed justified. With four sessions, this yielded six correlations for each spatial frequency. The mean of these six values was taken as the reliability for that condition. Table 3 contains the average test-retest reliabilities for the two-measure average thresholds. These reliabilities range from $r = 0.33$ to $r = 0.98$ averaging $r \geq 0.76$ for all spatial frequencies except 3 c/deg. Specifically, $r = 0.76$ for 1.5 c/deg, $r = 0.57$ for 3 c/deg, $r = 0.80$ for 6 c/deg, $r = 0.77$ for 12 c/deg and $r = 0.82$ for 18 c/deg. Test-retest reliabilities were high for 9% and 19% standard contrasts. Specifically, $r = 0.67$ for 5%, $r = 0.88$ for 9%, $r = 0.87$ for 19%, $r = 0.71$ for 35% and $r = 0.59$ for 56% standard contrast. Thus, the average test-retest reliabilities between 4 sessions on the SCTS were high for four of five spatial frequencies ($r \geq 0.76$) and two of five standard contrasts ($r \geq 0.87$). Test-retest reliabilities were average for the remaining two standard contrasts ($r \geq 0.67$). In summary, reliability was increased by averaging the repeated measurements within a session.

DISCUSSION

In general, the test-retest reliability of the SCTS suprathreshold chart is high for most test conditions, most correlations were ≥ 0.76. However, for some test conditions, correlations fell below 0.76. In these test conditions, however, subjects performed similarly, choosing the same comparison stimulus. For example, most observers chose the fourth comparison patch as a match to the 35% standard contrast at 3 c/deg. In conditions where the same patch was chosen by most observers, between-trial correlations fell to zero because of no variability in responses, which may be mistaken for low test-retest reliability.

To ensure that the SCTS is a useful vision test, practical considerations are also important (Kennedy et al., 1987). First, the test should be easy to administer. It was found that simple verbal or written instructions are sufficient to explain the procedure to naive observers. In most cases, observers can be taught to record their own answers. Observers find the method easy to understand and perform. In addition, the SCTS is portable and may be taken to different sites for administration. Second, the test should have a short administration time. Compared to a minimum of 1.5 hours required to obtain two measurements on 25 conditions using a CRT based system, the SCTS requires only 40 minutes for two repetitions in both eyes. Third, the test should accurately measure suprathreshold vision. The data obtained using the SCTS chart is comparable to CRT based computer systems. Fourth, the test should be economical. Compared to CRT based systems, the SCTS is only a fraction of the cost. Fifth, the test should have a short time to stability. The present study demonstrated that the SCTS chart is a reliable measure of contrast-matching estimates.

In summary, the SCTS test chart may be used as a reliable screening tool in adults providing similar data from the first to the eighth trial. Reliability of measurements was found in the trial-to-trial correlations. This reliability is important since it implies that measurements do not change as a function of practice and so the charts predictive ability would not change with repetitions. The demonstrated reliability of the SCTS suggests that in addition to practical effectiveness, the chart possesses other desirable psychometric attributes. This new suprathreshold test chart will allow more extensive data collection due to its low cost, high reliability, high validity, portability and ease and speed of administration. This increased data collection will in turn increase our scientific and clinical understanding of how visual channels behave at suprathreshold contrast levels in normal and abnormal vision.

EXPERIMENT 3: PREDICTING REAL-WORLD VISUAL PERFORMANCE

INTRODUCTION

Attempts have been made to find simple measures which accurately predict an individual's visual performance in the real world. If predictive tests can be established, these tests may be used to aid selection of capable individuals for driver's licencing, piloting, athletics and the military. As an understanding of the basis of visual performance increases, then an evaluation of the effects of other factors on vision in terms of this basis, such as aging, pathology or drugs, may be specified, and training procedures recommended.

Conventional evaluation of visual performance has emphasized tests of visual acuity, or the ability to see small, high contrast letters. For over a century it has been recognized that visual acuity is weakly related to visual performance (Galton, 1885; Koga and Morant, 1923; Leibowitz, Post and Ginsburg, 1980; Leibowitz, Post, Brandt and Dichgans, 1982; Merritt, Newton, Sanderson and Seltzer, 1978). One reason for the poor predictive ability of acuity measures is that many visual tasks involve relatively large objects presented at degraded contrast levels that acuity cannot measure (Ginsburg 1978, 1981, 1986).

Contrast sensitivity measures a range of object sizes, or spatial frequencies, and has been shown to relate to the ability to see objects in everyday contexts. Marron and Bailey (1982) found that contrast sensitivity predicts orientation and mobility performance in a test course for low vision patients. Evans and Ginsburg (1985) found a relationship between contrast sensitivity and the distance at which observers could discriminate road signs. Letter identification (Ginsburg, 1978), facial discrimination (Owsley, Sekuler and Boldt, 1981) and aircraft identification (Ginsburg, Evans, Sekuler and Harp, 1982; Ginsburg, Easterly and Evans, 1983) are also highly related to contrast sensitivity.

Although contrast sensitivity is a better predictor of real-world visual performance than acuity, it does not account for all of the variance associated with performance related tasks. For example, vision test batteries need to be developed which better predict visual performance than contrast sensitivity alone. For example, much contrast information is seen above visual threshold. Since much of the visual world consists of different sized objects presented above threshold, another possible predictor of real-world visual performance may involve the ability to see suprathreshold levels of stimulus contrast.

The study reported here uses a contrast-matching method to investigate the relationship between suprathreshold contrast perception and the detection and discrimination of complex objects.

In a contrast-matching task, observers are asked to match the perceived contrast of different size, or spatial frequency, patterns. One pattern, the standard, has an intermediate spatial frequency and the other pattern, the comparison, is either a higher or lower spatial frequency than the standard. At low contrast levels, normally sighted observers match the standard pattern to higher comparison contrasts. At high contrast levels, observers match the standard pattern to physically equal comparison contrasts. By matching different standard contrasts to comparison patterns of several spatial frequencies, a family of contrast-matching curves is obtained.

A rapid technique of obtaining a family of contrast-matching curves is the Suprathreshold Contrast Test System (SCTS). The SCTS is a vision test chart composed of five rows of vertically oriented comparison gratings of different spatial frequencies and three sets of five standard gratings. These gratings gradually decrease in contrast from left to right. The task is to push each standard grating along a track until the grating is positioned next to the comparison grating having the same apparent contrast. The SCTS measures a family of contrast-matching curves quickly, reliably and inexpensively and provides estimates which are similar to time-consuming and expensive computer-based systems.

Although the SCTS can generate practical contrast-matching curves, the question remained as to the capability of the data to help predict visual performance. Several performance related questions are addressed in this research. First, how well can contrast-matching curves predict real-world visual performance, such as the detection and discrimination of faces and letters? Second, can contrast-matching curves be predicted by the contrast sensitivity function? If so, then what additional information, if any, about visual performance can suprathreshold contrast-matching provide? Finally, do contrast-matching estimates at different standard contrasts relate to each other or provide different information about visual performance?

METHODS

Subjects. Nineteen normal eyes were tested. Observer ages were 14 to 72 years (mean age 43.8 years old, SD = 15). All observers wore normal corrective lenses during testing.

Procedure. Observers were tested monocularly on several tasks: near visual acuity, contrast-matching estimates on the SCTS chart, the detection and discrimination of faces and letters, and contrast sensitivity. The order of testing on these tasks was randomized. Experimental sessions lasted no longer than an hour. Observers were allowed to take breaks as needed. Specifics on each task will now be discussed.

Visual Acuity. Monocular visual acuity was measured using a

Lighthouse Near Visual Acuity Test (2nd ed) modified ETDRS. The average monocular acuity (minimum angle resolvable) for the observers was 1.06 (SD = 0.14).

Contrast-matching Estimates. A description of the procedure and stimulus conditions for the SCTS chart are provided in the Methods section of Experiment 2.

Performance Tasks. Contrast thresholds were measured for the detection and discrimination of faces and letters. Targets were digitized and displayed on an IBM 4055 monitor. Face targets were of male and female adults with no distinguishing extraneous characteristics. Hair and clothing were masked by a white/grey surround. Letters were helvetica type. Each trial contained either two faces or two letters. Half of the trials were of the same person or letter and half of the trials were different. Only one target type was tested in a single session.

An adaptation pilot study was conducted to determine what spatial frequency was strongly influenced for faces and letters in order to estimate the contrast threshold and contrast-matching conditions which would predict performance. From previous studies (Ginsburg, 1978), larger faces require relatively low spatial frequencies for discriminations while small letters require high spatial frequencies. Face targets subtended 3.0 degrees of visual angle and letters subtended 0.09 degrees of visual angle. Two observers, one of the authors and a naive observer, initially adapted for five minutes to 12 sine wave gratings ranging from 1 to 15 c/deg. Order of testing was randomized. Immediately following adaptation, observers indicated when they could just detect the presence of the faces or letters. Following the detection threshold estimate, the target contrast was increased until the observer could correctly discriminate whether the same or a different face or letter was being presented. Two measurements were taken at each of the 12 adapting frequencies. Control conditions were determined by obtaining detection and discrimination thresholds without adaptation. Detection and discrimination thresholds of faces and letters were found to be optimally effected by adaptation to a 3 and 12 c/deg grating stimulus, respectively.

Viewing was monocular for the performance task. The observers indicated on a response pad when anything was just detectable on the screen as the computer program gradually increased the stimulus contrast in 0.14% per second contrast steps. The subject was then asked to indicate on the response pad when they could discriminate whether the stimuli were the same face or letter or whether they were different. This method obtained both a measure of detection and discrimination thresholds. There were 16 face, and 14 letter, pairs tested in random order. Detection and discrimination performance was defined as the mean of the contrast threshold of the repeated measurements.

Contrast Thresholds. Monocular contrast sensitivity measurements were obtained using the VCTS chart. Three measurements were made for each eye using the three test chart versions, each version having different randomly oriented gratings to help prevent memorization. Contrast threshold measures were taken on 1.5, 3, 6, 12 and 18 c/deg sine wave gratings. Chart mean luminance was 144 cd/m^2. Contrast sensitivity for each spatial frequency was defined as the mean of the contrast threshold of three repeated measurements.

RESULTS

Four separate repeated measures analysis of variance for acuity, contrast-matching, performance and contrast sensitivity were performed. Since observer ages ranged from 14 to 72 years, observers were divided into three age groups: young, 14-38 years, N=7; middle-aged, 41-51 years, N=8; and older, 62-72, N=4. The acuity analysis results revealed that there was a significant decline with age in minimum angle resolvable ($F(2,16) = 3.85$, $p < 0.05$) consistent with previous reports (e.g., Gittings and Fozard, 1986).

Figure 7 presents the averaged contrast sensitivity and contrast-matching data for the three age groups: young (circles), middle-aged (squares) and older (triangles) adults. Contrast sensitivity data (CSF) demonstrated the usual age-related declines at high spatial frequencies as revealed by a significant age x spatial frequency interaction ($F(8,64) = 3.13$, $p < 0.01$) (e.g., Derefeldt, Lennerstrand and Lundh, 1979). Overall age differences in contrast-matching were not statistically significant as shown by the age x spatial frequency x standard contrast interaction term ($F(32,256) = 1.19$, $p > 0.05$).

Figure 8 presents the sensitivity data of young, middle-aged and older adults for the detection and discrimination of faces and letters. As expected, discrimination thresholds are higher than detection thresholds for all observers ($F(1,16) = 100$, $p < 0.0001$). Older observers show clear deficits in their ability to detect and discriminate these everyday objects ($F(2,16) = 13.5$, $p < 0.001$). These results are consistent with those of Owsley et al. (1981).

Much research designed to determine the relationship between visual measures taken in the laboratory and real-world performance have looked at simple Pearson-product moment correlation coefficients (Evans and Ginsburg, 1985; Ginsburg, Evans, Sekuler and Harp, 1981; Kruk, Regan, Beverely and Longeridge, 1981; O'Neal and Miller, 1987). Using a simple regression analysis, the results reported here are consistent with previous reports suggesting that contrast sensitivity and age are good predictors of the detection and discrimination of everyday objects while visual acuity is not. However, when more than one independent variable is used as in the present study, i.e., acuity, age, contrast sensitivity at five spatial frequencies, contrast-matching at five spatial frequencies and five standard contrasts, simple regression analysis may not be the appropriate analytical method because this type of analysis overlooks the possibility that the independent variables may be intercorrelated (Pedhazur, 1982). The independent variables may interact in their effects on the dependent variable, such as face detection, etc. To account for possible intercorrelations, a stepwise multiple regression analysis, with forward stepping, was performed on each dependent variable. This procedure initially selects the independent variable which best predicts detection or discrimination performance based on the amount of between-subject variance in performance. The statistical procedure then selects from the remaining independent variables that variable which increases predictability the most when combined with the first variable. Table 4 lists the 4 dependent variables and the 32 independent variables analyzed, including the separate spatial frequencies and standard contrast values used for contrast-matching.

To evaluate how effectively the independent variables predict the detection and discrimination of faces and letters, four separate multiple regression analyses (for each of four dependent variables) were performed on the data. As shown in Table 5, the multiple regression analyses selected the independent variables which best predicted detection or discrimination thresholds. Statistically significant (alpha = 0.05) independent variables are listed in the order of entry into the model. The results suggest that face detection was best predicted by contrast thresholds (CSF) at 18 c/deg. In the case of the remaining three dependent variables, age was the best predictor of contrast thresholds for real-world targets.

Observer age is known to relate highly to acuity (e.g., Gittings and Fozard, 1986), sine-wave contrast thresholds (e.g., Derefeldt, Lennerstrand and Lundh, 1983) and detection and discrimination thresholds for real-world targets (Evans and Ginsburg, 1985; Ginsburg, 1978; Ginsburg et al., 1982; Ginsburg et al., 1983; Marron and Bailey, 1982; Owsley, Sekuler and Boldt, 1981). Our data also show that age correlates highly to performance. Since age adds little additional information and may mask the effects of the other independent variables, the regression analysis was repeated excluding age. Table 6 presents the best-fitting model for each dependent variable with age excluded from the model. The models which excluded age as an independent variable accounted for less variance on average (45%) than the models which incorporated age as a predictor (62%). The percentage of variance in the data accounted for by each model (R^2) is also shown. The general result was that high spatial frequency (18 c/deg) contrast sensitivity (CSF), not acuity, emerged as a significant predictor of face detection and discrimination. Letter detection and discrimination was best predicted by contrast sensitivity at 12 c/deg and contrast-matching (CM) at 12 c/deg and 19% standard contrast with contrast sensitivity as the first predictor for these threshold tasks. Including contrast-matching into the model accounted for an additional 12% of the variance. Thus, when intercorrelations between the independent variables are taken into account, contrast sensitivity at 12 c/deg and contrast-matching estimates at 19% standard contrast and 12 c/deg comparison stimulus are good predictors of letter detection and discrimination. The predictive ability of 12 c/deg gratings was expected since a pilot experiment found that the letter stimuli were optimally effected by a 12 c/deg adapting grating.

To determine if contrast-matching estimates can be predicted by contrast threshold measures, an intercorrelation matrix was constructed between contrast sensitivity and contrast-matching data. In general, contrast sensitivity and contrast-matching scores are correlated at low standard contrasts and are therefore not independent (see Table 7). Thus, contrast sensitivity measurements may generally predict contrast-matching estimates under some low contrast conditions and high spatial frequencies (i.e., 5% standard contrast and 18 c/deg comparison spatial frequencies). The significant relationship between contrast sensitivity and low contrast-matching can help explain why lower standard contrasts were not good predictors or add little information about everyday performance in the regression analysis discussed earlier. These results also imply that contrast-matching data may provide unique information about contrast perception at higher contrasts. This result was expected since contrast gain mechanisms are activated at contrasts above 10% (Georgeson and Sullivan, 1975).

It is important to know if contrast-matching responses at one standard contrast could be used to predict contrast matches at other standard contrasts. To test this possibility, correlation coefficients were computed between contrast matches made at different standard contrasts for each spatial frequency. Strong and statistically significant correlations were found (see Table 8) for standard contrasts just above and below the test contrast, with an abrupt falloff in the correlation coefficients as standard contrast increased or decreased from the test contrast. This suggests that contrast matches made at one standard contrast can not be used to predict contrast matches at other standard contrasts. There is a falloff in the relationship between contrast matches made at different stardard contrasts as contrast is increased or decreased. This was found at all spatial frequencies.

Discussion

The current research used multiple regression analysis to investigate how well measures of acuity, contrast sensitivity, and contrast-matching predict the detection and discrimination of faces and letters. The results of this research suggest that threshold and suprathreshold contrast are predictive of an observer's visual performance in the real world. Contrast threshold alone can account for 40% and 56% of the variance associated with letter detection and discrimination respectively, while certain suprathreshold contrast-matching data can account for an additional 12% of the variance for both tasks. Variance associated with the detection and discrimination of faces can be attributed to contrast threshold task only, which accounts for 27% and 31% of the variance, respectively. If an observer has lower sensitivity to high spatial frequencies, that observer will have difficulty detecting and discriminating faces and letters. In addition, if an observer matches the contrast of an intermediate spatial frequency grating to that of a higher frequency grating with lower physical contrast, that observer will have difficulty detecting and discriminating letters. Contrast sensitivity and suprathreshold contrast-matching estimates can be used by clinicians to better predict the everyday visual problems of patients.

Contrast sensitivity and suprathreshold contrast-matching were found to be highly correlated only at certain low standard contrasts and high spatial frequencies. This finding is in agreement with that of Georgeson and Sullivan (1975) who found contrast constancy at contrast levels above 10%. Suprathreshold contrast matches at high standard contrasts are relatively independent of the contrast sensitivity function. Apparent and physical contrasts across spatial frequency are similar at suprathreshold contrast levels.

Strong correlations were found between contrast-matching estimates for neighboring standard contrasts within a spatial frequency. This relationship between neighboring contrasts suggests that the responses of contrast mechanisms in normal observers are selective to a range of contrast levels. This selectivity may be similar to the bandwidths seen for spatial frequency mechanisms (e.g., Blakemore and Campbell, 1969).

A pilot experiment (see Methods section) found face stimuli to be maximally effected by adaptation to 3 c/deg stimuli, however, in the actual experiment, detection and discrimination of faces was predicted by contrast sensitivity at 18 c/deg. This apparent contradiction may be because observers in the pilot experiment worked in these laboratories and were very familiar with the faces used in the experiment, whereas, naive observers from outside of the laboratory, were used in the actual experiment. Results suggest that both low and high spatial frequency information can be used in the recognition of faces (Fiorentini, Maffei and Sandini, 1983; Ginsburg, 1978, 1981). Discriminating between two unfamiliar faces may involve high frequency detection. On the other hand, holistic cues or lower spatial frequencies, may be used for the discrimination of familiar faces. It is possible that observers in the pilot adaptation experiment and those in this study were using different cues to discriminate the faces. This possibility was borne-out since verbal reports of naive observers revealed that many were detecting and discriminating the eyes within the faces.

In support of previous work (Owsley and Sloane, 1987), when age is included as an independent variable in a regression analysis, age is an important predictor of visual performance. Older observers required more contrast to detect sine waves, faces and letters and to discriminate between faces and letters than did young observers. This is in agreement with the work of Owsley, Sekuler and Boldt (1981) who reported that older observers required about three times as much contrast to detect and discriminate faces than young observers. However, since age is highly correlated with acuity and contrast sensitivity, further analysis excluding age as a predictor revealed that contrast sensitivity and suprathreshold contrast-matching estimates can identify observers who have lower sensitivity to real-world targets. This result indicates that, although an observers age is important, it is not sufficient for the prediction of sensitivity to objects.

Also in agreement with other studies, acuity was not found to be a good predictor of performance on real-world tasks (Abrahamsson and Sjostrand, 1986; Ginsburg, 1978, 1983; Owsley et al., 1981; Sivak, Olson and Pastalan, 1981). Although useful for refraction and for identifying problems in seeing fine detail, acuity measurements are not predictive of the perception of larger objects.

Several reports have asserted that contrast sensitivity is not a good predictor of real-world performance (Rubin, 1990). For example, Monaco and Hamilton (1984) measured target detection performance and several laboratory vision tasks (high and low contrast acuity, acuity with glare, lateral movement, dynamic visual acuity, accommodative flexibility, dark focus and contrast sensitivity). There were several methodological problems with this investigation (O'Neal and Miller, 1988), but in addition to these, the researchers failed to include contrast sensitivity in the stepwise regression analysis. For this reason, conclusions about which vision tasks could significantly account for the variance in the target detection task are erroneous since the analysis did not include contrast sensitivity as a predictor variable even though a significant correlation was found between contrast sensitivity at 11.4 c/deg and target detection slant range. In addition, Kruk, Regan, Beverley and Longridge (1981) failed to find a relationship between contrast sensitivity and flying grades or number of crashes, however, between-subject differences in contrast sensitivity were very small, not allowing for sufficient variance to result in significant correlations. Other studies failing to find a significant relationship between contrast sensitivity and performance have measured sensitivity to a single spatial frequency (Kruk, Regan and Beverley, 1983; Kruk and Regan, 1983; and Kruk et al., 1981). To determine the relationship between contrast sensitivity and performance related tasks, a wide range of spatial frequencies should be tested. Lastly, O'Neal and Miller (1987) used only one measurement of contrast sensitivity per subject to define contrast sensitivity. Since contrast threshold is a variable measure, several repetitions are required to obtain a valid estimate of an individual's sensitivity. Tnus, methodological and analytic problems abound in reports indicating a poor relationship between contrast sensitivity and visual performance. It should be noted that these investigations showing no relationship are sometimes addressed without comparable reference to the numerous investigations showing a strong relationship between contrast sensitivity and visual performance.

According to a pilot study, the letter targets used here were processed by spatial frequency mechanisms sensitive to 12 c/deg. Smaller or larger targets would have stimulated different mechanisms since the spatial frequency range which best predicts sensitivity to real-world targets depends on the actual target size used for the task (Ginsburg, 1980; Ginsburg and Evans, 1981; Ginsburg, Evans, Sekuler and Harp, 1982; Owsley, Sekuler and Boldt, 1981). To obtain complete information about an observer's visual capability, it is important to measure contrast sensitivity along the entire frequency spectrum. Also in agreement with this statement are the results of Ginsburg et al. (1982) who found significant correlations between target detection distance under high visibility conditions and contrast sensitivity to spatial frequencies greater than 8 c/deg and significant correlations between target detection distance under low visibility conditions and contrast sensitivity to spatial frequencies below 8 c/deg. These results suggest that contrast sensitivity measurements taken over a range of spatial frequencies is predictive of detection performance under a variety of visibility conditions.

These results emphasize that measuring only peak contrast sensitivity values as suggested by Rubin (1986), has poor predictive ability of real-world performance. Rubin (1986) reported that sensitivity at the contrast sensitivity function peak is adequate for the prediction of reading performance. However, the letters used in his experiment ranged from 24 minutes to the observer's acuity threshold and it appears that Rubin (1986) averaged reading rate thresholds to all sized stimuli rather than assigning the different sized letters as separate dependent variables in the analysis. If this is the case, then the average of these letter sizes would most likely measure responses of spatial frequency mechanisms near the contrast sensitivity function peak. Rubin's reading task included letters ranging in size from 24 minutes to the acuity limit. Assume that the low vision patients in the Rubin study had visual acuities around 20/40 (6/12) corresponding to a letter size of 10 minutes. This means that the average letter size used in the reading task was (24 + 10)/2 = 17 minutes which translates to between 3 and 4 c/deg, or near the peak of the contrast sensitivity function. Thus, the recommendation made by Rubin (1986), that the peak of the contrast sensitivity function is adequate to predict real-world behavior is unfounded.

In conclusion, contrast sensitivity and suprathreshold contrast-matching are good predictors of everyday performance. The present study demonstrated the potential of suprathreshold contrast-matching as a predictor of performance in everyday visual tasks. It should be noted that the sample used in this study was small, and additional data needs to be collected using larger samples and samples which are more representative of the overall population to determine the strength of these preliminary conclusions. Suprathreshold contrast-matching at low standard contrasts and at high spatial frequencies was found to be related to contrast sensitivity. Lastly, suprathreshold contrast-matching at one standard contrast can not be used to predict contrast-matching at another standard contrast level. It is essential that further multivariate analyses be employed to identify other vision-related variables significantly influencing target detection and discrimination performance.

EXPERIMENT 4: SUPRATHRESHOLD CONTRAST-MATCHING POPULATION NORMS

INTRODUCTION

The visual world contains objects of different sizes and contrast levels. In order to comprehensively assess everyday visual function, measures of objects of different sizes, or spatial frequency, should be tested at low and high contrast. Contrast sensitivity measures low contrast perception and refers to the contrast visibility limits of an object. One way of studying suprathreshold contrast perception is to use the method of contrast-matching, where comparison gratings of different spatial frequencies and contrast are matched in perceived contrast with a standard grating of fixed spatial frequency and contrast. The resulting data is usually plotted as the reciprocals of the physical contrast needed to match the standard as a function of spatial frequency. Contrast-matching curves have the same inverted-U shape as the contrast sensitivity function when the standard grating is presented at low contrasts, but when the standard grating is set to higher contrasts, contrast-matching curves flatten. In other words, two high contrast gratings of different spatial frequency match in perceived contrast when their physical contrasts are similar.

Normative population data has been collected on contrast sensitivity measures defining normal limits of contrast sensitivity. No data exists to determine whether an individual set of contrast-matching curves is normal or abnormal when compared to normal population data. This study provides normative data of suprathreshold vision in healthy eyes and determines whether there is an age-related deficit in suprathreshold contrast perception.

Many studies have reported measurements of contrast-matching functions at a number of levels above threshold (Blakemore, Muncey and Ridley, 1973; Bowker, 1983; Georgeson and Sullivan, 1975; Swanson, Wilson and Giese, 1984; Watanabe, Mori, Nagata and Hiwatashi, 1968). Observers are presented with sinusoidal grating patterns on a computer operated split-screen cathode-ray-tube (CRT) display. On one half of the display is the standard grating, with spatial frequency near the contrast sensitivity function peak, and on the other half of the display is a comparison grating, which is at any of a number of spatial frequencies. The standard contrast is set to various suprathreshold contrast levels, and the observer adjusts the comparison grating contrast to the match the standard in apparent contrast. When this is done at a number of comparison spatial frequencies, contrast-matching functions are derived at different suprathreshold contrast levels.

However, computer operated systems are extremely time-consuming, hindering the collection of contrast-matching norms. The Suprathreshold Contrast Test System (SCTS) is an inexpensive, valid and reliable test chart which rapidly measures an entire family of contrast-matching curves. The current research uses this new testing chart to obtain normative data on suprathreshold contrast vision.

METHODS

Subjects. Contrast-matching curves were obtained in 336 eyes. All observers reported being in good health with no history of vision problems as indicated on a detailed medical history questionnaire. Monocular visual acuity was measured using a ETDRS near acuity chart with mean luminance of 100 cd/m^2. For the purposes of normative analysis, observers were classified into age decades. Individuals younger than 20 formed a single group. Decade grouping within this division would have resulted in sample sizes too small to generate dependable estimates of contrast-matching thresholds. The number of observers, mean visual acuity and acuity standard deviation in each decade are provided in Table 9. Acuities for each decade are similar to other developmental data (Gittings and Fozard, 1986).

Procedure. A description of the procedure and stimulus conditions for the SCTS chart are provided in the Methods section of Experiment 2.

RESULTS

Previous population normative data for contrast sensitivity using the Vistech Vision Contrast Test System (VCTS) chart used median data since the chart involves a discontinuous contrast scale and since means were not representative of the data because contrast sensitivity shows an asymmetry which is dependent upon age and spatial frequency (Ginsburg, Evans, Cannon, Owsley and Mulvanny, 1984). Figure 9 demonstrates the asymmetrical relationship between contrast sensitivity and spatial frequency. These curves come from the normative contrast sensitivity data of Ginsburg (1989). Asymmetric distributions make nonparametric statistics, such as the median, a more appropriate average than the arithmetic mean (Winer, 1971).

Unlike the CRT systems often used in research, the SCTS determines contrast-matching estimates using a discontinuous contrast scale which may effect the frequency distribution. To determine whether parametric versus nonparametric procedures should be used on the SCTS data, cumulative distributions were plotted for each condition within an age grouping. Two typical distributions are shown in Figure 10. Panel a presents the cumulative distribution for observers in the 20-29 age range for a 1.5 c/deg comparison spatial frequency. Panel b shows the distribution for 60-69 year olds at 1.5 c/deg. Each panel includes the number of observers who chose a particular comparison contrast patch for each of the five standard contrasts: 56% (open circles), 35% (filled circles), 19% (open triangles), 9% (filled triangles) and 5% (open squares). Except for the 56% standard contrast condition, all standard contrasts are symmetrically distributed. The 56% standard contrast condition was asymmetrical most likely because many observers chose the highest contrast comparison as a match. The symmetrical distributions are broader at lower standard contrasts suggesting greater variation in the comparison contrast chosen across observers. In addition, older observers show greater variation than do younger observers at the two lowest standard contrasts. In sum, distributions were generally symmetrical across spatial frequencies for young and older observers.

The finding that suprathreshold contrast-matching data is symmetrically distributed across age and spatial frequency suggests that parametric statistics may be used to analyze this data. In addition, Barbeito and Simpson (1991) have suggested that the type of measurement scale, continuous versus discontinuous, should not govern the type of statistic used. These reasons justify the use of parametric procedures on the suprathreshold contrast-matching data. Comparison of the means and medians for each condition within a decade confirm that although there is a substantial difference between mean and median contrast sensitivity, contrast-matching data shows little difference between mean and median scores for any age group. The finding that contrast-matching estimates are normally distributed is not surprising since all gratings on the SCTS chart are visible to normal observers. Contrast sensitivity scores, however, are not normally distributed due to visibility limits at lower contrast levels.

Figure 11 presents the mean contrast-matching estimates for each of the age decades. Each of the standard contrasts are represented with different symbols: 5% (open squares), 9% (filled triangles), 19% (open triangles), 35% (filled circles) and 56% (open circles). Normative contrast sensitivity data from Ginsburg (1989) is presented as filled squares. The flattening of contrast-matching curves occurs at a higher standard contrast for the elderly than for the young adults.

Analysis of variance for repeated measures revealed a significant spatial frequency x standard contrast x age interaction ($F(112,5248) = 1.28$, $p < 0.05$). To clarify this relationship, the significant interaction between spatial frequency and age was first explored ($F(28,1312) = 1.55$, $p < 0.05$). The means comprising this interaction are shown in Figure 12 for comparison grating spatial frequencies of 1.5 (open circles), 3 (filled circles), 6 (open triangles), 12 (filled triangles) and 18 c/deg (open squares). Age decades are shown on the abscissa and 1/comparison contrast on the ordinate. This figure demonstrates that at high spatial frequencies, 12 and 18 c/deg, older individuals match the standard grating to a higher comparison contrast than do younger observers.

Figure 13 shows how standard contrast interacts with age ($F(28,1312) = 2.63$, $p < 0.0001$). The vertical axis in this figure are similar to those in Figure 12 except that 1/comparison contrast has been plotted on a linear axis to better demonstrate the relationship between age and standard contrast. Five standard contrasts are shown in this figure using the same symbols as those used in Figure 11. This figure demonstrates how at low standard contrasts, older individuals match the standard grating to a higher comparison contrast compared to younger observers. These two results shed light on the three way interaction between spatial frequency, standard contrast and age by suggesting that there is an age dependent influence on contrast matches under conditions which are close to contrast threshold (low standard contrast and high spatial frequencies). However, age dependent differences did not arise under suprathreshold contrast-matching conditions in agreement with the results of Tulunay-Keesey et al. (1988).

Contrast Constancy as a Function of Age

Figure 14 emphasizes how standard contrast influences contrast matches for different spatial frequency comparison stimuli. Each panel presents the data for a different age group ranging from 5 (Panel a) to 89 (Panel h) years. Each panel presents the comparison contrast necessary to match the standard pattern for comparison spatial frequencies of 18 (inverted triangles), 12 (triangles), 6 (filled circles), 3 (squares) and 1.5 c/deg (open circles). The filled circles represent the conditions where the standard and comparison spatial frequencies were the same. The diagonal line indicates that observers were able to accurately match comparison and standard physical contrasts. For all observers, 12 and 18 c/deg comparison stimuli were perceived to have lower contrast than the 6 c/deg standard grating at low standard contrasts. However, at high standard contrasts, the standard and comparison stimuli were perceived to be equal in contrast when their physical contrast was the same. As mentioned in the Introduction, this is known as contrast constancy (Georgeson and Sullivan, 1975). Contrast constancy at high standard contrasts appears to be similar in young and older adults. On the other hand, contrast-matching at low standard contrasts is noticeably different across ages starting at 19% contrast.

DISCUSSION

The results of this study suggest that there is an age-dependent difference in perceived contrast at low standard contrasts. Older observers match a low contrast, 6 c/deg standard grating to higher contrast comparison stimuli than do young observers. At 12 and 18 c/deg and standard contrasts equal to and below 19%, contrast constancy differs as a function of age. The compensation seen in contrast constancy in young observers appears to be lessened with age under these conditions. Age differences can be seen by the more gradual flattening of the contrast-matching curves with increases in standard contrast at high spatial frequencies predominantly in those observers over the age of 50.

Although not statistically significant, age differences could also be seen in the contrast-matching data of Tulunay-Keesey, Ver Hoeve and Terkla-McGrane (1988) at low standard contrasts.

Georgeson and Sullivan (1975) proposed a compensatory mechanism, called contrast constancy, to explain the flattening of contrast-matching curves with increasing standard contrasts. Essentially, contrast constancy occurs when a spatial channel "detects" degradation of a stimulus. For example, to compensate for high spatial frequency blur, the visual mechanism most sensitive to that stimulus will compensate by elevating stimulus gain, thereby increasing stimulus visibility.

Contrast-matching curves of amblyopes do not necessarily exhibit the flattening at higher standard contrasts seen in normal curves (Ginsburg, 1978). It has been suggested (Georgeson and Sullivan, 1975; Swanson et al, 1984) that amblyopic eyes may fail to normalize across spatial mechanisms, and thus reduce the peak responses of these mechanisms. It is possible that this normalization does not occur until higher contrasts in older individuals. In other words, there could be an age-related change in the gain of the spatial mechanisms at low ($\leq$19%) contrasts.

A change in the contrast gain of low contrast mechanisms with age is only one possible explanation for the results of this study. Our results cannot distinguish between ocular and neural factors as would laser interferometric techniques (e.g., Burton, Owsley and Sloane, 1991). It is possible that contrast threshold models may account for these age-related differences in suprathreshold contrast-matching. However, this is unlikely since previous research has suggested that contrast is processed differently at threshold and suprathreshold levels (Bowker, 1983; Georgeson and Sullivan, 1975). However, it may be that only high contrasts are processed differently than threshold contrast. A third possibility is that low contrast-matching requires a decision making process which differs in young versus older individuals.

In summary, this data provides the first suprathreshold contrast normative data ever from 336 eyes for eight age decades and present results which extend the findings of age-related changes in high spatial frequency contrast sensitivity to include low contrast suprathreshold contrast perception.

EXPERIMENT 5: SUPRATHRESHOLD CONTRAST-MATCHING IN CLINICAL POPULATIONS

INTRODUCTION

Contrast sensitivity measurements are now widely used in the diagnosis and assessment of visual diseases (Ginsburg, 1981; Loshin and White, 1984; Regan, Silver and Murray, 1977; Ross, Bron and Clarke, 1984; Zimmern, Campbell and Wilkinson, 1979). Contrast sensitivity for sinusoidal gratings of different spatial frequencies has been found to be abnormal in ophthalmological diseases affecting eye optics, the retina or the central visual system.

There are large individual differences between and within disease categories where contrast sensitivity deficits may be seen at high, medium or low spatial frequencies or at a combination of frequencies. Amblyopia results in marked losses of contrast sensitivity particularly at high spatial frequencies, but may also result in "notch" losses which selectively affect intermediate frequencies (Ginsburg, 1978; Rogers, Bremer and Leguire, 1987). Contrast sensitivity testing with low and intermediate spatial frequencies is suggested to be an efficient screening device for glaucoma (Arden, 1978; Arden and Jacobson, 1978; Atkin et al., 1979; Ross, Bron, Reeves and Emmerson, 1985). Contrast sensitivity losses may occur at only the intermediate or high frequencies, or across all spatial frequencies in cataract patients (Ginsburg, Osher, Blauvelt and Blosser, 1987; Hess and Woo, 1978). Contrast sensitivity is also affected in macular degeneration (Sjostrand, 1979). These differences between disease categories makes the contrast sensitivity function a valuable tool for diagnosis, monitoring and evaluation of improvement resulting from different therapies.

Though detection threshold measures indicate many of the performance properties of the eye, the application of suprathreshold measures to the investigation of clinical disorders may be a valuable addition for more comprehensively describing abnormal functioning of the disorder. This information may lead to a better understanding of the etiology and underlying mechanisms of the eye disease. A greater understanding may subsequently lead to more accurate diagnoses and effective treatments.

One method used to measure the apparent contrast of suprathreshold gratings is contrast-matching. In a contrast-matching experiment, observers match the perceived contrast of two grating patterns (Georgeson and Sullivan, 1975; Watanabe, Mori, Nagata and Hiwatashi, 1968). The contrast of a comparison grating is varied until the observer reports a match in contrast to a standard grating of fixed contrast. The comparison and standard gratings may be the same or different spatial frequencies. In normal observers, apparent contrast equals physical contrast when the spatial frequency of the comparison and standard gratings are the same. Contrast constancy occurs when apparent contrast equals physical contrast at standard grating contrasts above 10% (Georgeson and Sullivan, 1975). On the other hand, at standard contrasts below 40%, at high comparison spatial frequencies, observers choose a higher comparison contrast as a match to an intermediate frequency standard grating. Thus, at low contrast levels, physical contrast does not equal apparent contrast when comparing gratings of different spatial frequencies.

Compared to contrast sensitivity measurements, relatively little research has been devoted to investigating the effects of disease on suprathreshold contrast perception. Contrast-matching thresholds have been obtained as a function of amblyopia (Ginsburg, 1978; Hess and Bradley, 1980; Hess, Bradley and Piotrowski, 1983; Mac Cana, Cuthbert and Lovegrove, 1986). Ginsburg (1978) measured contrast-matching thresholds in a 20-year old amblyope. When the standard and comparison spatial frequencies were the same (2 c/deg), physical and apparent contrast were similar, as seen in normal observers. For higher spatial frequency comparison gratings and standard contrasts ranging from 1% to 67%, the amblyopic eye showed complex relationships, including a high spatial frequency "notch", between apparent and physical contrast.

Hess and Bradley (1980) and Mac Cana, Cuthbert and Lovegrove (1986) found no significant deficits in contrast-matching in anisometropic amblyopes at low standard contrasts. However, when the standard and comparison spatial frequencies were the same, amblyopes did show a tendency toward choosing lower comparison contrasts than the standard. This tendency in contrast-matching was greater at higher spatial frequencies. When standard and comparison spatial frequencies were different, there was no deficit seen in amblyopes at low comparison spatial frequencies. At high comparison spatial frequencies, however, the amblyopic eye required a higher contrast than normals to match a 4 c/deg standard grating (Mac Cana et al., 1986). Thus, research suggests small deficits in contrast-matching in amblyopes.

The purpose of this study was to evaluate the clinical value of the Suprathreshold Contrast Test System (SCTS, Vision Sciences Research Corp.) in amblyopes. This system was designed to provide an inexpensive, convenient and rapid procedure for obtaining contrast-matching curves. To initially determine the potential for the SCTS to screen normal from abnormal contrast-matching estimates, data was collected in amblyopic patients. In addition, preliminary data will be presented for self-reported cataract, glaucoma and macular degeneration patients revealed during our collection of normative population data on contrast-matching.

METHODS

Subjects. Contrast-matching estimates were obtained from twentyfive subjects having one of four abnormal conditions; amblyopia, age-related macular degeneration, cataract and glaucoma. The subjects were selected if they had no known record of a visually impairing ocular disease additional to the one they reported. Amblyopic subjects were given a preliminary examination which included retinoscopy, refraction, biomicroscopy, ophthalmoscopy, tonometry and visual fields. All subjects wore their best refractive correction for the experiment.

Procedure. Monocular contrast-matching functions were determined for diseased and control subjects using the SCTS. Natural pupils were used throughout the experiment. The eye not being tested was occluded by a cover paddle. Five suprathreshold contrast levels were used for the standard gratings (5%, 9%, 19%, 35%, and 56%) to determine the effects of physical contrast on the judgment of apparent contrast across spatial frequencies. Five spatial frequency comparison contrasts were tested (1.5, 3, 6, 12 and 18 c/deg). For comparisons across spatial frequencies, observers were instructed to make their judgments based on contrast and not on other criteria such as visibility (Georgeson and Sullivan, 1975). The procedure for testing is provided in the Methods section of Experiment 2.

RESULTS

The current research investigated whether amblyopia, glaucoma, cataracts or macular degeneration result in suprathreshold contrast deficiencies using a contrast-matching paradigm in a chart format.

There are many ways to present the clinical contrast-matching data. First, the data from all patients within a clinical group may be averaged. This representation furthers understanding about the disease process in general. Figure 15 presents the averaged contrast-matching data for four visual pathologies: six amblyopic eyes (panel a), five cataract (panel b), ten glaucoma (panel c) and two eyes with macular degeneration (panel d). Five standard contrasts were measured: 5% (open squares), 9% (filled triangles), 19% (open triangles), 35% (filled circles) and 56% (open circles). Average normal population data from 336 eyes are shown by solid connecting lines. In all averaged clinical cases (dotted lines), the contrast-matching curves are similar to those of normal observers. These results suggest that clinical patients show little deficit in suprathreshold contrast processing when the data is averaged.

Individual Differences

Although general statements may be made from averaged data, this type of examination prevents inspection of individual differences due to unique rates of progression or severity in the disease. One way of examining individual differences which may be used in visual screening is to visually compare the data for each patient with age-matched control subjects. This method of comparison, however, has the potential of being misleading. Control subjects also show great diversity. For example, Figure 16 presents the contrast-matching data for two 69-year old normal controls. The contrast-matching curves of the 69-year old normal subject in panel a are dramatically different than those obtained from the same aged subject in panel b. These individual differences within the normal control group make comparisons with the diseased eyes difficult at best. If a clinical observer was compared to the normal subject in panel a, the conclusions may be different than if the same clinical patient was compared to the normal subject in panel b. For this reason, a more appropriate way to investigate individual differences within a clinical group would be to compare the clinical data to that of normal population data.

Figures 17-22 present the individual data of each patient (broken curves) with that of normative data (solid curves). Normative data collected in 336 normally sighted observers on the SCTS has been grouped into age decades: 5-19 (n = 59), 20-29 (n = 61), 30-39 (n = 31), 40-49 (n = 45), 50-59 (n = 34), 60-69 (n = 59), 70-79 (n = 36) and 80-89 (n = 11). Thus, for example, the data from a clinical observer who is 42 years old are plotted against data of the 40-49 year age range.

Figures 17, 19-22 have been summarized in Table 10 which presents the number of clinical contrast-matching estimates which are higher (H), lower (L) or similar (S) on the figures as that chosen by the normative group within one standard error. Hash marks represent conditions not chosen.

Figure 17 presents the contrast-matching data for six amblyopic patients ranging in age from 14 to 42 years (age is shown in parenthesis). At low spatial frequencies (1.5 and 3 c/deg), 17 conditions were matched to a similar contrast chosen by normal observers in the same age range. The majority of these similar contrast matches were at higher standard contrasts. In 10 contrast-matching conditions, amblyopes chose a lower comparison contrast than normals. In the control condition where the standard and comparison spatial frequencies were both 6 c/deg, most conditions were matched to a similar comparison contrast as normals (n = 18) than to a lower (n = 3) or higher contrast (n = 8). Some amblyopes were not capable of performing all matches at 6 c/deg or at high spatial frequencies. Of those amblyopes who were able to perform the task, only one showed the traditional flattening of the contrast-matching curves (panel b). At high comparison spatial frequencies (12 and 18 c/deg), most amblyopes chose similar contrasts as the norms (n = 16). In summary, most amblyopes chose similar contrast comparison patches as normals at all spatial frequencies, particularly at high standard contrasts. However, in a substantial number of low spatial frequency conditions, a lower comparison contrast was chosen by amblyopes than that chosen by normals.

Figure 18 presents the contrast sensitivity data for five of six amblyopes (open circles). The data for one observer was not obtained. Filled circles show mean normative data from a large contrast sensitivity sample study by Ginsburg (1989). Three of five amblyopes show lowered contrast sensitivity compared to normals. To determine if suprathreshold contrast-matching curves can be predicted by an individual's contrast sensitivity, a correlational matrix was constructed between contrast-matching estimates and contrast sensitivity. Missing data were coded as ones. Significant correlations ($p < 0.05$) were found between contrast sensitivity and lower visibility contrast-matching conditions such as low standard contrasts and high comparison spatial frequencies. Thus, the contrast sensitivity function may be used to predict the high frequency portion of contrast-matching functions for standard contrasts $\leq$ 35%. These results suggest that suprathreshold contrast-matching estimates at low spatial frequencies and low standard contrasts are a useful tool for screening anisometropic amblyopia while contrast sensitivity measures are sufficient using high spatial frequency conditions.

Figure 19 presents the data for five cataract patients, ages 64-80. Table 10 also provides summary data for this figure. At low spatial frequencies, most cataract patients chose a similar comparison contrast patch as did normals (n = 13), particularly at higher standard contrasts. For a comparison spatial frequency of 6/deg, most patients (n = 18) chose comparison contrasts which were equal in contrast to that chosen by normal observers of the standard contrast. Six patients chose a lower contrast and eight patients chose a higher contrast comparison than the standard. At high comparison spatial frequencies, most patients again chose a similar physical contrast as the normals (n = 16) than for a higher (n = 5) or lower (n = 3) comparison contrast. In summary, most cataract patients chose similar comparison contrasts as normals, particularly at high standard contrasts which suggests that suprathreshold contrast-matching estimates are not a worthwhile tool for screening patients for cataract.

Figures 20 and 21 show the contrast-matching data for ten eyes with glaucoma. The patients range in age from 49-83 years. All patients show dramatic differences from one another except for the data of the two 49-year old eyes which was taken from the two eyes of one observer. Five of ten data sets are incomplete because patients were unable to perform the task under all conditions. At low spatial frequencies, most glaucoma patients chose similar comparison contrast as the normals (n = 20), particularly at high standard contrasts. However a substantial number of conditions resulted in both higher (n = 11) and lower (n = 19) contrast-matching curves suggesting that suprathreshold contrast processing was abnormal in these observers, especially at lower standard contrasts. When the standard and comparison spatial frequencies were the same (6 c/deg), most patients (n = 34) chose similar comparison contrast as normals. In 11 conditions, on the other hand, contrast-matching curves were higher for glaucoma patients, suggesting that a lower comparison contrast was chosen as a match for the standard. Most patients also chose similar comparison contrast as normals at high spatial frequencies (n = 29). But again, eleven conditions showed that lower comparison contrasts were chosen by the glaucoma patients than by normals. In summary, most conditions resulted in similar contrast matches in normals and glaucoma patients, however in many cases the data for the patients deviated from the norm. At all spatial frequencies, many patients chose lower comparison contrasts than did normals. At low spatial frequencies, many patients also chose higher comparison contrast than did normals. Thus, suprathreshold contrast-matching estimates are a useful tool for screening most glaucoma patients.

The data for two 49-year old eyes (same patient) with macular degeneration are shown in Figure 22. For both eyes, low visibility conditions such as high spatial frequencies and low standard contrasts were undetectable. At low spatial frequencies, lower contrast-matching curves were found compared to normals, suggesting that this macular degeneration patient chose higher contrast comparison patches than did normal subjects. In the 6 c/deg comparison spatial frequency condition, the patient chose either higher comparison contrasts or a similar contrast as normals. At high spatial frequencies, in conditions which the patient could perform, most responses were similar to normals. Thus, in many cases, at low and intermediate spatial frequencies, macular degeneration results in lower contrast-matching curves than those obtained in normals making these estimates valuable for clinical screening of macular degeneration.

Discussion

The main finding of this study was that many patients with ocular pathologies show abnormal contrast-matching curves. In general, these differences are present at low standard contrasts. Just as with contrast sensitivity, individual differences in contrast-matching estimates are present between patients within a disease category. Some patients were not able to determine contrast matches at high spatial frequencies and/or low standard contrasts since the stimuli were below their contrast threshold.

Significant correlations between contrast sensitivity and low standard contrast-matching conditions in amblyopes suggests that measures including contrast sensitivity may be sufficient for a screening devise. Suprathreshold contrast-matching estimates may add little to the diagnostic value of contrast sensitivity in amblyopic patients. Further research is needed to determine the sensitivity and specificity of the SCTS chart compared to contrast sensitivity measures.

Contrast-matching curves have been previously obtained in amblyopic patients. The current results, under conditions where the comparison and standard spatial frequencies were the same, are in agreement with this literature (Ginsburg, 1978; Hess and Bradley, 1980; Hess et al., 1983; Mac Cana et al., 1986). That is, in four of six amblyopes, apparent contrast was similar to physical contrast.

The current findings do not support the claim of Hess and Bradley (1980) and Hess et al. (1983) that amblyopes have normal suprathreshold contrast-coding. When the comparison spatial frequency was lower than the standard, four of six amblyopes chose a lower comparison contrast than normals. One amblyope, chose a higher comparison contrast than normals at low comparison spatial frequencies. Mac Cana et al. (1986) found a high spatial frequency deficit in amblyopes. The current results did not uncover this deficit since four of six patients were unable to determine contrast matches at high spatial frequencies using the SCTS chart. One reason Mac Cana et al. (1986) did not find a deficit at low spatial frequencies in contrast-matching could be that those observers also did not have a low spatial frequency deficit in contrast sensitivity.

The finding that amblyopes show contrast coding deficits when the spatial frequency of the standard and comparison gratings are different but there is no deficit when the stimuli are the same spatial frequency agrees with the data of Mac Cana et al. (1986). They hypothesized that the performance of amblyopes is not impaired when contrast processing is taking place within a single spatial frequency, but that amblyopes have a deficit in cooperative neural activity across channels.

In spite of abnormal contrast sensitivity in cataract patients (Ginsburg, Osher, Blauvelt and Blosser, 1987; Hess and Woo, 1978), the suprathreshold vision of cataract patients was normal. This finding suggests that there is some compensatory mechanism operative in suprathreshold vision such that the gain of the system is not adversely affected by the decreased contrast at threshold levels. These observations demonstrate that threshold contrast sensitivity tests are more appropriate for discovering vision related problems due to cataract.

The contrast-matching results of glaucoma patients suggests that some patients with this disease have abnormal suprathreshold contrast processing. Most conditions resulted in similar contrast matches in normals and glaucoma patients, however at all spatial frequencies, many patients chose lower comparison contrasts than did normals. At low spatial frequencies, many patients also chose higher comparison contrast than did normals. These results suggest that the SCTS may be added to existing evaluation regimens as a glaucoma screening tool.

In the one macular degeneration patient tested, in many cases, suprathreshold contrast processing was abnormal. At low and intermediate spatial frequencies, macular degeneration results in lower contrast-matching curves than those obtained in normals possibly making these estimates useful for clinical screening of macular degeneration.

The findings of this study suggest that high contrast suprathreshold and threshold contrast processing may be mediated by different contrast mechanisms. Other studies have provided evidence for this suggestion. Ginsburg (1978) reported contrast-matching curves in an anisometropic amblyope which were not consistent with her threshold data. The gain mechanisms in this amblyope were complex: both over and under compensation were seen at different spatial frequencies at suprathreshold contrasts. Georgeson and Sullivan (1975) suggested that more complex gain systems may exist in diseased observers.

In summary, individual differences were seen in normals and clinical patients. General trends in the data suggest that in most conditions amblyopes, cataract, glaucoma and macular degeneration patients choose similar comparison contrasts as normals. There were some exceptions. In amblyopes, many patients show a trend toward lower curves in the low spatial frequency portion of contrast-matching functions. In glaucoma many patients show higher curves at all spatial frequencies with some showing lower curves at low spatial frequencies. At low and intermediate spatial frequencies, macular degeneration results in lower contrast-matching curves than those obtained in normals. Thus, in general, the shape of the contrast-matching function at low standard contrasts differs in amblyopes, glaucoma and macular degeneration patients from that obtained from normal control subjects.

CONCLUSIONS

This Phase II research project has extensively examined a new vision test chart, the SCTS. The chart design was optimized to be fast, easy, portable and inexpensive. The SCTS chart was found to be a valid testing instrument which produces reliable contrast-matching estimates and has predictive ability of real-world visual performance which goes beyond the predictive ability of contrast sensitivity. Normative population data was collected in 336 eyes and was used to determine the diagnostic and assessment potential of the SCTS on clinical populations. The SCTS was found to be a valuable screening tool for amblyopia, glaucoma and macular degeneration.

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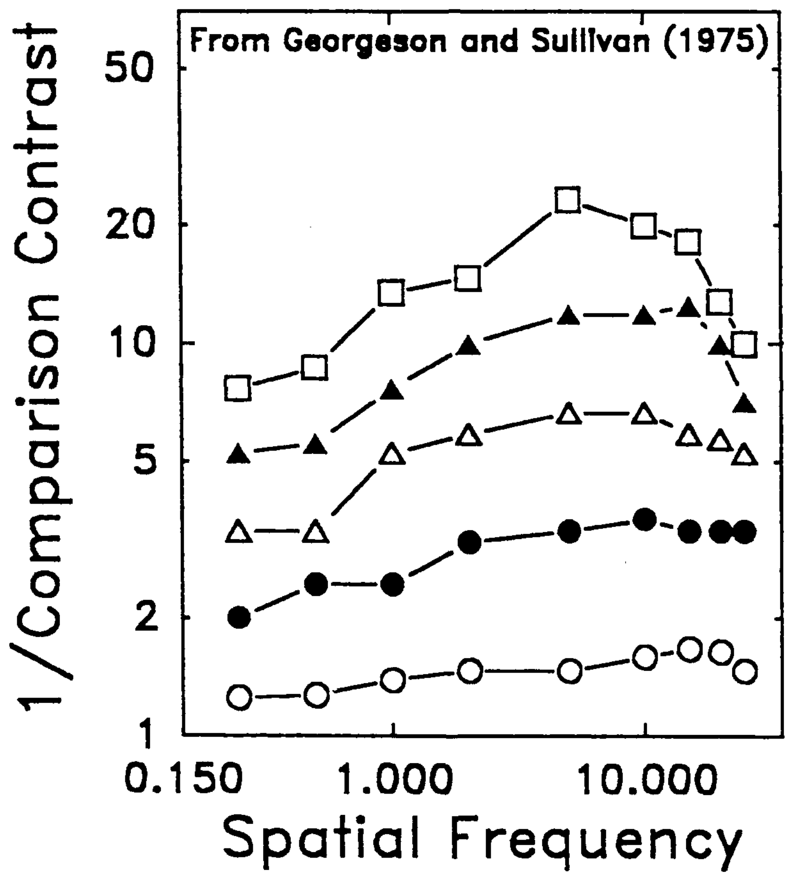

From Georgeson and Sullivan (1975)
1/Comparison Contrast
50
20
10
5
2
1
0.150
1.000
10.000
Spatial Frequency

Figure 1

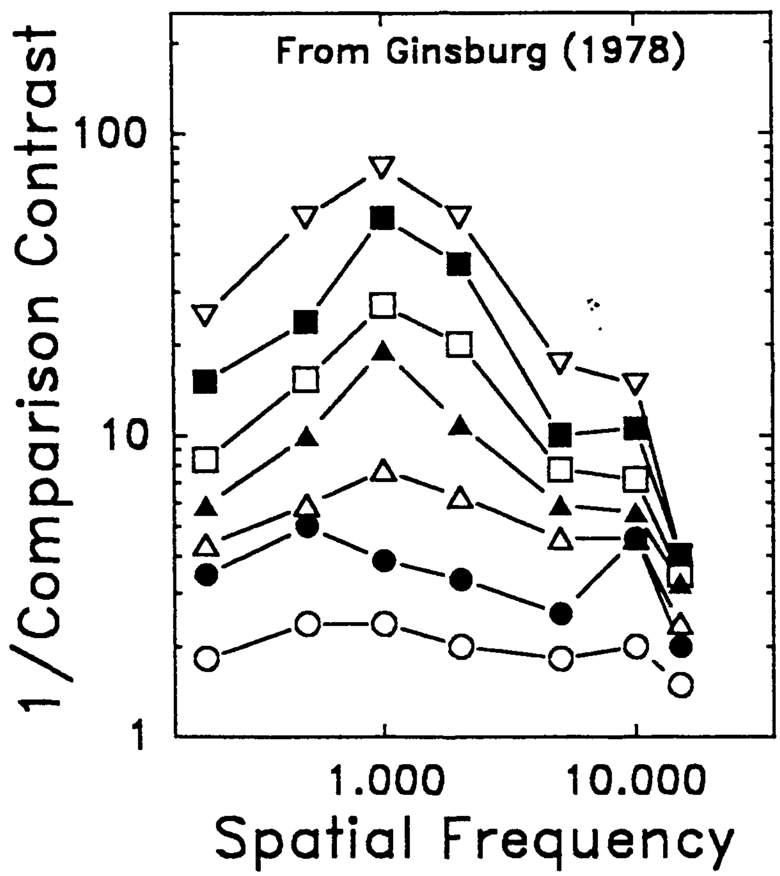

From Ginsburg (1978)
100
10
1
1/Comparison Contrast
1.000
10.000
Spatial Frequency

Figure 2

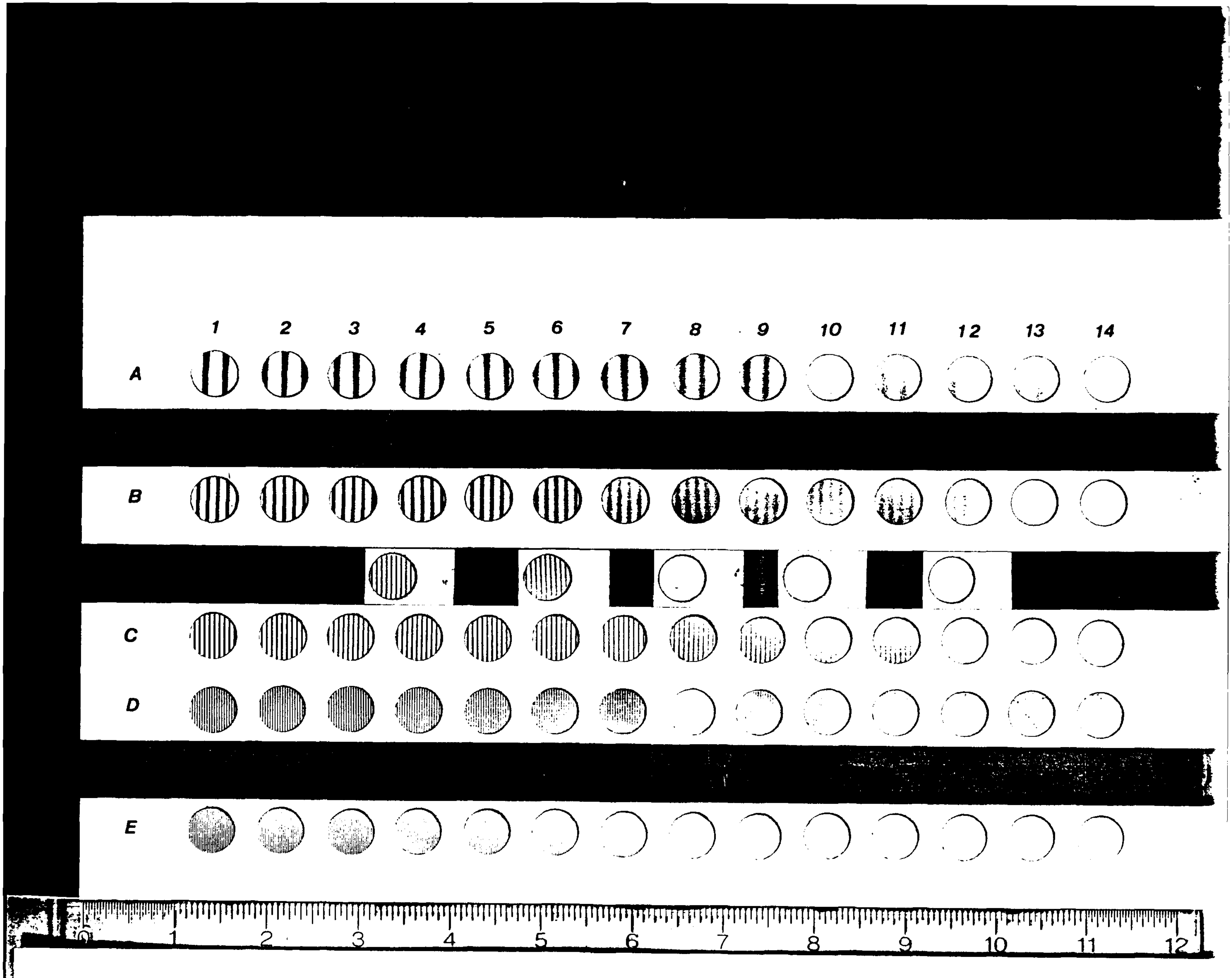
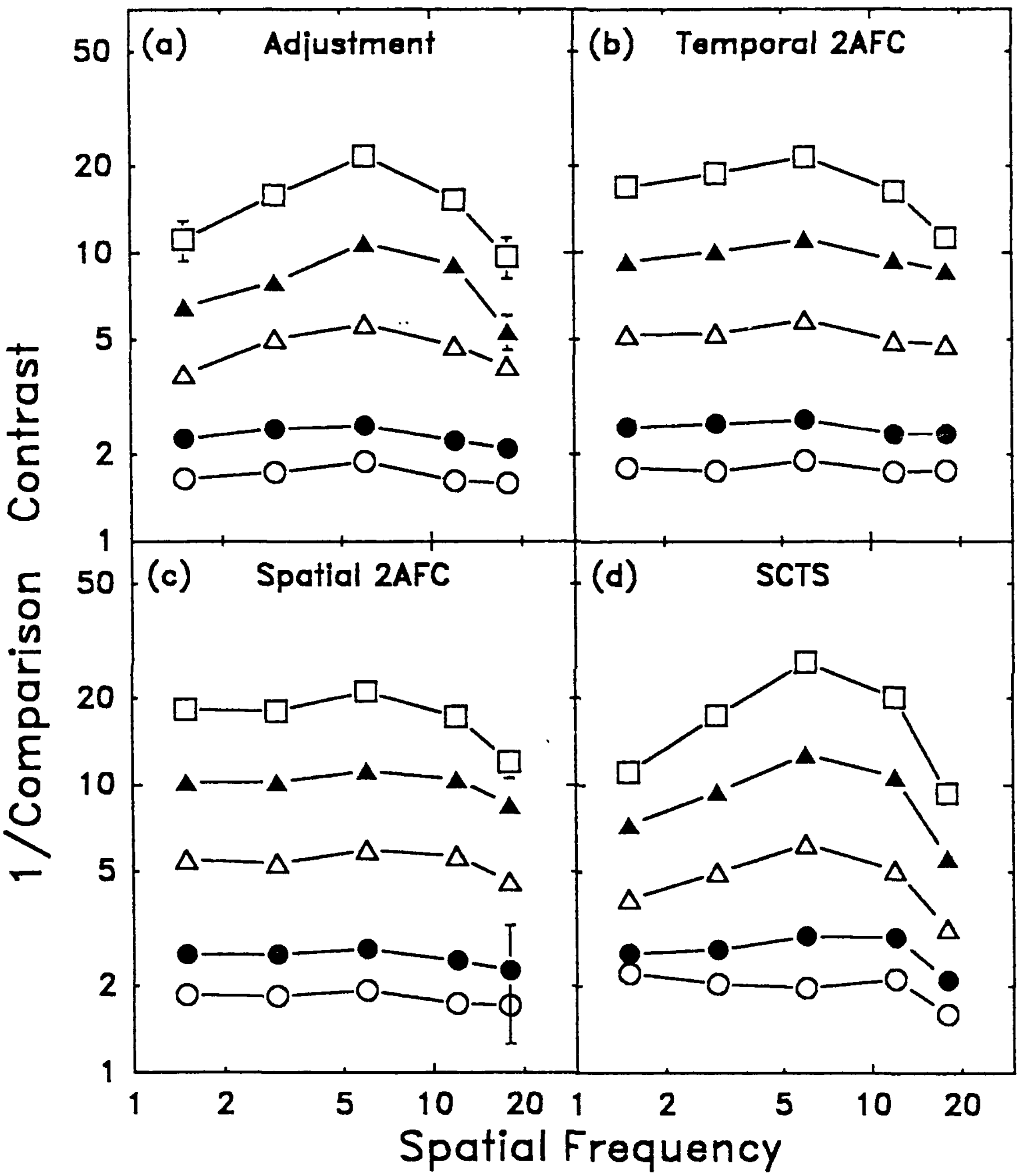


Figure 3

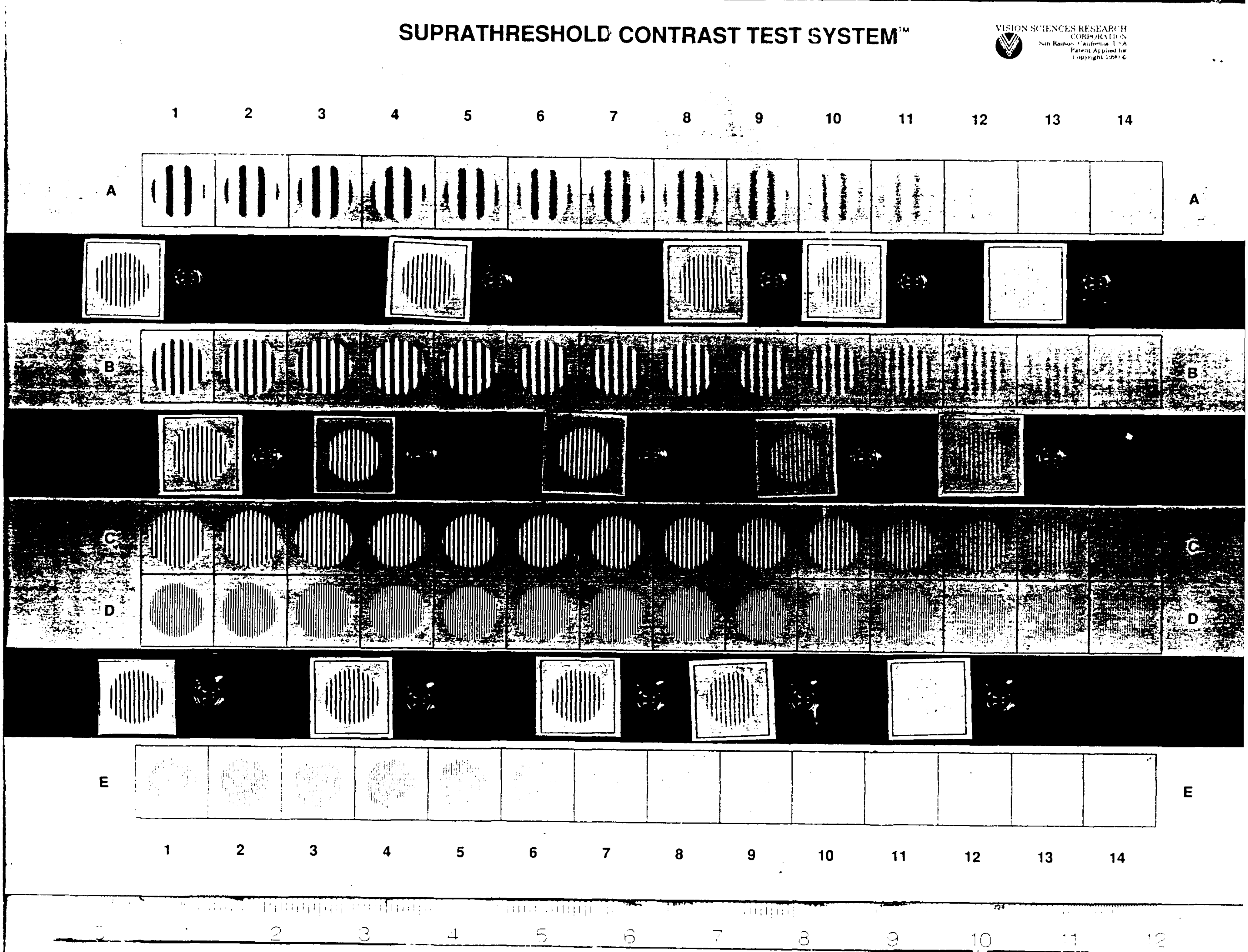
Table 1. SCTS contrast values for chart used in Experiment 1.

		Patch Number													
Row	SF	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	1.5	47	45	42	40	38	36	31	25	19	16	14	12	10	8
B	3	54	47	43	40	36	29	20	18	16	13	11	9	6	5
C	6	60	54	47	41	33	27	21	17	14	11	8	6	4	3
D	12	55	46	39	35	33	27	24	19	15	10	8	7	6	4
E	18	70	67	60	55	49	45	40	35	30	28	20	16	13	10



(a) Adjustment
(b) Temporal 2AFC
(c) Spatial 2AFC
(d) SCTS
1/Comparison Contrast
50
20
10
5
2
1
1
2
5
10
20
Spatial Frequency

Figure 4



SUPRATHRESHOLD CONTRAST TEST SYSTEM™
VISION SCIENCES RESEARCH CORPORATION
1 2 3 4 5 6 7 8 9 10 11 12 13 14
A
B
C
D
E
1 2 3 4 5 6 7 8 9 10 11 12 13 14

Figure 5

Table 2. Average test-retest reliabilities of 28 matrices

Standard Contrast	1.5	3	6	12	18	Average
5%	0.08	0.29	0.5	0.88	0.85	0.64
9%	0.92	0.64	0.77	0.84	0.91	0.82
19%	0.89	0.51	0.86	0.8	0.95	0.8
35%	0.6	0.25	0.85	0.61	0.78	0.62
56%	0.4	0.29	0.85	0.4	0.44	0.48
Average	0.7	0.4	0.77	0.71	0.79	

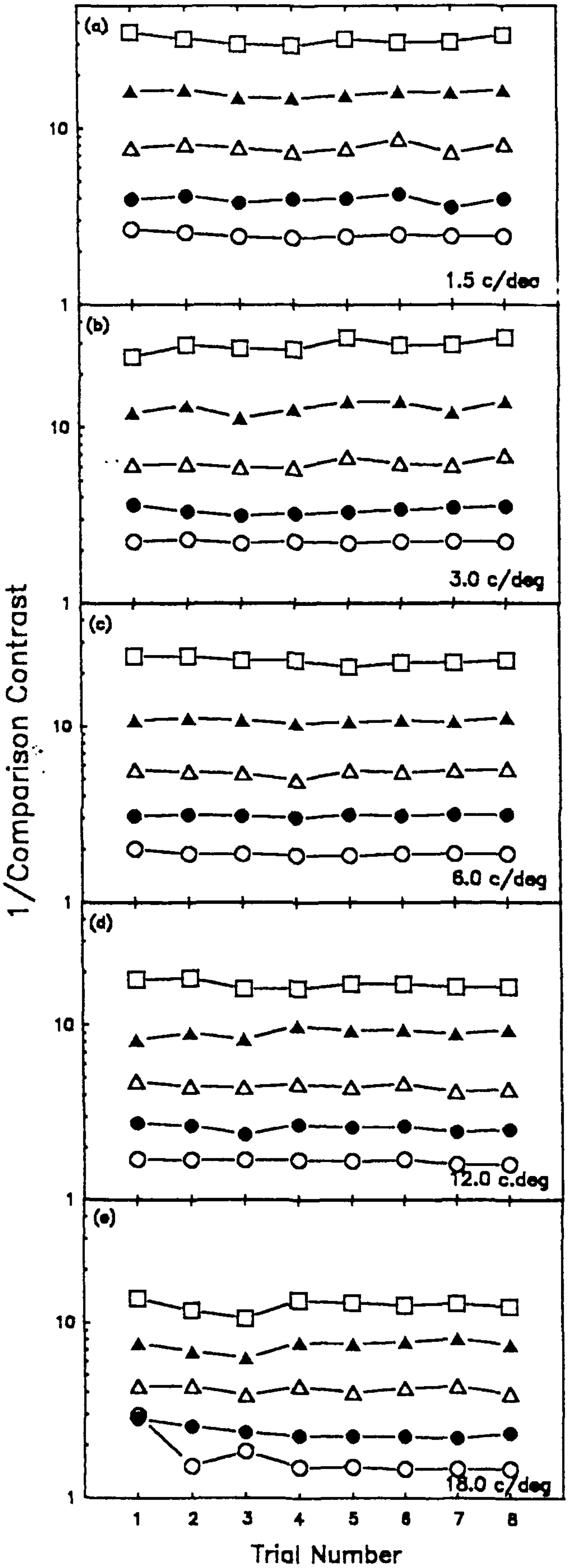
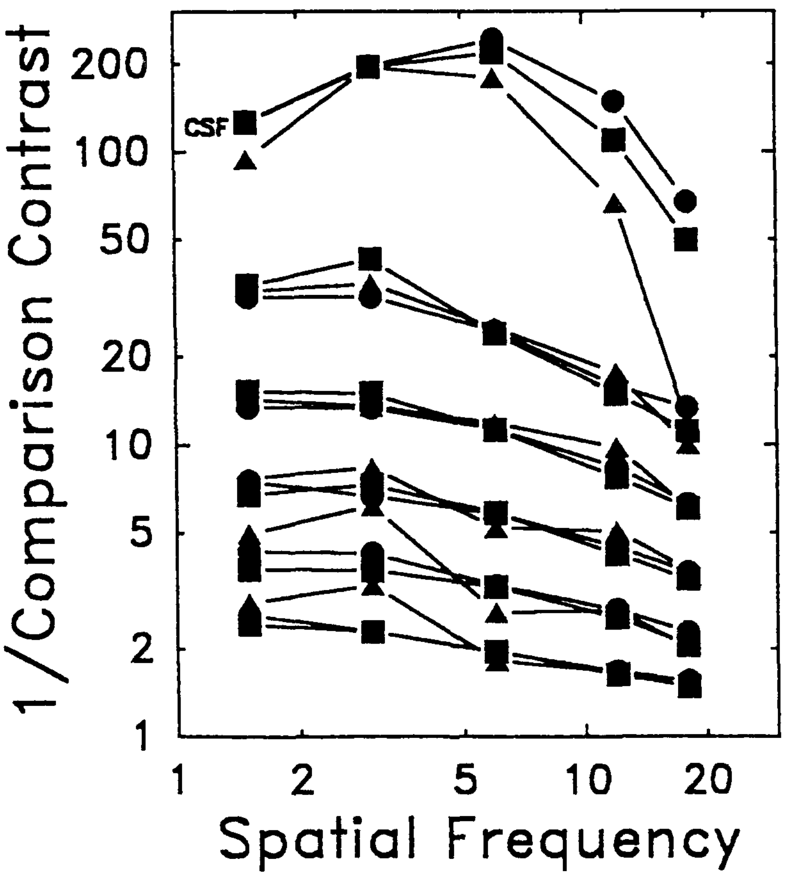

(a)
(b)
(c)
(d)
(e)
1.5 c/deg
3.0 c/deg
6.0 c/deg
12.0 c.deg
18.0 c/deg
1/Comparison Contrast
Trial Number
1
10
1
2
3
4
5
6
7
8

Figure 6

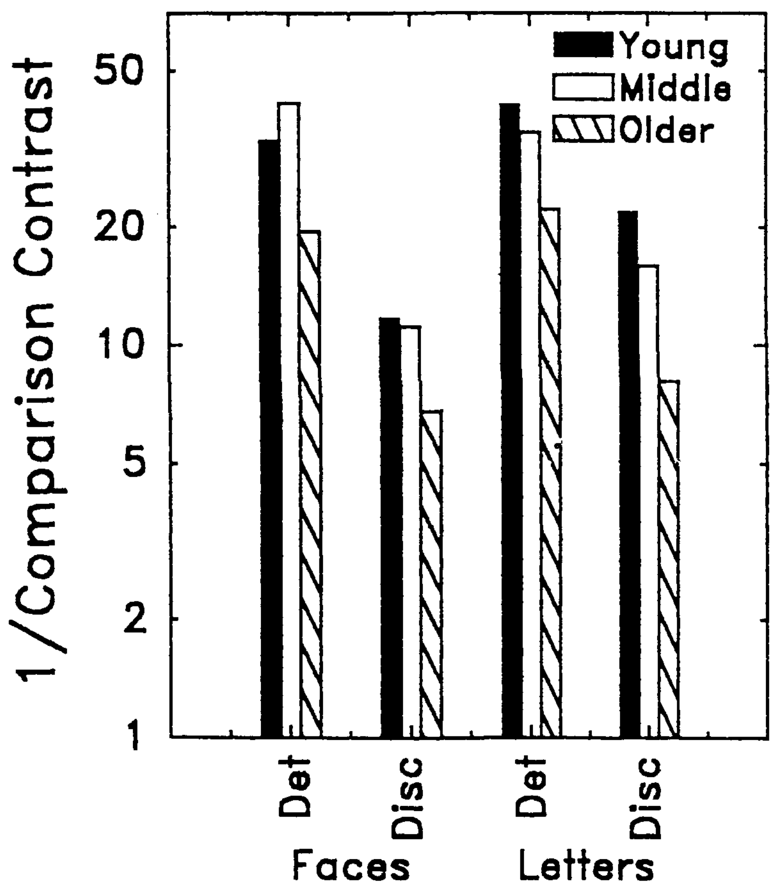
Table 3. Average test-retest reliabilities of 6 matrices

Standard Contrast	1.5	3	6	12	18	Average
5%	0.67	0.34	0.48	0.95	0.91	0.67
9%	0.96	0.78	0.8	0.92	0.94	0.88
19%	0.93	0.64	0.91	0.88	0.98	0.87
35%	0.66	0.39	0.88	0.77	0.85	0.71
56%	0.58	0.68	0.95	0.33	0.42	0.59
Average	0.76	0.57	0.8	0.77	0.82	



1/Comparison Contrast
200
100
50
20
10
5
2
1
CSF
1
2
5
10
20
Spatial Frequency

Figure 7



1/Comparison Contrast
50
20
10
5
2
1
Young
Middle
Older
Det
Disc
Det
Disc
Faces
Letters

Figure 8

Table 4

Dependent Variables
Face Detection
Face Discrimination
Letter Detection
Letter Discrimination
Independent Variables
Age
Visual acuity
Contrast-matching at comparison spatial frequencies of:
1.5 c/deg
3
6
12
18
and at standard contrasts of:
5%
9%
19%
35%
56%
Contrast Sensitivity at:
1.5 c/deg
3
6
12
18

Table 5. Regression analysis including age.

Dependent Variable	Independent Variable	R^2 for model
Face Detection	CSF 18 c/deg	0.27
Face Discrimination	Age CM 5% 3 c/deg CSF 1.5 c/deg	0.82
Letter Detection	Age	0.56
Letter Discrimination	Age CM 5% 3 c/deg	0.81

Table 6. Regression analysis excluding age.

Dependent Variable	Independent Variable	R^2 for model
Face Detection	CSF 18 c/deg	0.27
Face Discrimination	CSF 18 c/deg	0.31
Letter Detection	CSF 12 c/deg CM 19% 12 c/deg	0.52
Letter Discrimination	CSF 12 c/deg CM 19% 12 c/deg	0.68

Table 7. Correlational matrix between contrast-matching and contrast sensitivity.

		Contrast Sensitivity				
		1.5	3	6	12	18
56%	1.5	-0.72*	-0.05	-0.03	-0.17	-0.45
56%	3	-0.70*	-0.14	-0.28	-0.44	-0.60*
56%	6	0	0.24	0.17	0.24	0.19
56%	12	0.32	0.21	0.03	0.22	0.31
56%	18	-0.09	0	-0.01	0.27	-0.05
35%	1.5	-0.71*	0.02	0/01	0.03	-0.25
35%	3	-0.47*	-0.04	-0.29	-0.22	-0.35
35%	6	0.31	0.48*	0.51*	0.66*	0.80*
35%	12	0.36	0.36	0.10	0.29	0.25
35%	18	0.26	0.17	0.15	0.45	0.44
19%	1.5	-0.56*	-0.10	-0.07	0.17	-0.02
19%	3	-0.19	0.08	-0.26	-0.04	-0.19
19%	6	0.15	0.46*	0.52*	0.68*	0.60
19%	12	0.23	0.33	-0.01	0.15	0.08
19%	18	0.33	0.31	-0.04	0.23	0.20
9%	1.5	-0.41	0.01	-0.09	0.08	0.06
9%	3	0	0.27	0.03	0.13	0.04
9%	6	-0.40	0.36	0.31	0.32	0.13
9%	12	0.19	0.26	-0.07	0.11	0.07
9%	18	0.46*	0.54*	0.46*	0.52*	0.48*
5%	1.5	-0.42	-0.04	0	-0.05	-0.14
5%	3	-0.59*	0.21	0.19	0.07	0
5%	6	-0.19	0.47*	0.30	0.42	0.47*
5%	12	0.27	0.30	0.46*	0.47*	0.55*
5%	18	0.31	0.46*	0.47*	0.56*	0.48*

Table 8. Correlational matrix between standard contrasts at five spatial frequencies.

		5%	9%	19%	35%	56%
5%	1.5	1	0.71	0.63	0.69	0.45
	3	1	0.46	0.26	0.42	0.51
	6	1	0.56	0.57	0.28	-0.25
	12	1	0.84	0.76	0.8	0.46
	18	1	0.74	0.7	0.61	0.21
9%	1.5	0.71	1	0.79	0.52	0.29
	3	0.46	1	0.76	0.56	0.19
	6	0.56	1	0.24	0.1	0.11
	12	0.84	1	0.95	0.93	0.71
	18	0.74	1	0.88	0.56	0.08
19%	1.5	0.63	0.79	1	0.75	0.45
	3	0.26	0.76	1	0.78	0.33
	6	0.57	0.24	1	0.67	0.12
	12	0.76	0.95	1	0.9	0.76
	18	0.7	0.88	1	0.7	0.33
35%	1.5	0.67	0.52	0.75	1	0.73
	3	0.42	0.56	0.78	1	0.71
	6	0.28	0.1	0.67	1	0.31
	12	0.8	0.93	0.9	1	0.75
	18	0.61	0.56	0.7	1	0.43
56%	1.5	0.45	0.29	0.45	0.73	1
	3	0.51	0.19	0.33	0.71	1
	6	-0.25	0.11	0.12	0.31	1
	12	0.46	0.71	0.76	0.75	1
	18	0.21	0.08	0.33	0.43	1

Table 9. Descriptive statistics for observers in Experiment 4.

Age Group	N	MAR Acuity	Acuity Stan Dev
5-20	59	.9	.24
20-30	61	.9	.19
30-40	31	1	.44
40-50	45	1.2	.41
50-60	34	1.5	.87
60-70	59	1.4	.58
70-80	36	1.5	.25
80-90	11	1.7	.41

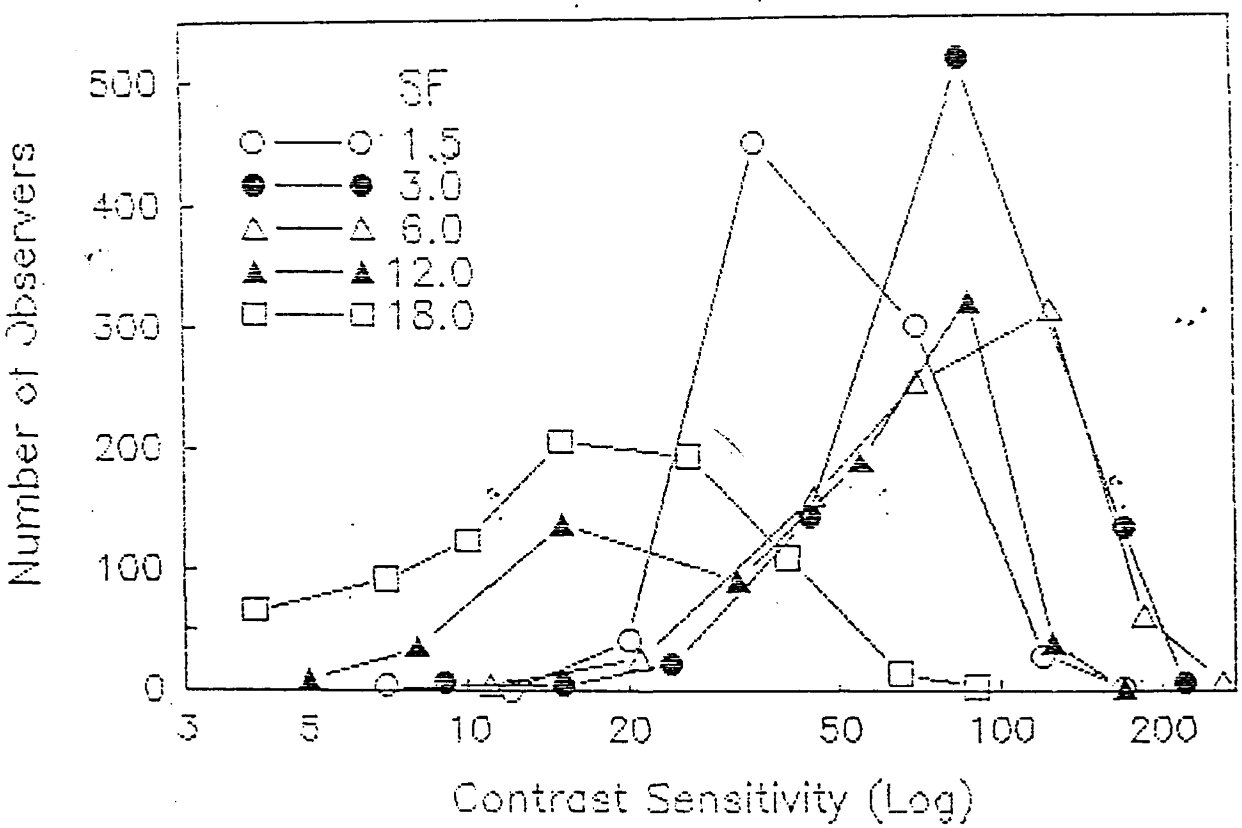

SF
1.5
3.0
6.0
12.0
18.0
500
400
300
200
100
0
Number of Observers
3
5
10
20
50
100
200
Contrast Sensitivity (Log)

Figure 9

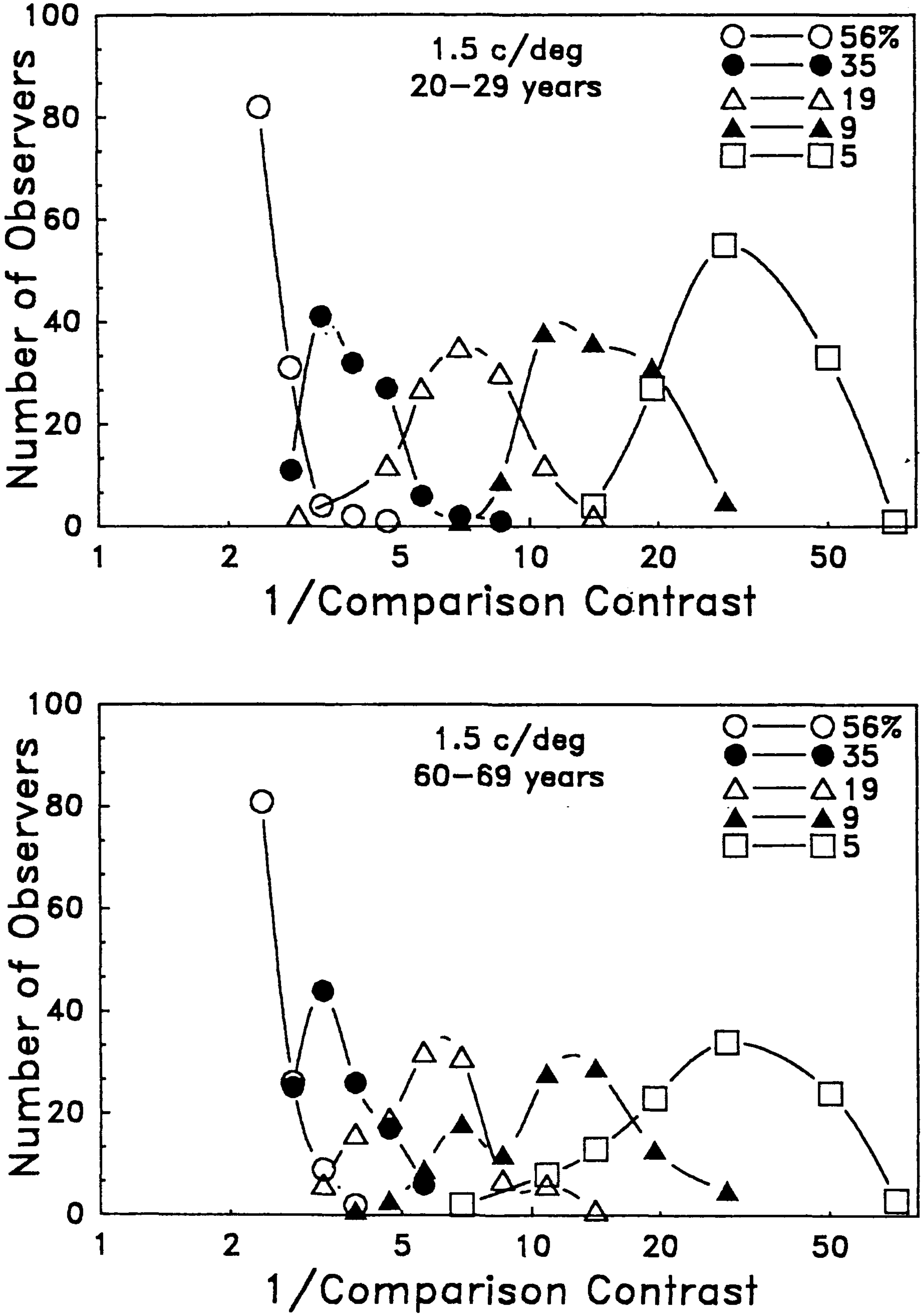

1.5 c/deg
20–29 years
56%
35
19
9
5
Number of Observers
100
80
60
40
20
0
1
2
5
10
20
50
1/Comparison Contrast
1.5 c/deg
60–69 years
56%
35
19
9
5
Number of Observers
100
80
60
40
20
0
1
2
5
10
20
50
1/Comparison Contrast

Figure 10

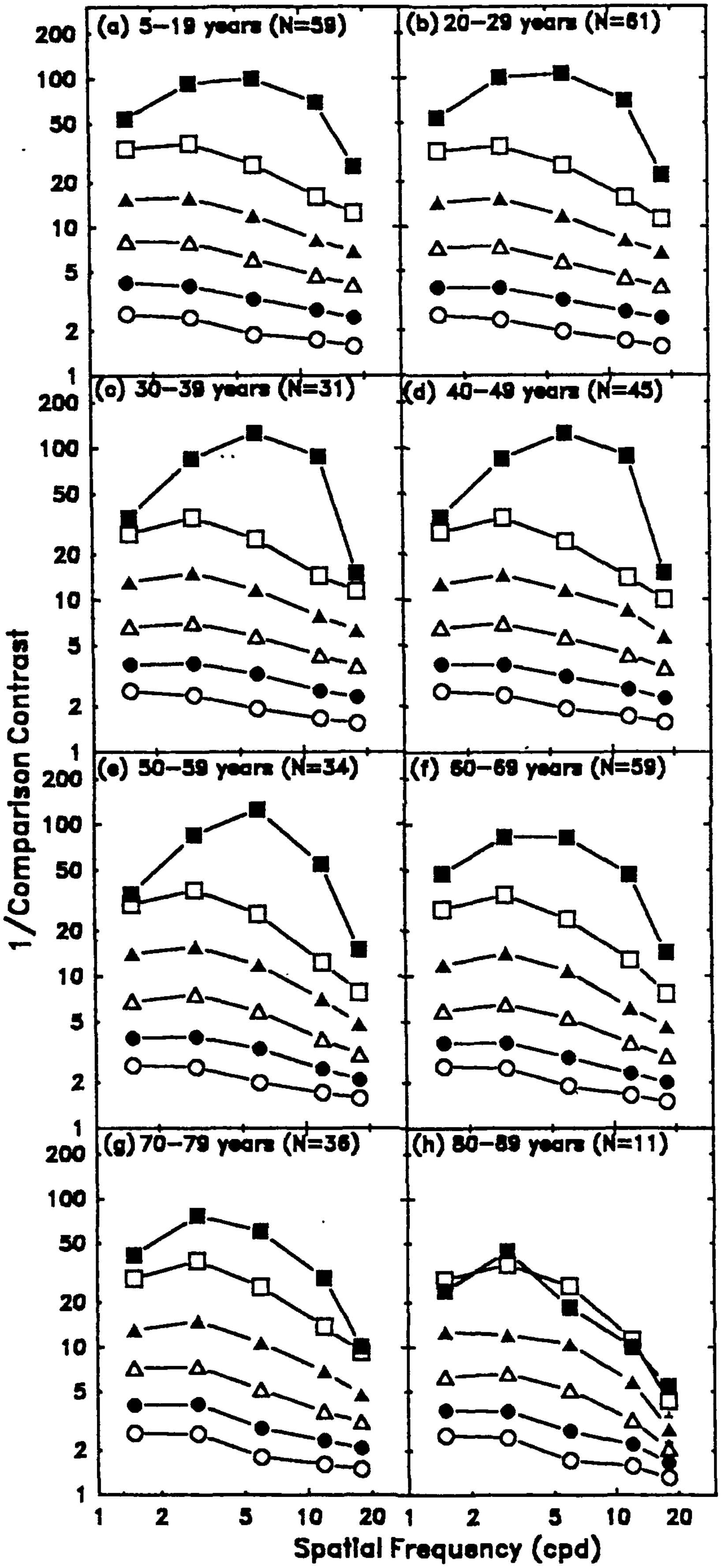
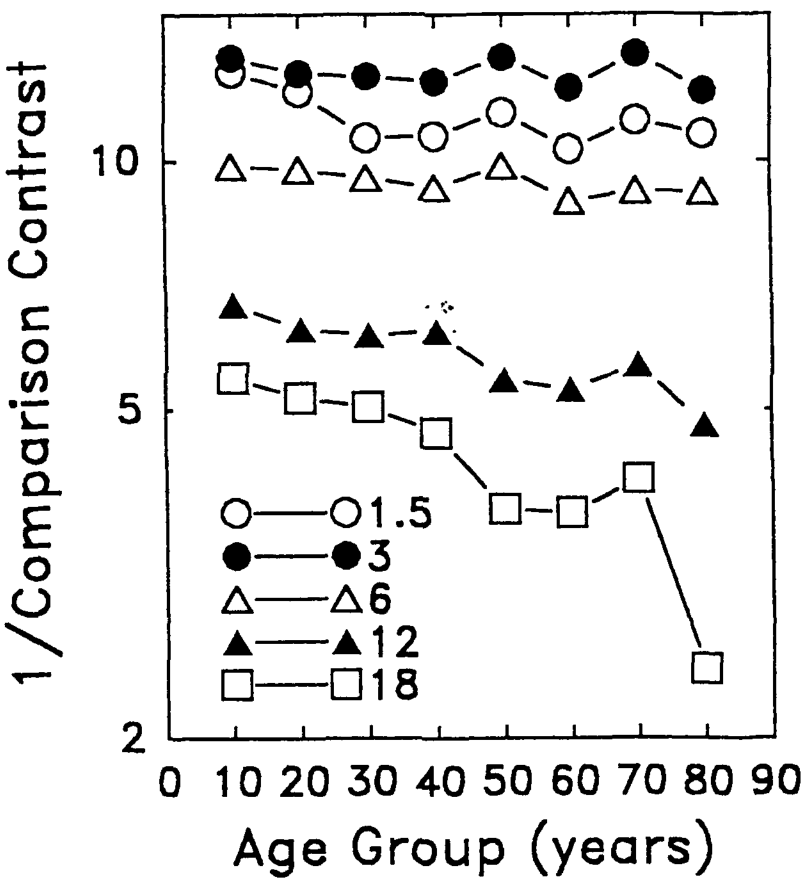
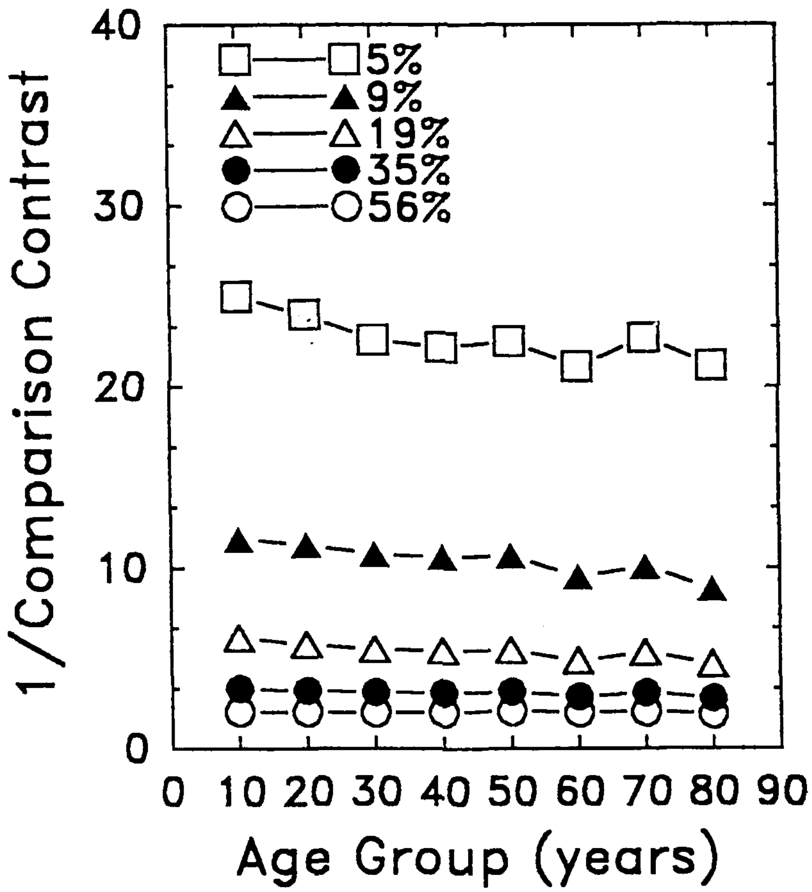

(a) 5–19 years (N=59)
(b) 20–29 years (N=61)
(c) 30–39 years (N=31)
(d) 40–49 years (N=45)
(e) 50–59 years (N=34)
(f) 60–69 years (N=59)
(g) 70–79 years (N=36)
(h) 80–89 years (N=11)
1/Comparison Contrast
Spatial Frequency (cpd)
1
2
5
10
20
50
100
200

Figure 11



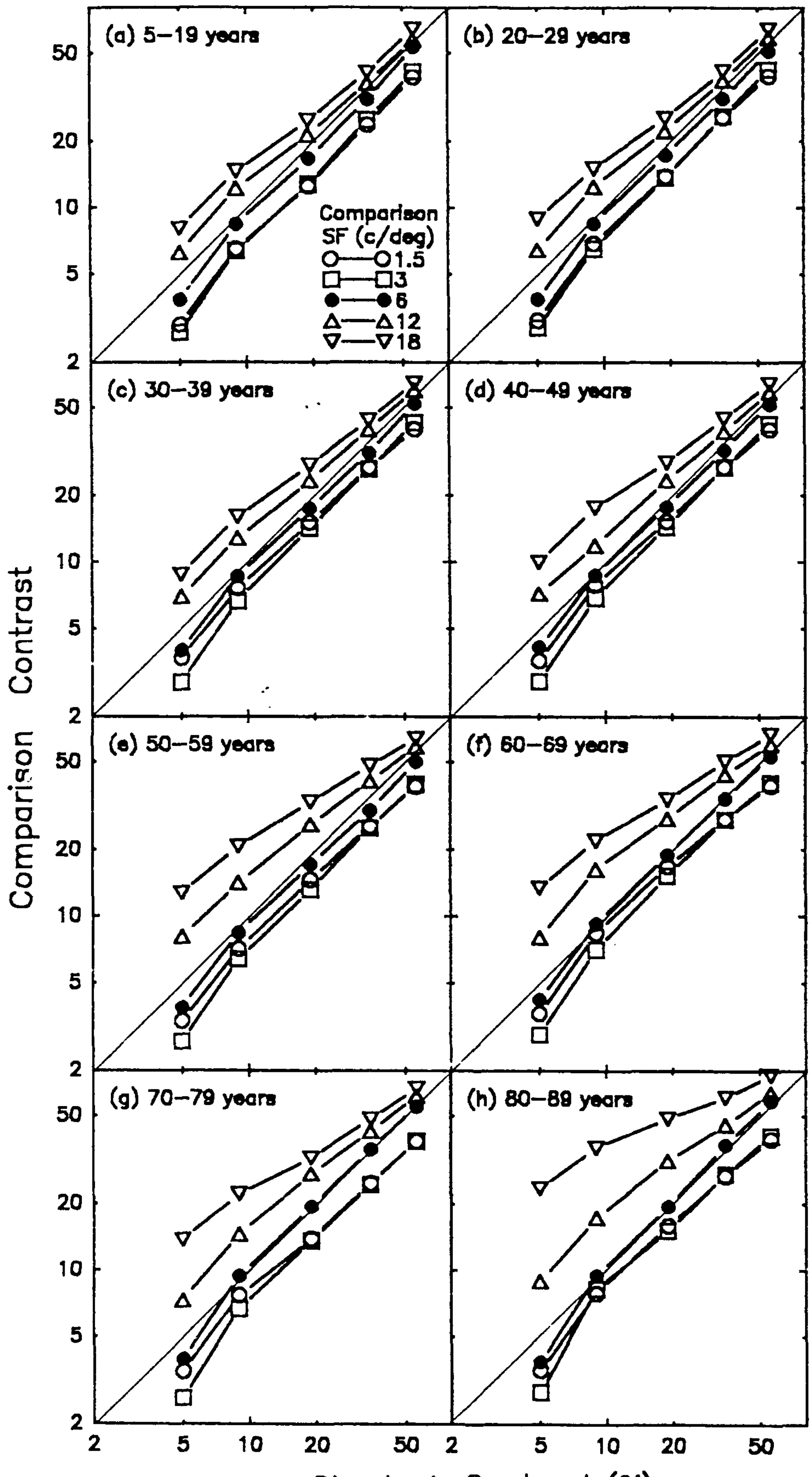
1/Comparison Contrast
10
5
2
0
10
20
30
40
50
60
70
80
90
Age Group (years)
1.5
3
6
12
18

Figure 12



40
30
20
10
0
1/Comparison Contrast
5%
9%
19%
35%
56%
0
10
20
30
40
50
60
70
80
90
Age Group (years)

Figure 13



(a) 5–19 years
(b) 20–29 years
(c) 30–39 years
(d) 40–49 years
(e) 50–59 years
(f) 60–69 years
(g) 70–79 years
(h) 80–89 years
Comparison SF (c/deg)
1.5
3
6
12
18
Comparison Contrast
Standard Contrast (%)
2
5
10
20
50

Figure 14

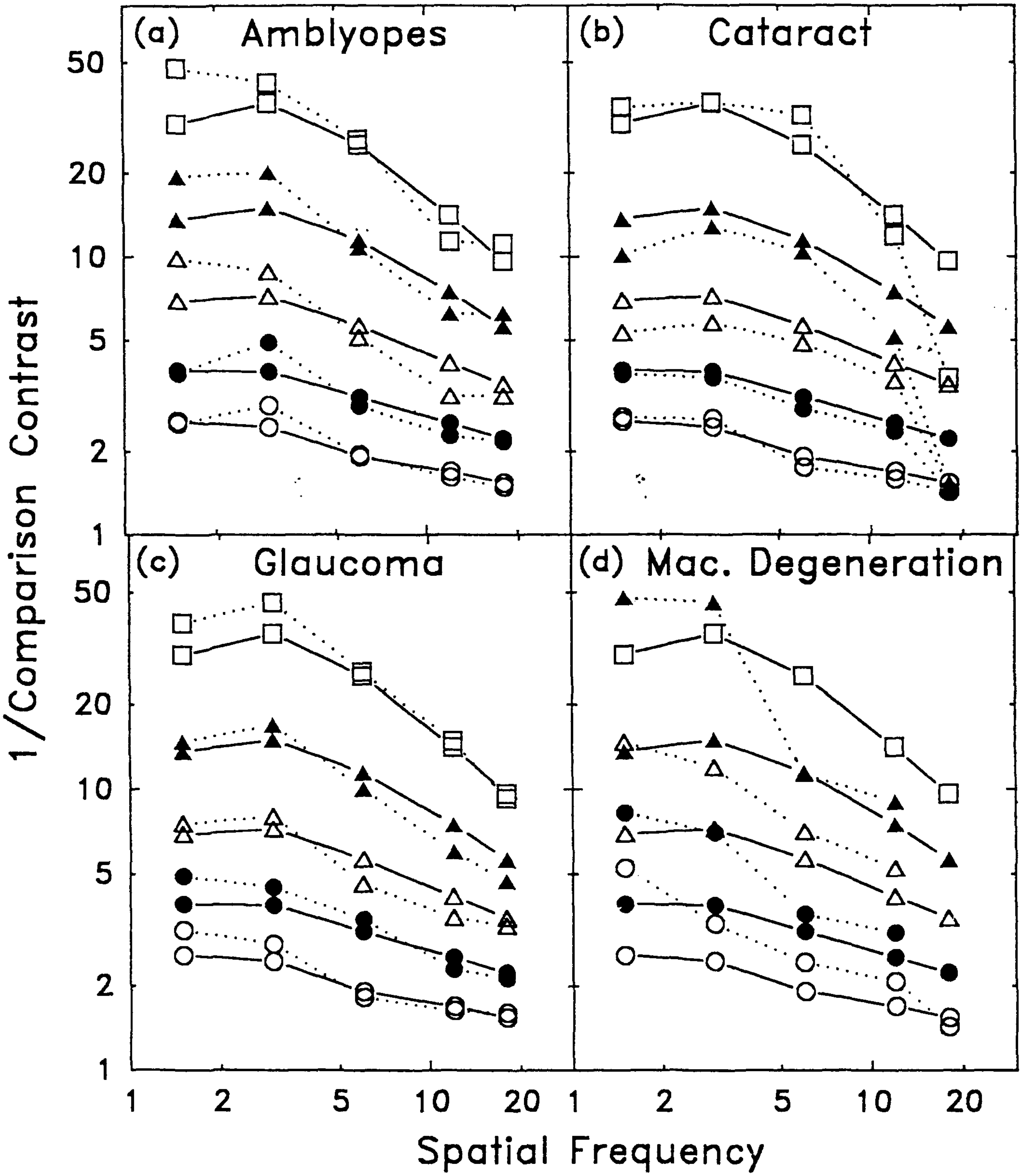
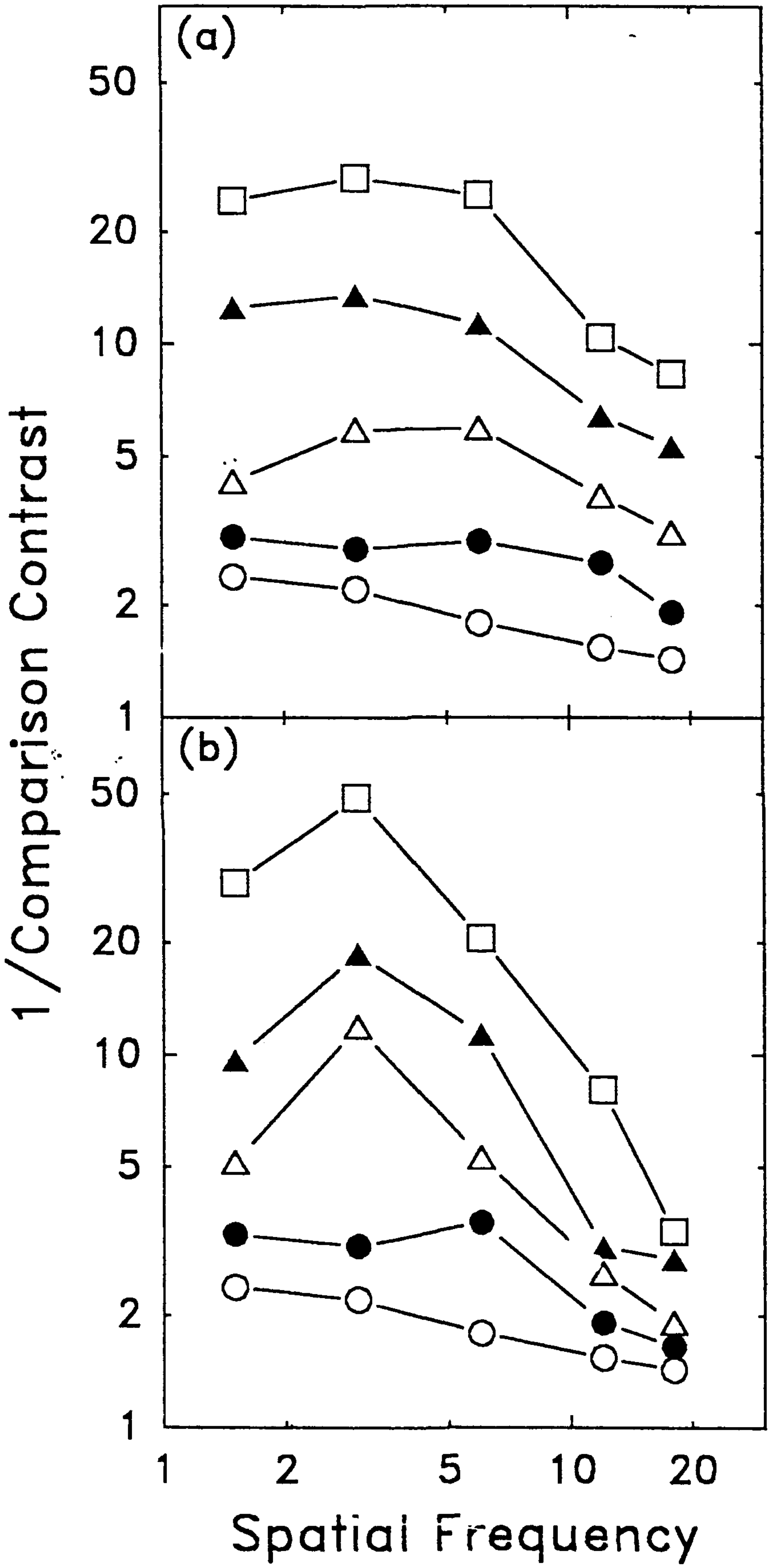

(a) Amblyopes
(b) Cataract
(c) Glaucoma
(d) Mac. Degeneration
1/Comparison Contrast
50
20
10
5
2
1
Spatial Frequency
1
2
5
10
20

Figure 15

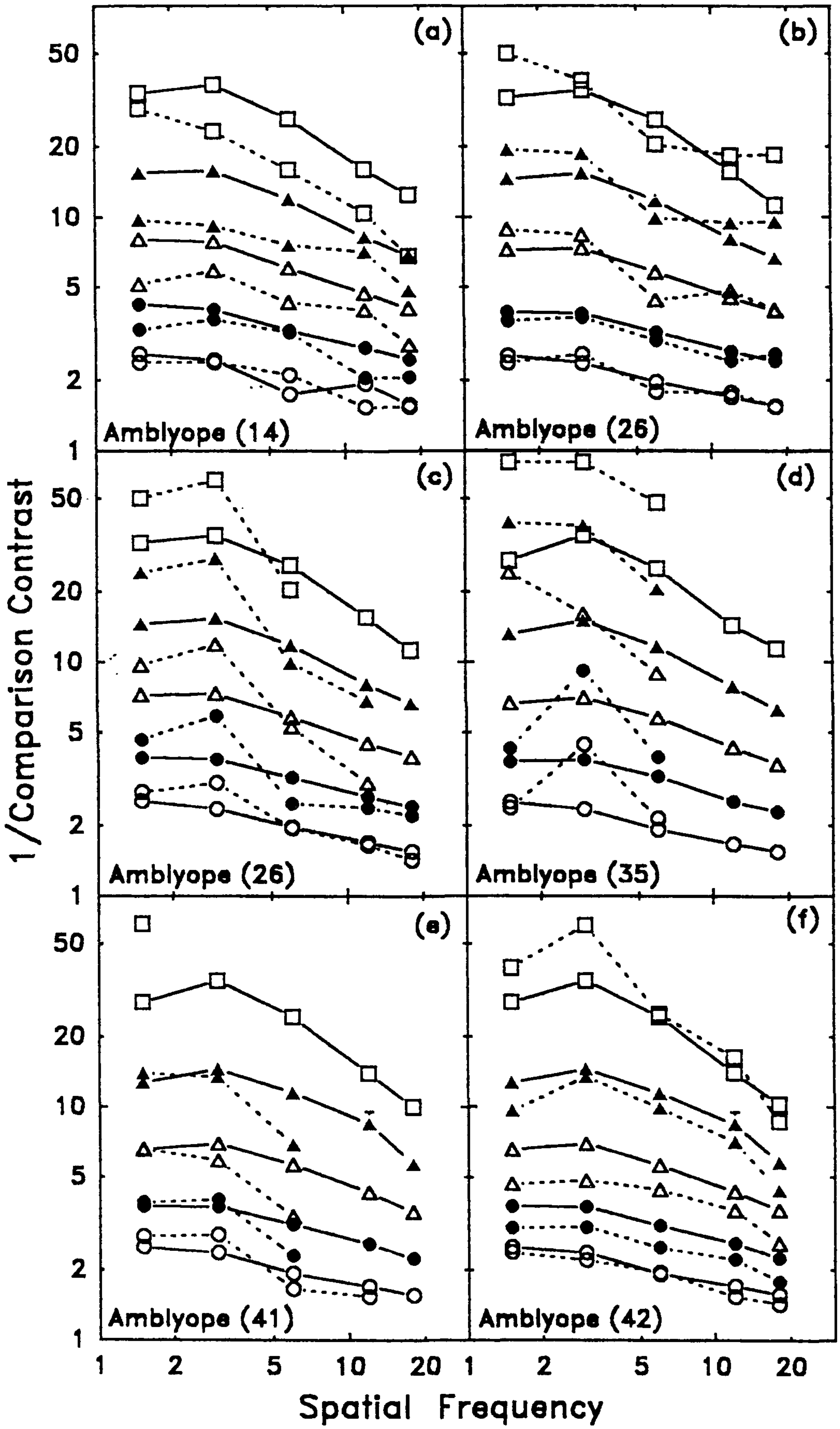


(a)
(b)
50
20
10
5
2
1
1/Comparison Contrast
1
2
5
10
20
Spatial Frequency

Figure 16

Table 10. Number of contrast matching scores higher, lower and the same as normative controls for four clinical groups.

	Amblyope			Cataract			Glaucoma			Mac Deg		
# eyes	6			5			10			2		
	H	L	S	H	L	S	H	L	S	H	L	S
Low SF												
5	-	3	3	1	2	-	4	5	1	-	-	-
9	1	2	3	3	-	2	4	4	2	-	1	-
19	2	2	2	2	-	3	2	2	6	-	2	-
35	-	2	4	-	1	4	1	4	5	-	2	-
56	-	1	5	-	1	4	-	4	6	-	2	-
Sum	3	10	17	6	4	13	11	19	20	0	7	0
6 c/deg												
5	1	1	3	1	2	2	1	2	7	-	-	-
9	2	1	3	-	-	5	3	1	6	-	-	1
19	2	1	3	1	-	4	4	-	6	-	1	1
35	3	-	3	1	1	3	2	1	7	-	-	2
56	-	-	6	-	1	4	1	1	8	-	2	-
Sum	8	3	18	3	4	18	11	5	34	0	3	4
High SF												
5	1	-	2	1	1	2	2	2	4	-	-	-
9	-	-	4	2	1	2	2	1	5	-	-	-
19	1	-	3	2	1	2	4	-	4	-	-	1
35	1	-	3	-	-	5	3	1	6	-	-	2
56	-	1	4	-	-	5	-	-	10	-	1	1
Sum	3	1	16	5	3	16	11	4	29	0	1	4



(a)
(b)
(c)
(d)
(e)
(f)
Amblyope (14)
Amblyope (26)
Amblyope (26)
Amblyope (35)
Amblyope (41)
Amblyope (42)
1/Comparison Contrast
Spatial Frequency
1
2
5
10
20
50

Figure 17

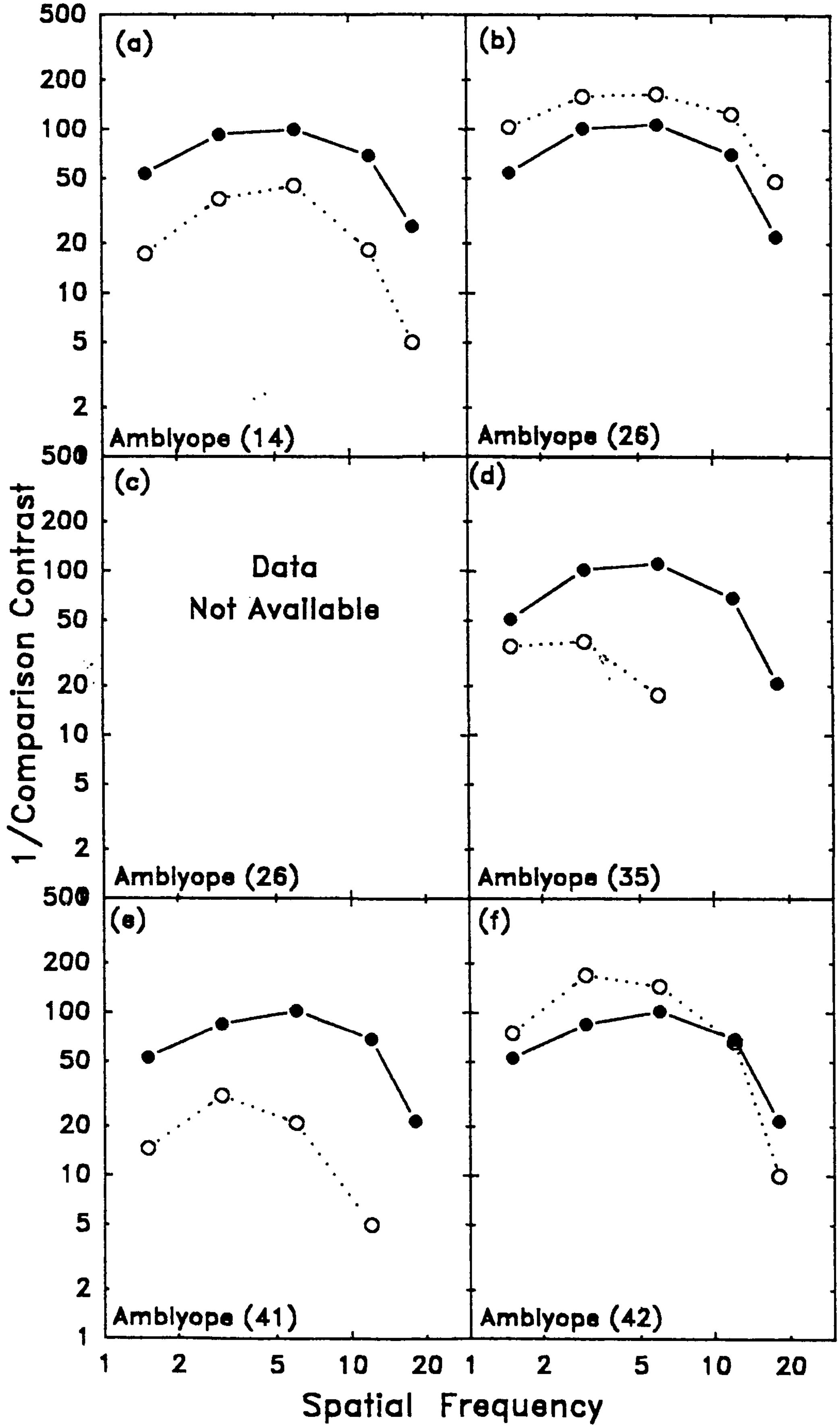

(a)
Amblyope (14)
(b)
Amblyope (26)
(c)
Data
Not Available
Amblyope (26)
(d)
Amblyope (35)
(e)
Amblyope (41)
(f)
Amblyope (42)
1/Comparison Contrast
Spatial Frequency

Figure 18

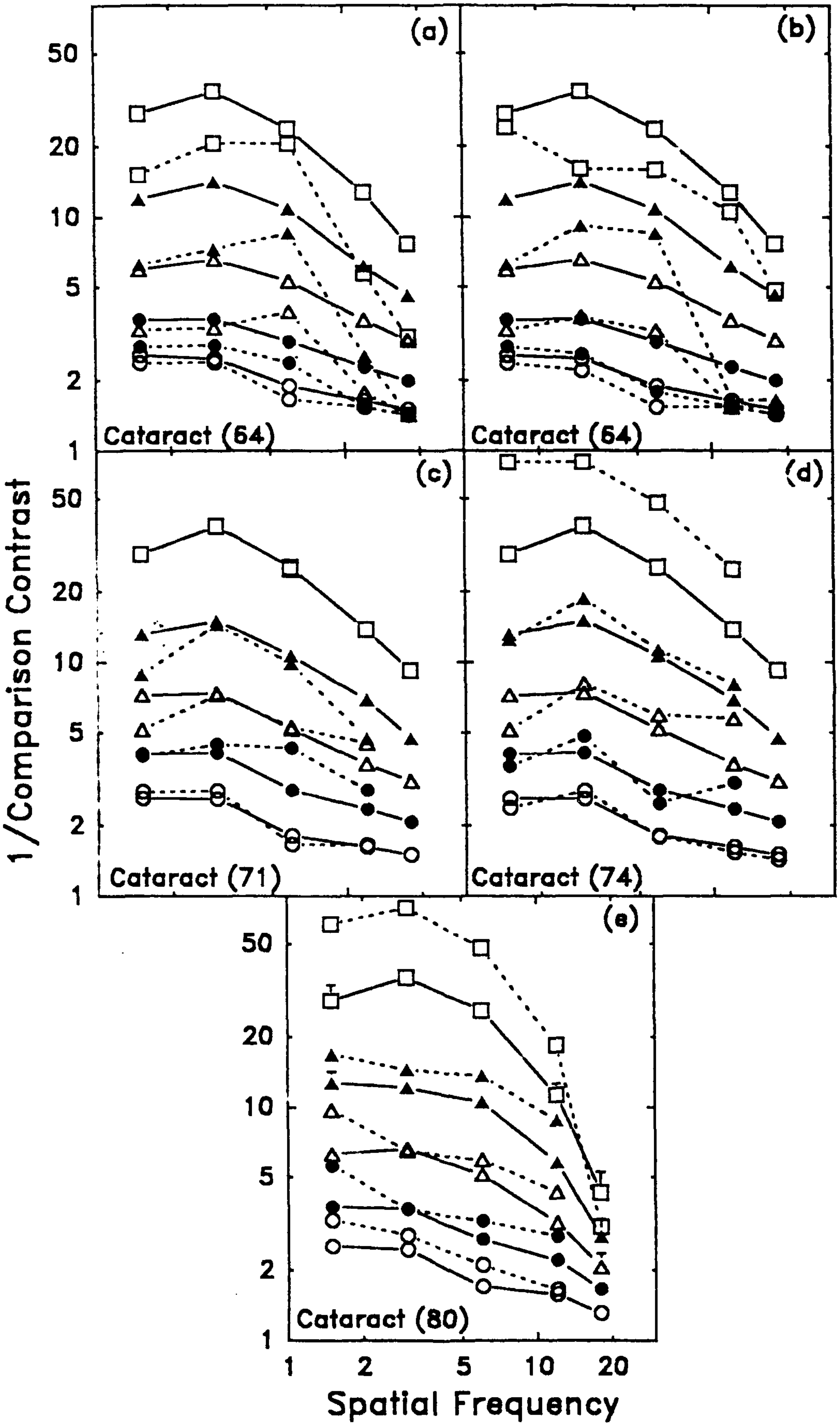

(a)
(b)
(c)
(d)
(e)
50
20
10
5
2
1
Cataract (64)
Cataract (64)
Cataract (71)
Cataract (74)
Cataract (80)
1/Comparison Contrast
1
2
5
10
20
Spatial Frequency

Figure 19

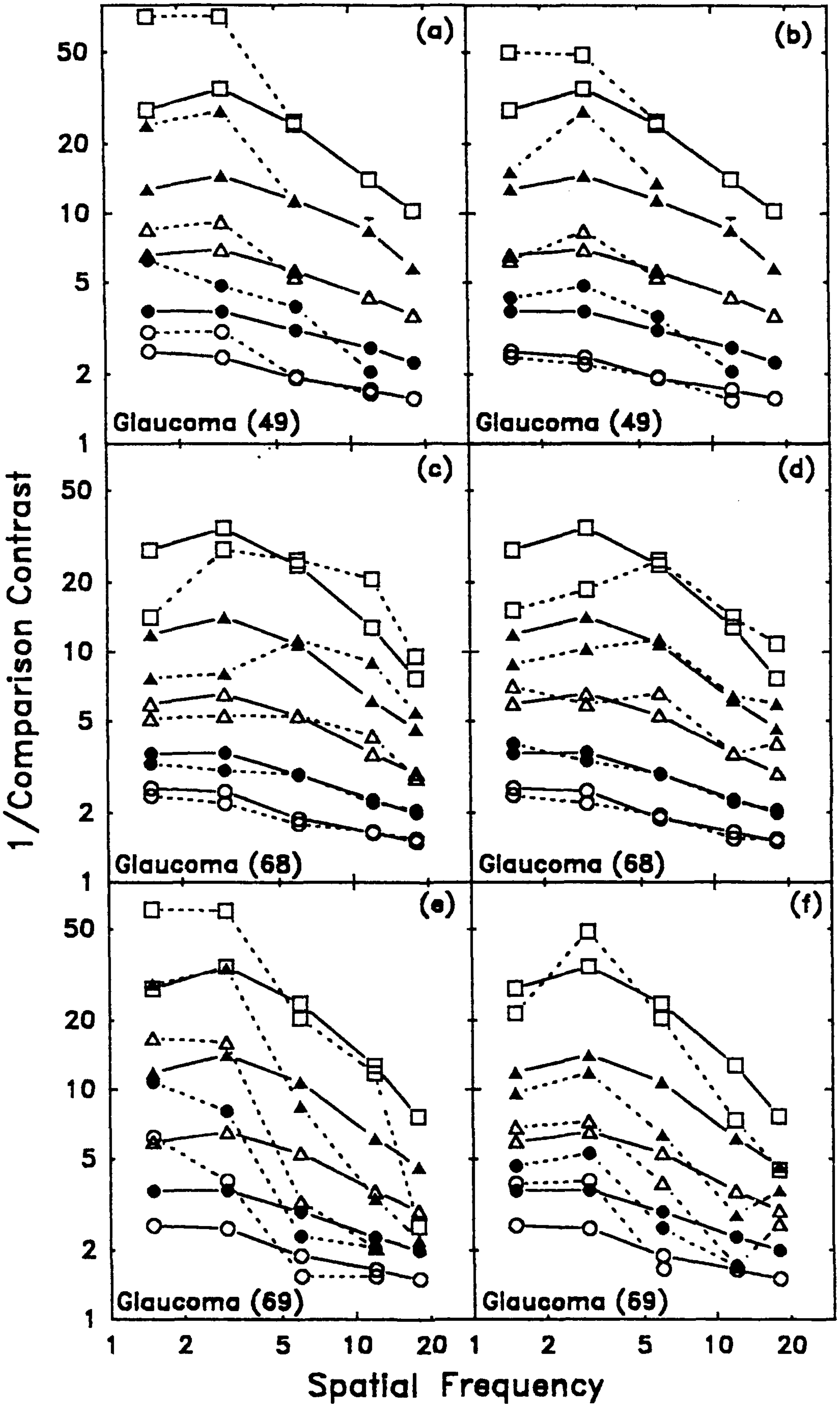
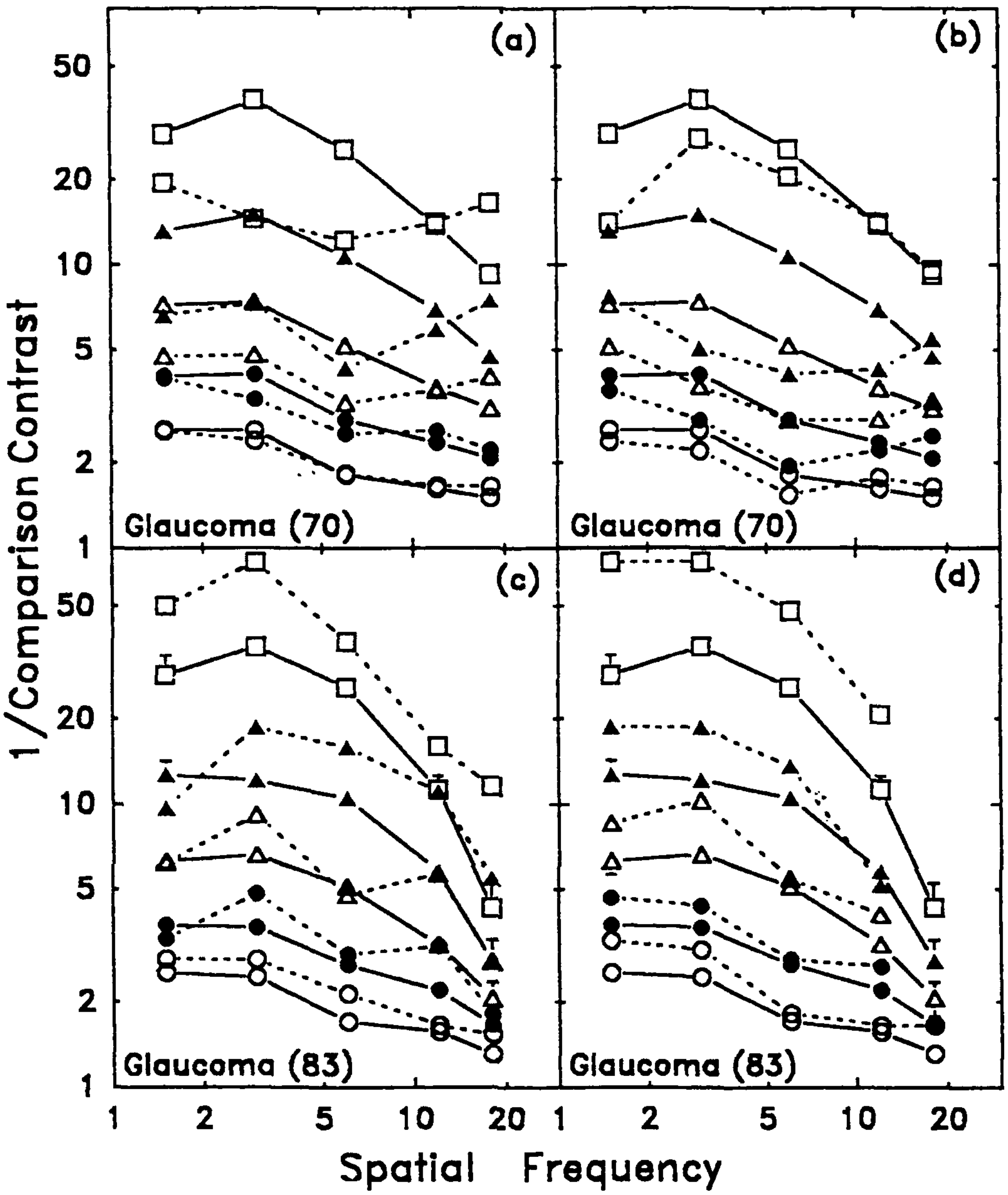
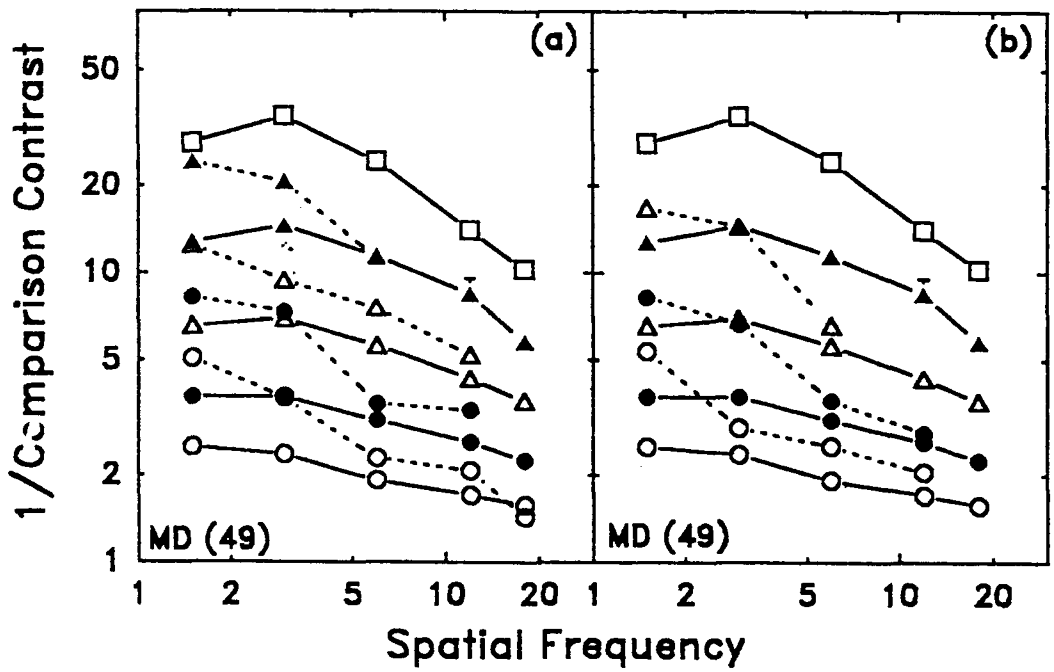

(a)
(b)
(c)
(d)
(e)
(f)
Glaucoma (49)
Glaucoma (49)
Glaucoma (68)
Glaucoma (68)
Glaucoma (69)
Glaucoma (69)
1/Comparison Contrast
Spatial Frequency
1
2
5
10
20
50

Figure 20



(a)
(b)
(c)
(d)
1/Comparison Contrast
50
20
10
5
2
1
Glaucoma (70)
Glaucoma (70)
Glaucoma (83)
Glaucoma (83)
1
2
5
10
20
Spatial Frequency

Figure 21



(a)
(b)
1/Comparison Contrast
50
20
10
5
2
1
MD (49)
MD (49)
1
2
5
10
20
Spatial Frequency

Figure 22