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Individual Letter Contrast Thresholds: Effect of Object Frequency and Noise

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Abstract

Purpose—To compare differences in contrast threshold among individual Sloan letters presented in additive white luminance noise and in the absence of noise.

Methods—Contrast threshold for letter identification was measured for 3 visually normal subjects (ages 22, 25, 34 years) using letters from the Sloan set (C, D, H, K, N, O, R, S, V, Z). The letter size was equivalent to 1.5 log MAR and the letters were either unfiltered or band-pass filtered to limit the object frequency content (cycles-per-letter; cpl) to a one-octave wide band centered at 1.25, 2.5, 5, and 10 cpl. Letters were presented for an unlimited duration against a uniform adapting field or in the presence of additive white luminance noise. Contrast threshold for each letter was determined using a 10 alternative forced choice interleaved staircase procedure.

Results—For standard unfiltered Sloan letters presented against a uniform field, contrast threshold for individual letters differed by as much as a factor of 1.5, consistent with a previous report. When measured in luminance noise, the individual letters differed by as much as a factor of 1.8. Bandpass filtering the letters to include only low object frequencies increased the differences in contrast threshold among the individual letters (approximately a factor of 3) compared to unfiltered letters and letters filtered into high object frequency bands.

Conclusions—The addition of white luminance noise had relatively small effects on inter-letter contrast threshold differences, whereas band-pass filtering had large effects on inter-letter threshold differences, greatly increasing variation among the letters that contained only low object frequencies. Letters that contain only high object frequencies may be useful in the design of letter charts because the inter-letter threshold differences are relatively small for these optotypes and the object frequency information mediating identification is known.

Keywords

visual noise; letter identification; contrast threshold; object spatial frequency

Sloan letters are commonly used in the clinical assessment of visual acuity (e.g. the Lighthouse Distance Visual Acuity Chart) and contrast sensitivity (e.g. the Pelli-Robson

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contrast sensitivity chart). The standard Sloan letter set consists of 10 letters (C, D, H, K, N, O, R, S, V, Z) that were originally selected for visual acuity testing.[1] These 10 letters have been shown to be similarly identifiable when presented at a large size (1.3 log MAR) in tests of contrast sensitivity.[2] In clinical tests, the use of a set of similarly identifiable letters is important to ensure that the differences within a line (inter-letter differences) are less than the difference between lines. However, inter-letter differences in contrast sensitivity become greater (differences of approximately a factor of two among the 10 letters) for letters that approach the visual acuity limit.[2] The explanation for the increased inter-letter contrast sensitivity differences at small sizes may be related to the object frequency information (measured in cycles per letter, cpl[3]) that mediates letter contrast sensitivity for small versus large letters. That is, identification of small letters tends to be based on low object frequencies that correspond to the general shape of the letter,[2, 4–6] whereas higher object frequencies that correspond to edges are used for larger letters.[2, 6, 7]

As reviewed elsewhere,[8] there is less useful information for letter identification for letters that are limited to low object frequencies (i.e. blurry letters) than for letters restricted to high object frequencies. This would be expected to increase confusion among low-pass filtered letters compared to high-pass filtered letters, leading to larger differences in contrast sensitivity among individual letters when identification is based on low object frequencies. In addition to the use of low object frequencies for small letters, the optics of the eye can attenuate high object frequencies, requiring judgments to be based on (blurry) low object frequency information.[9] The attenuation due to optical factors may be particularly great in patient populations with degraded ocular optics. Consequently, understanding inter-letter contrast sensitivity differences for both standard and filtered optotypes is important for clinical testing. However, the relationship between inter-letter contrast sensitivity differences and the object frequency information that underlies letter identification has not been studied systematically.

In standard tests of visual acuity and contrast sensitivity, individual letters are typically presented against a uniform field, but studies have suggested that an additional measurement made in the presence of additive white luminance noise can provide important information regarding the factors mediating performance.[10–12] In fact, a diagnostic test for amblyopia has been proposed that compares visual acuity measurements for Sloan letters made in the presence and absence of white luminance noise.[11] Furthermore, it has recently been shown that luminance noise can shift the object frequency information mediating letter contrast sensitivity to higher values,[13] a finding most pronounced for large letters. A shift to higher object frequencies, due to the addition of noise, may be expected to reduce inter-letter threshold differences, as high object frequencies convey letter identity information that is more reliable than low object frequencies, as noted above. Alternatively, each letter has a unique frequency spectrum and noise may act to elevate contrast threshold for certain letters more than others, which would increase inter-letter threshold differences. For example, noise masking of the gap in the letter ‘C’ may markedly elevate threshold, compared to a smaller threshold elevation due to noise masking of other Sloan letters that contain redundant information. At present, the effect of luminance noise on inter-letter contrast sensitivity differences is not well understood.

The goal of the present study was to determine the extent to which individual Sloan letters have similar contrast thresholds for standard (broad-band) and spatially filtered (narrow-band) letters in the presence and absence of white luminance noise. Large letters (equivalent to the letter size of the Pelli-Robson chart) from the standard Sloan set were either unfiltered or band-pass filtered (1 octave in width; centered at 1.25, 2.5, 5, and 10 cpl). The letter sets were presented in white luminance noise or against a uniform field. Contrast thresholds were determined for each letter individually, which allowed us to assess the extent to which the individual letters have similar contrast thresholds and also permitted the determination of stimulus characteristics that yield the lowest threshold differences among the individual letters. These data will be of use in the development of letter charts for contrast sensitivity measurement that have less variation within a line (due to inter-letter threshold differences) than between lines.

METHODS

Subjects

Three of the authors (ages 22, 25, and 34 years) who have no history of eye disease, normal best-corrected visual acuity assessed with the ETDRS distance visual acuity chart, and normal contrast sensitivity assessed with the Pelli-Robson contrast sensitivity chart served as subjects. The experiments were approved by an institutional review board at the University of Illinois at Chicago and the study adhered to the tenets of the Declaration of Helsinki.

Apparatus and Stimuli

Stimuli were generated using a computer-controlled ViSaGe stimulus generator (Cambridge Research Systems) and were displayed on a Mitsubishi Diamond Pro (2070) CRT monitor with a 100-Hz refresh rate and a screen resolution of 1024 × 768. The only source of illumination in the room was the monitor which was viewed monocularly through a phoropter with the subject's best refractive correction. Luminance values used to generate the stimuli were determined by the ViSaGe linearized look-up table (14-bit DAC resolution), and were verified with a Minolta LS-110 photometer.

Contrast threshold for letter identification was measured using letters from the Sloan set (C, D, H, K, N, O, R, S, V, Z). The letters were either unfiltered or band-pass filtered with a cosine log filter[14] to generate letters that contained a one-octave wide band of frequencies centered at 1.25, 2.5, 5, and 10 cpl. Of note, this choice of center frequency and bandwidth produces non-overlapping frequency bands. Examples of the unfiltered and filtered letter 'H' presented against a uniform adapting field are shown in Fig. 1 (upper row). The letter size was equivalent to 1.5 log MAR (the letter size used for the Pelli-Robson CS chart). Letters were presented for an unlimited duration against a uniform adapting field (50 cd/m^2) or in additive white luminance noise that had a mean luminance of 50 cd/m^2. The static noise field covered an area that was approximately 1.5 times larger than the letter and consisted of independently generated square checks with luminances drawn randomly from a uniform distribution with a root-mean-square contrast of 0.18. The onset and offset of the noise and stimulus were identical (i.e. synchronous static noise). There were three noise checks per letter stroke (15 noise checks per letter). Examples of the unfiltered and band-pass filtered letter ‘H’ presented in white luminance noise are shown in Fig. 1 (lower row).

Contrast threshold was determined for each letter using a 10 alternative forced choice staircase procedure. Ten staircases, one for each letter, were interleaved. The contrast (C) of the unfiltered letters was defined as Weber contrast:

$$C=(L_L - L_B)/L_B \quad (1)$$

where L_L is the luminance of the letter and L_B is the background luminance. The contrast of complex images, such as band-pass filtered letters, is difficult to define[14] and standard definitions such as Weber and Michelson contrast are problematic when applied to complex stimuli. First, a small high-luminance region (and/or low-luminance region) of the filtered letter would define the contrast value, which could be misleading. Second, individual band-pass filtered letters within a set have different luminance profiles and therefore have different Weber (and Michelson) contrast values. To avoid these issues, a relative definition of contrast, which has been used in numerous studies,[e.g. 7, 13, 15, 16] was used to characterize the band-pass filtered letters. Specifically, when the contrast of the original unfiltered letter was 1.0, the filtered letter was also assigned a relative contrast of 1.0, regardless of the complex luminance distribution of the resulting filtered image. As an example, each filtered letter in Fig. 1 was assigned a contrast value of 0.66 because the original unfiltered letter (left) had a contrast value of 0.66.

Procedures

The start of each stimulus presentation was signaled with a brief warning tone. A single letter was selected for each trial at random from the Sloan set. The subject identified the letter verbally, which was then entered by the experimenter; no feedback was given. All three subjects were familiar with the Sloan set and only letters from the Sloan set were accepted as valid responses. A preliminary estimate of threshold was obtained before each staircase by presenting a randomly selected letter at a super-threshold contrast level and then subsequently decreasing the contrast by 0.3 log units until the subject gave an incorrect response. After this preliminary search, log contrast threshold was calculated using a two-down, one-up decision rule, which provides an estimate of the 76% correct point on a psychometric function.[17, 18] Each staircase proceeded until 16 reversals had occurred, and the average of the last 6 reversals was taken as contrast threshold. Excluding the preliminary search, the total staircase duration was typically 35 to 40 trials per letter, which produced stable measurements. The size of the final steps of the staircase was typically 0.03 to 0.1 log units. For each one-hour testing session, a filter band (unfiltered, 1.25, 2.5, 5, and 10 cpl) and a noise paradigm (noise present or absent) were selected pseudorandomly for testing.

Modeling

Inter-letter contrast threshold differences were predicted based on a previous approach of quantifying the “dissimilarity” among letters.[19] In brief, the 10 letters within a set were summed to create a complex hybrid image. Then, each individual letter was subtracted from the mean image and the root-mean-square (rms) contrast of the difference image for each individual letter was calculated as:[14]

$$\mathrm{rms}=\left[\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\overline{x})^2\right]^{1/2}, \quad (2)$$

where x_i is a normalized pixel luminance value such that $0 \leq x_i \leq 1$ and $\overline{x}$ is the mean normalized background level. Individual letters that are highly distinct from the other letters in the set have high rms contrast values. Of note, “dissimilarity” can equivalently be calculated in the frequency domain by obtaining the frequency spectrum of the difference image, as described elsewhere.[19]

RESULTS

Fig. 2 shows log contrast threshold measured in the absence of noise for each of the 10 unfiltered letters (red circles) and for the letters filtered into each object frequency band (given at the right of each function). The log threshold values for the different bands have been displaced vertically to permit visualization of the differences among the letters (the unfiltered, 1.25, 2.5, 5.0, and 10.0 cpl bands have been shifted by 1.78, 0.82, 0.98, 0.44, and 0.16 log units, respectively). The data are displaced such that the mean for each frequency band is aligned at the horizontal gridlines. The solid lines represent the predictions from the model (i.e. the log rms contrasts for each letter). For the unfiltered letter set, contrast thresholds for the individual letters differed by as much as 0.17 log units (a factor of 1.5), which is consistent with previous work using large letters.[2] Band-pass filtering increased the inter-letter threshold differences for the low object frequency bands (the range was 0.50 log units for the 1.25 cpl band and 0.33 log units for the 2.5 cpl band). However, band-pass filtering had smaller effects for the higher frequency bands (the range was 0.16 log units for the 5.0 cpl band and 0.22 log units for the 10.0 cpl band).

The model predictions provided a good account of the data (the root mean-squared error between the model prediction and the data was 0.08) and accounted well for the high contrast thresholds for the letters ‘R’ and ‘S’ of the 1.25 cpl band. That is, these letters had relatively little rms contrast in the difference image (‘R’ and ‘S’ were highly similar to the sum of the letters in the 1.25 cpl set), which resulted in the high contrast thresholds. The model prediction also accounted well for the overall variance within each filter band, indicating minimal differences among the letters of the unfiltered set (as well as the 5.0 and 10.0 cpl sets) and large expected differences among letters in the 1.25 cpl set.

The relationship between the measured contrast threshold and the predicted threshold is further explored in Fig. 3. In Fig. 3, log contrast threshold for each letter in each filter band is plotted as a function of the log rms contrast of the difference image. Each data point represents a different letter, the different symbols represent the different filter bands (given by the key), and the lines are linear regression fits to the data. Fig. 3 shows that letters that have high rms contrast in the difference image generally have low contrast threshold. Overall, thresholds were high for the letters in the 1.25 cpl band (i.e. a vertical shift relative to the other data points in Fig. 3). For example, for a letter with a log rms contrast in the difference image of 0.9, threshold was approximately a factor of two higher for the 1.25 cpl band compared to the 2.5 cpl band. Despite the high thresholds for the letters in the 1.25 cpl band, log contrast threshold was related to the log rms contrast of the difference image. For the two highest frequency bands (5 and 10 cpl) contrast threshold and the rms contrast in the difference image varied only minimally and there was no relationship between log contrast threshold and the log contrast in the difference image.

Log contrast threshold measured in white luminance noise for each of the 10 unfiltered letters (red circles) and for the letters within each filter band (given at the right of each function) is shown in Fig. 4. As in Fig. 2, the log threshold values for the different object frequency bands have been displaced vertically to permit visualization of the differences among the letters (the unfiltered, 1.25, 2.5, 5.0, and 10.0 cpl bands have been shifted by 1.65, 0.72, 0.70, 0.02, and 0.00 log units, respectively). The data are displaced such that the mean for each frequency band is aligned at the horizontal gridlines. The solid lines represent the predictions from the model and are replotted from Fig. 2. For the unfiltered letter set, contrast thresholds for the individual unfiltered letters in noise differed by as much as 0.25 log units (a factor of 1.8), which is larger than the variation observed in the absence of noise (c.f. Fig. 2, red circles). Band-pass filtering increased the inter-letter threshold differences for the low object frequency bands (the range was 0.41 log units for the 1.25 cpl band and 0.38 log units for the 2.5 cpl band). However, band-pass filtering had smaller effects for the higher frequency bands (the range was 0.18 log units for the 5.0 cpl band and 0.19 log units for the 10.0 cpl band). As in Fig. 2, the model predictions provided a good account of the data (the root mean-squared error between the model and the data was 0.07).

The arbitrarily scaled individual letter plots shown in Figs. 2 and 4 allow for comparisons of individual letter thresholds within a band, but do not permit comparison of contrast thresholds among the different filter bands in the presence and absence of noise. To allow comparisons among the different frequency bands, the letter thresholds for each band were averaged for the 10 letters and 3 subjects, the mean threshold data were converted to sensitivity (i.e. 1/threshold), and these data are plotted in Fig. 5. Log contrast sensitivity (CS) is plotted as a function of log filter center frequency for measurements made in the absence of noise (circles) and in the presence of noise (squares). The error bars represent the standard deviation of the 10 letters (after averaging across the three subjects) and the gray boxes represent the range (maximum and minimum CS) for the 10 letters. For example, the upper gray box plotted at minus infinity represents the range of CS for the 10 letters, averaged across the three subjects, such that the maximum of the range (mean log CS of 1.85 for the three subjects) was set by the letter ‘V’ and the minimum of the range (mean log CS of 1.68 for the three subjects) was set by the letter ‘C.’

CS was highest for the unfiltered letters (in both the presence and absence of noise), suggesting that subjects typically use a band of object frequencies that is somewhat greater than one octave in width.[6, 12, 15] The functions relating log CS and log center frequency in the presence and absence of noise both peaked at 2.5 cpl. In fact, the two functions had a similar shape but were displaced vertically by approximately 0.8 log units. That is, noise reduced CS by approximately the same amount for all center frequencies, as would be expected for white noise, which attenuates all spatial frequencies similarly over the frequency region of interest. The standard deviations (and ranges) were greater for the low filter bands (1.25 cpl and 2.5 cpl), compared to the higher object frequency bands (5.0 cpl and 10.0 cpl). This was the case in both the presence and absence of luminance noise. A two-way analysis of variance was performed to compare the effects of noise (present vs absent) and frequency band (unfiltered, 1.25, 2.5, 5.0, 10.0 cpl) on the inter-letter standard deviations. The ANOVA indicated a main effect of frequency band ($F = 11.16$, $p = 0.02$), but not noise ($F = 0.35$, $p = 0.57$). This finding indicates that filtering the letter significantly affects the inter-letter CS differences, whereas adding noise does not significantly affect inter-letter CS differences.

DISCUSSION

This study determined the extent to which individual Sloan letters have similar contrast thresholds for standard letter optotypes and for letters that have been spatially filtered. In general, we found that for standard unfiltered Sloan letters presented against a uniform field, contrast threshold for individual letters differed by as much as a factor of 1.5, consistent with a previous report,[2] whereas in the presence of white luminance noise, the individual letters differed by as much as a factor of 1.8. Band-pass filtering the letters to include only low object frequencies substantially increased the differences in contrast threshold among the individual letters, compared to unfiltered letters and letters filtered into high object frequency bands.

The inter-letter threshold differences could be predicted based on magnitude of the difference between a given letter and all other letters in the set, quantified as the rms contrast of the difference image. This prediction provided a good account of the inter-letter threshold differences under all conditions (letters presented in noise and against a uniform adapting field, as well as for all filter bands). These results are consistent with a previous study that demonstrated that the power in the difference spectrum of letter pairs is a strong predictor of visual acuity.[19]

Letter identification is mediated by relatively low object frequencies for letters of small angular subtense,[2, 4–7, 15, 20] like those used in visual acuity measurements. Consequently, under these conditions, contrast threshold differences among individual letters would be expected to be relatively large. Indeed, the present study found large inter-letter threshold differences for letters that contained only low object frequencies. The explanation for the high inter-letter threshold differences for letters that contain only low object frequencies is that relatively little letter identity information is conveyed by low object frequencies compared to high object frequencies. This can be appreciated in Fig. 1 by comparing the 'H' filtered into a low object frequency band (e.g. 1.25 cpl) to that filtered into a high object frequency band (e.g. 10 cpl): when the 'H' only contains frequencies near 1.25 cpl, distinguishing among 'H', 'K' or 'N' is difficult. Conversely, when the 'H' only contains frequencies near 10 cpl, distinguishing among the other letters is less prone to error. This result is consistent with the low inter-letter threshold differences in an acuity task reported for pseudo-high-pass-filtered letters ("vanishing optotypes"), compared to standard broadband letters.[21]

Despite the large inter-letter contrast threshold differences for letters that contain only low object frequencies, a subset of letters can be selected from the 1.25 cpl band that differ in threshold by less than 0.15 log units (i.e. less than the change in contrast between letter triplets on the Pelli-Robson CS chart): ‘D,’ ‘H,’ and ‘K’ differ by 0.11 log units in the absence of noise. These results also indicate that removal of the letters ‘C’ and ‘V’ from the standard unfiltered Sloan letter set would likely reduce the inter-letter contrast threshold difference from approximately 0.17 log units (full Sloan set) to 0.09 (8 letters). This finding is consistent with previous work[22, 23] that suggested limiting the effects of confusion between ‘O’ and ‘C’ by accepting ‘C’ for ‘O’ and ‘O’ for ‘C.’

The addition of white luminance noise tended to increase the threshold differences among letters, but the increased variation was small and not statistically significant. This finding is somewhat surprising, as noise obscures critical details (e.g. the gap in the ‘C’) that are used to differentiate among the letters. This might be expected to increase confusion among certain letters thereby increasing the inter-letter threshold differences. However, this was not found to be the case, which supports the use of the full Sloan letter set (or at least 8 of the 10 letters) in CS measurements performed in the presence and absence of noise.

In conclusion, inter-letter CS differences are relatively small for the standard large letter targets that are typically used in CS measurements. However, restricting the spatial frequency content to low object frequencies greatly increased the differences in contrast threshold among letters. Conversely, letters that contained only high object frequencies had relatively small differences in contrast threshold among letters. Letters that have been band-pass filtered to include only high object frequencies may be useful for future clinical charts, as these optotypes reduce inter-letter contrast threshold differences and the object frequency information mediating identification is known. These features may help increase reliability in future clinical tests.

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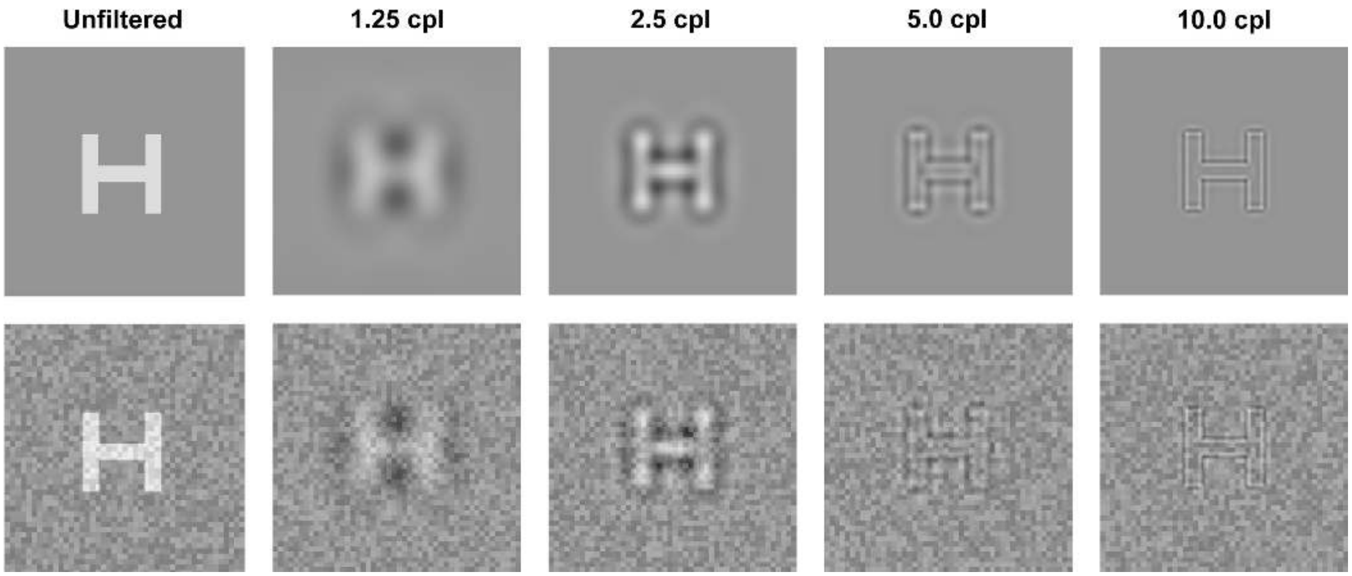

Figure 1.

Examples of unfiltered and band-pass filtered letter stimuli. The letter H is shown in the absence of noise (top row) and in additive white luminance noise (bottom row).

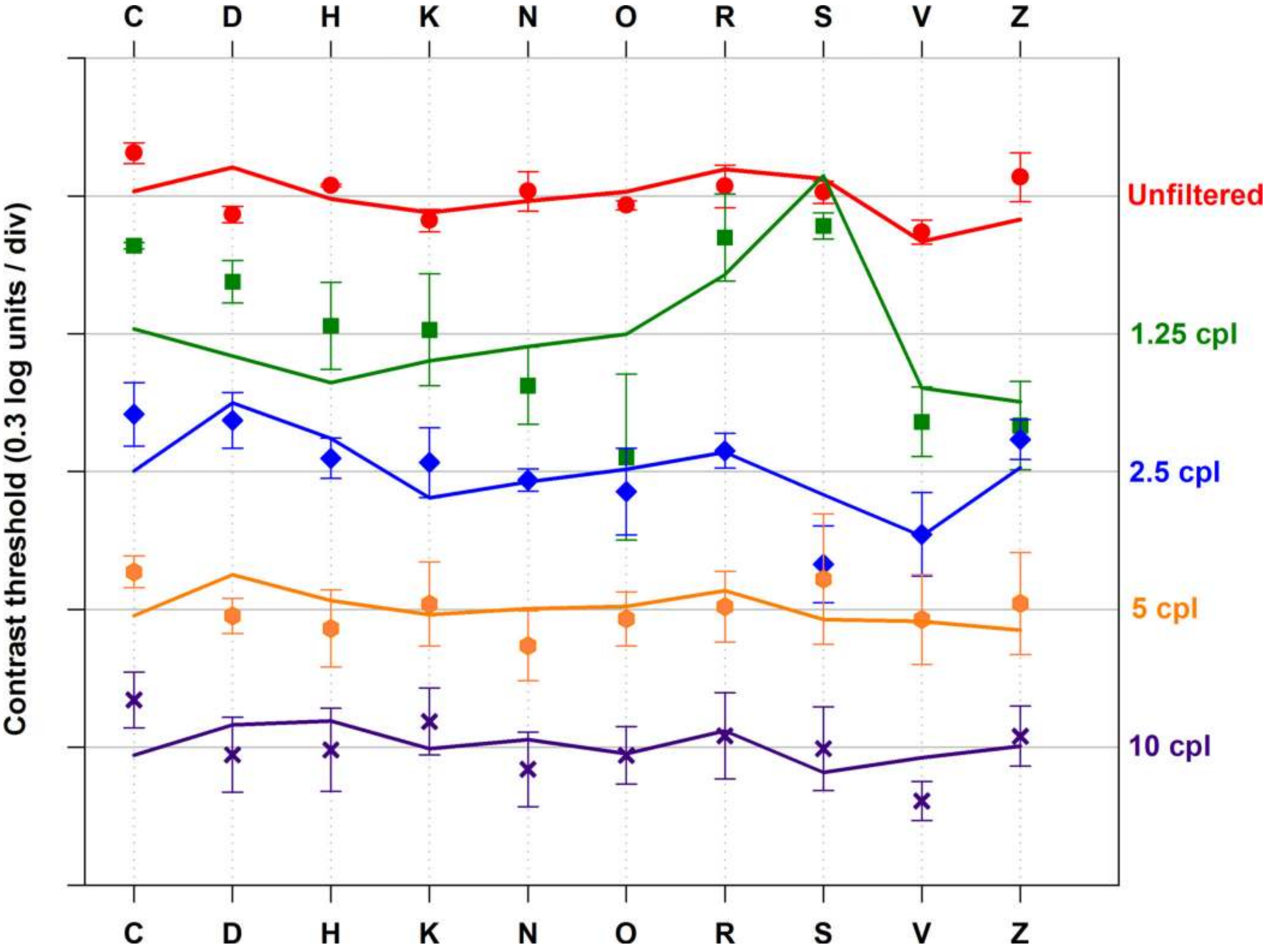

Figure 2.

Mean log contrast threshold (± 1 SEM) of the three subjects for the individual Sloan letters. The top function represents threshold for the 10 unfiltered letters. The four lower functions represent threshold for letters filtered into different frequency bands, as indicated to the right. The solid lines are predictions of the model, as described in the text. A color version of this figure is available online at www.optvissci.com.

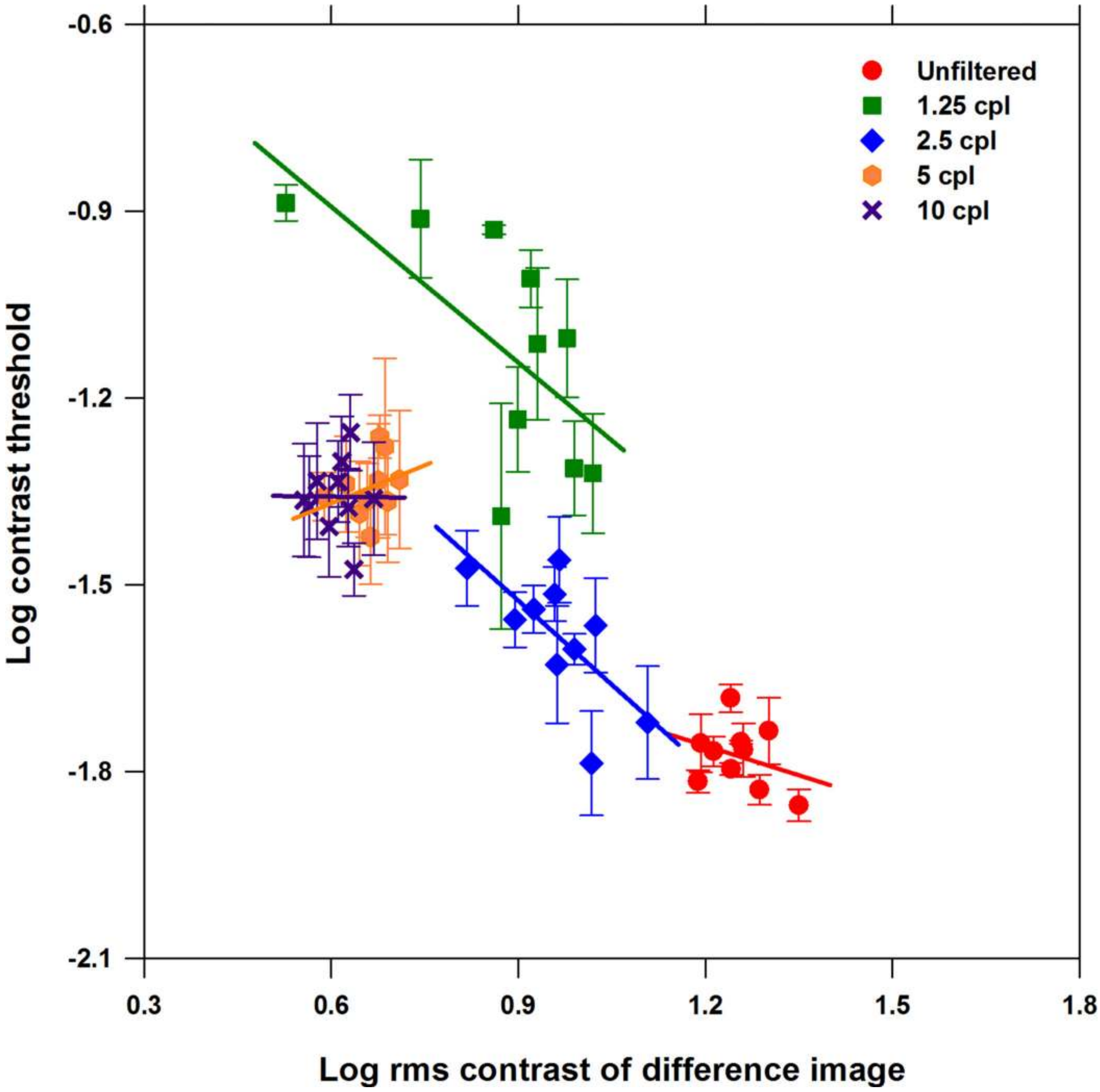

Figure 3.

Mean log contrast threshold for the three subjects (± 1 SEM) for the individual letters as a function of the individual letter's log rms contrast difference value. Each symbol represents a different letter in a filter band (given by the key) and the lines are linear regression fits to the data. A color version of this figure is available online at www.optvissci.com.

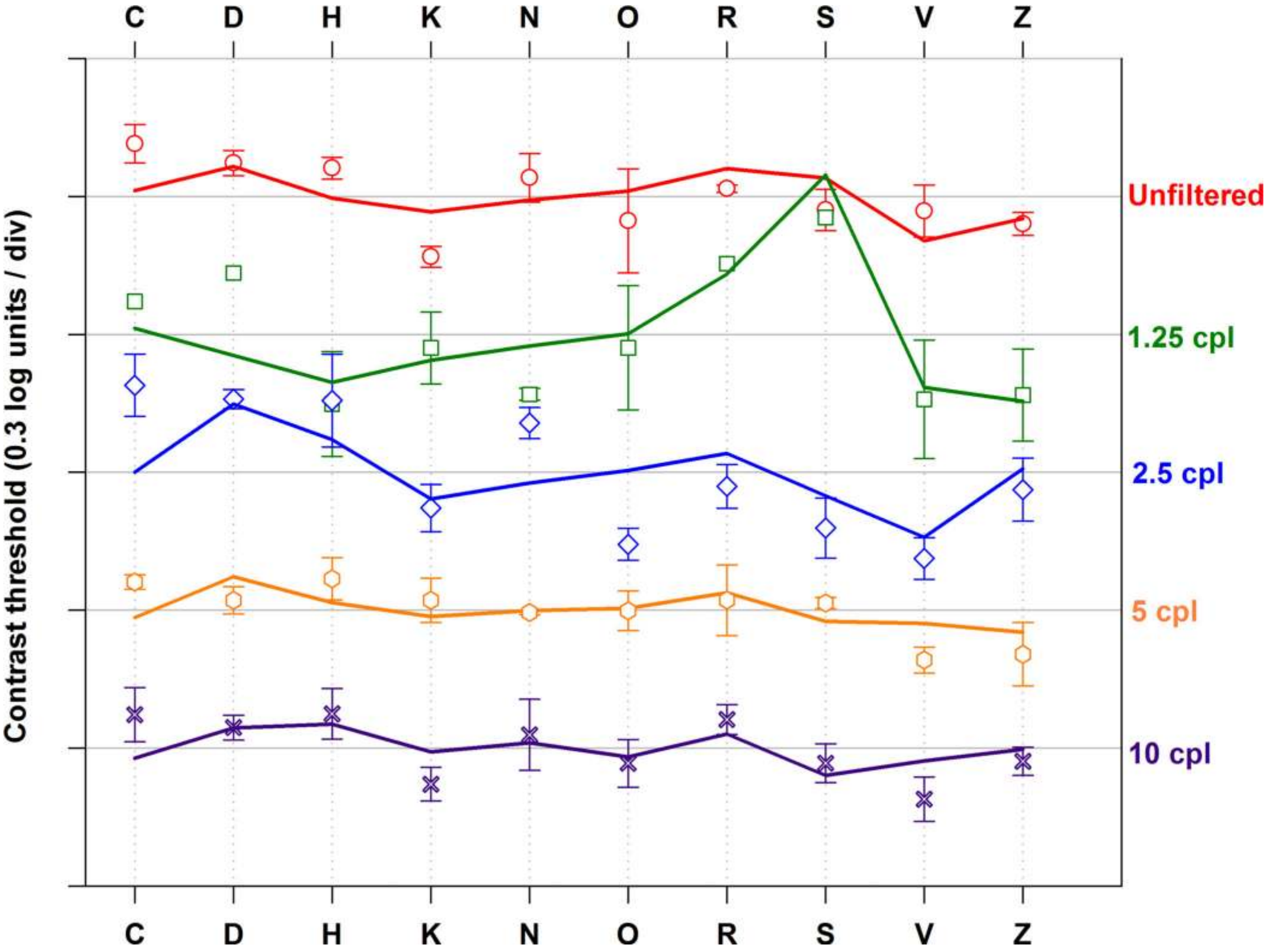

Figure 4.

Mean log contrast threshold (± 1 SEM) of the three subjects for the individual Sloan letters presented in white noise. The top function represents threshold for the 10 unfiltered letters. The four lower functions represent threshold for letters filtered into different frequency bands, as indicated to the right. The solid lines are predictions of the model, as described in the text. A color version of this figure is available online at www.optvissci.com.

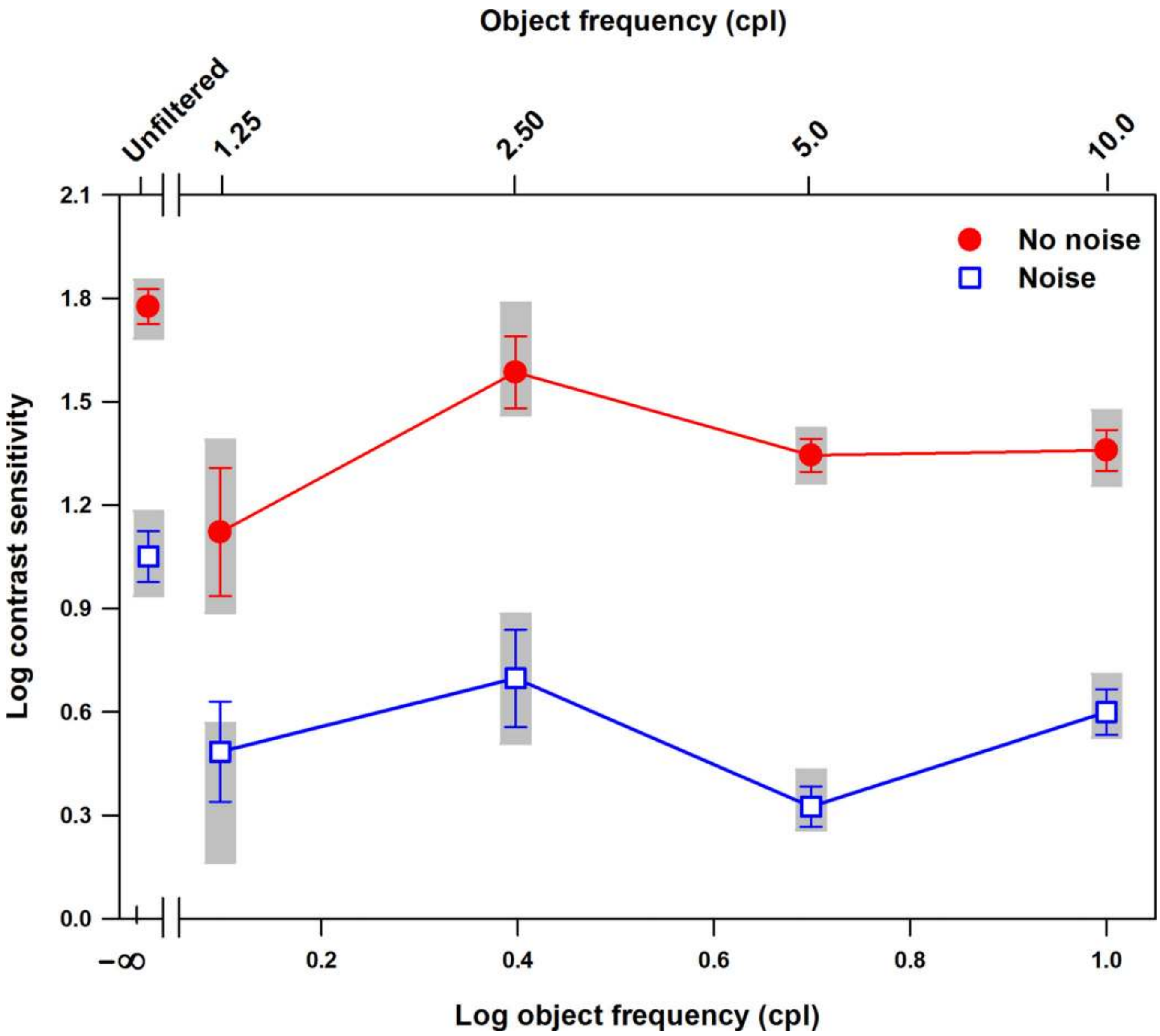

Figure 5.

Mean log contrast sensitivity for the 10 letters for each filter band averaged across the three subjects. The error bars represent the standard deviation and the boxes represent the range (maximum and minimum) for the 10 letters. Filled black circles (red online) represent contrast sensitivity measured in the absence of noise and the open squares represent contrast sensitivity in noise. A color version of this figure is available online at www.optvissci.com.