

# Using geometric moments to explain human letter recognition near the acuity limit

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When the size of a letter stimulus is near the visual acuity limit of a human subject, details of the stimulus become unavailable due to ocular optical and neural filtering. In this study we tested the hypothesis that letter recognition near the acuity limit is dependent on more global features, which could be parsimoniously described by a few easy-to-visualize and perceptually meaningful low-order geometric moments (i.e., the ink area, variance, skewness, and kurtosis). We constructed confusion matrices from a large set of data (approximately 110,000 trials) for recognition of English letters and Chinese characters of various spatial complexities near their acuity limits. We found that a major portion of letter confusions reported by human subjects could be accounted for by a geometric moment model, in which letter confusions were quantified in a space defined by low-order geometric moments. This geometric moment model is universally applicable to recognition of visual patterns of various complexities near their acuity limits.

Keywords: visual acuity, computational modeling, object recognition

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## Introduction

Visual acuity, often defined as the minimal angle of resolution, is a most important visual function. While the primary visual acuity optotype is Landolt C (International Organization for Standardization (ISO), 1986; National Academy of Science National Research Council (NAS-NRC), 1980), visual acuity is measured almost exclusively with letters in literary adults. In the US, the most popular visual acuity assessment is the ETDRS visual acuity chart (Ferris, Kassoff, Bresnick, & Bailey, 1982), which is made of 10 uppercase English letters of a specific typeface (Sloan letters). Subjects have to read these letters of progressively smaller sizes until no reliable recognition is possible. Therefore, visual acuity assessment is a pattern recognition process under a condition where visual information is severely degraded by ocular optics. How does a human subject recognize these letters?

In vision science, studies of letter recognition have focused on spatial frequency channels. Recent studies of contrast thresholds for recognizing spatially filtered and/or

noise masked large letter stimuli indicated that a narrow band (1–2 octaves) centered at a relatively low frequency (1–2 cycles/letter) is critical for letter recognition (Ginsburg, 1977; Parish & Sperling, 1991; Solomon & Pelli, 1994). Bondarko and Danilova (1997) calculated the Fourier spectra of Landolt C and Snellen E, and concluded that the primary information that could indicate the orientations of these optotypes at the resolution limit also resides in a narrow band centered at 1.4–1.7 cycles/letter. The low frequency channels identified in these studies cannot transmit the visual information of fine details of the stimulus, and thus suggest an important role of global

Although phase information of Fourier components is in theory capable of differentiating mirror images, there is little empirical data or theoretical speculations on how human subjects utilize phase information in this situation.

As a working model, spatial template matching in various forms has been used to explain pattern recognition (Chung, Legge, & Tjan, 2002; Gold, Bennett, & Sekuler, 1999; Tjan, Braje, Legge, & Kersten, 1995). While such models have been powerful tools in testing hypotheses about visual channels, the notion that a set of fixed spatial templates exist somewhere in the visual system, ready to be matched with visual inputs, may not explain why human subjects can effortlessly recognize patterns they have never encountered, for example, a new font face.

Cognitive science has a tradition of characterizing letter stimuli as collections of features and explaining human letter recognition as a process of matching feature sets extracted from stimuli with those stored in memory (Neisser, 1967). A recent study argued that human letter recognition has to be performed by features, because a holistic letter channel or template matching would have resulted in much higher efficiency than observed (Pelli, Burns, Farell, & Moore-Page, 2006). At the basis of any feature analysis model is the set of perceivable attributes of letters that are crucial to the recognition task at hand. Feature sets of existing models for recognition of letters or letter-like stimuli consist mainly of natural graphic features, such as horizontal, vertical and oblique strokes, dots, and gaps or openings (Geyer & DeWald, 1973; Gibson, 1969

global features of barely resolvable Sloan letters and Chinese characters because these stimuli have a fixed orientation and a predominantly orthogonal structure. For example, the observation that a human observer can determine the orientation of a Landolt C or a Snellen E by judging which side of the stimulus has less ink could be readily explained by the difference in the 3rd-order GMs (skewness) of the ink distribution. The contribution of height-to-width quotient to letter recognition demonstrated by Bouma (1971) could be associated with the ratio of 2nd-order GMs in  $x$ - and  $y$ -directions. Specifically, we propose a feature analysis model for letter recognition near the acuity limit, in which the feature set consists of global characteristics of stimulus patterns quantified by low-order GMs, and recognition is achieved by comparing GM compositions of letters. Because recognition confusions occur when crucial features are shared, we used the model to analyze the patterns of letter confusions obtained from identifying letters that were





centroid of the pattern. They were not used in the following simulation because the task was to recognize a single letter. Information about centroids of multiple letters is important in tasks such as word recognition or reading. The 2nd-order moments  $\mu_{2,0}$  and  $\mu_{0,2}$  defined in Equation 5 are equal to 1.0. Because the width/height ratio might be informative in letter recognition, we set  $\mu_{2,0}$  and  $\mu_{0,2}$  to  $\sigma_x$  and  $\sigma_y$  defined in Equation 3. We subtracted 3 from the kurtosis in the  $x$ - and  $y$ -directions ( $\mu_{4,0}$  and  $\mu_{0,4}$ ) defined in Equation 5 to comply with the common practice that when the distribution along the  $x$ - or  $y$ -axis was a Gaussian, the kurtosis was zero.

The centralized GMs of some simple geometric shapes were shown in Figure 1a to illustrate that low-order GMs were directly associated with perceivable global properties of 2-D images. For binary images ( $\mu_i \in \{0, 1\}$ ) in Figure 1a, the 0th-order GM is the number of ink pixels, which can be perceived as the general lightness or darkness of a letter. In Figure 1a, patterns with more strokes have a larger  $\mu_{0,0}$  than those with fewer strokes and appear darker if individual strokes cannot be distinguished. Pure 2nd-order moments (moments that are 0-order in one direction)  $\mu_{2,0}$  and  $\mu_{0,2}$  are dispersion of ink distribution. For the vertical bar in Figure 1a (height/width = 5/1),  $\mu_{2,0} < \mu_{0,2}$  (2.872 vs. 14.431). For the horizontal bar,  $\mu_{2,0} > \mu_{0,2}$  (14.431 vs. 2.872). In fact, when only GMs up to the second order are considered, the original image is completely equivalent to a constant irradiance ellipse, whose size, orientation, aspect ratio, and center are completely specified by the GMs (Teague, 1980). Pure 3rd-order moments  $\mu_{3,0}$  and  $\mu_{0,3}$  represent the skewness of ink distributions on the  $x$ - and  $y$ -directions. For the letter “E,”  $\mu_{3,0}$  has a positive value (0.18), but  $\mu_{0,3}$  is zero. Perceptually, the letter appears darker on the left side (skewed to the left), but appears symmetric in the vertical direction. The distribution of letter “L” is heavily skewed to the left in the horizontal direction and to the bottom in the vertical direction ( $\mu_{3,0} = 0.85$ ,  $\mu_{0,3} = -0.85$ ). Notice that the skewness is both directional specific ( $\mu_{2,0}$  vs.  $\mu_{0,2}$ ) and positional specific (positive vs. negative). Pure 4th-order moments  $\mu_{4,0}$  and  $\mu_{0,4}$  specify whether ink distributions on the  $x$ - and  $y$ -directions are more peaked or flat-topped than a Gaussian. In letter “H,” the distribution along  $x$ -axis is the lowest in the middle, due to the two vertical strokes, and thus  $\mu_{4,0}$  has a large negative number (−1.72). The distribution of letter “T,” on the other hand, has a strong peak in the middle, and  $\mu_{4,0}$  has a positive number (0.046). Mixed moments indicate the clustering of ink pixels around oblique axes. For example,  $\mu_{2,2}$  is large for letter “X,” but small for Chinese character 口 (1.60 vs. 0.81).

### Feature analysis models using GMs as feature sets

This model used GMs extracted from stimulus bitmaps as features. To simplify the notation, we used one index to denote moments involved in the model as  $\mu_1, \mu_2, \dots, \mu_n$ .

For example, if a model used ink area,  $x$ - and  $y$ -direction skewness and  $x$ - and  $y$ -direction kurtosis, then these moments were denoted as  $\mu_1, \mu_2, \mu_3, \mu_4$ , and  $\mu_5$ . In a model involving  $n$  moments, each stimulus was represented by a vector  $\{\mu_1, \mu_2, \dots, \mu_n\}$ , in an  $n$ -dimensional moment space. The difference between the  $i$ th and  $j$ th stimuli,  $d_{ij}$ , was measured by the distance between these stimuli in the  $n$ -dimensional moment space. To reflect different contributions of moments to the recognition of a set of stimuli, a weighting,  $w_i$ , was given to each moment dimension:

$$d_{ij} = \sum_{i=1}^n \left[ \left( \mu_i - \mu_j \right) \right]^2. \quad (6)$$

This weighted Euclidean distance (Getty, Swets, Swets, & Green, 1979; Mukundan & Ramakrishnan, 1998) was a pure physical measure of pair-wise difference between stimuli. For a letter recognition experiment that involves letters,  $\{d_{ij}\}$  forms a  $n$ -by- $n$  symmetric matrix with zeros on the diagonal. To simulate human recognition performance,  $d_{ij}$  needed to be converted to a measure of perceptual similarity. There are both empirical evidence and theoretical justification (Shepard, 1987) that the conversion should be monotonic and should take an exponential shape:

$$s_{ij} = e^{-\tau d_{ij}} \quad (\tau > 0). \quad (7)$$

The quantity  $s_{ij}$  was called “measure of stimulus generalization” (Shepard, 1987) or “similarity scale” (Luce, 1963b) and was used in several previous studies of human letter recognition (Getty et al., 1979; Keren & Baggen, 1981; Loomis, 1990). For a set of  $n$  letters,  $\{s_{ij}\}$  was a  $n$ -by- $n$  similarity symmetric matrix. Because  $s_{ii} = 0$ , similarity between a stimulus and itself,  $s_{ii} = 1.0$ , which sets the scale for similarity. The fact that all diagonal entries of similarity matrix  $\{s_{ij}\}$  equal 1.0 simply indicates that all stimuli had the same degree of similarity to themselves. The free parameter in Equation 7,  $\tau$ , determined how fast similarity fell from perfection. Intuitively, the probability of confusion between the  $i$ th and  $j$ th letter should be proportional to perceptual similarity  $s_{ij}$ , but  $s_{ij}$  was not the empirical probability of the  $i$ th letter being reported as the  $j$ th letter, because the column sum of matrix  $\{s_{ij}\}$  was not 1.0. A similarity matrix  $\{s_{ij}\}$  was converted into a theoretical CM through a column-wise normalization (Luce, 1963b):

$$c_{ij} = s_{ij} / \sum_{j=1}^n s_{ij}. \quad (8)$$

The  $n$ -by- $n$  CM  $\{c_{ij}\}$  differed from  $\{s_{ij}\}$  in several ways. First, each column of  $\{c_{ij}\}$  summed up to 1.0, indicating that it summarized all responses to a stimulus

letter. Second, the diagonal line entries were no longer

function (CSF) (see [Appendix A](#) for details). A total of 10 GM models were constructed using GMs of 4th order and below. Key features of these models were shown in [Table 1](#). Zero-order GM  $_{0,0}$  was used in all GM models, and the 1st-order GMs,  $_{1,0}$  and  $_{0,1}$ , were never used. This is because when the center of the coordinate was moved to the center of gravity of stimulus image ([Equation 4](#)),  $_{1,0}$  and  $_{0,1}$  became 0 for all stimuli. Model GM1(lu) used  $_{0,0}$  (lu) only. Models GM3(lu,va), GM3(lu,sk), and GM3(lu,ku) used  $_{0,0}$  (lu) and one pair of pure GMs,  $_{2,0}$  and  $_{0,2}$  (va),  $_{3,0}$  and  $_{0,3}$  (sk), and  $_{4,0}$  and  $_{0,4}$  (ku). Models GM3(lu,va,sk), GM3(lu,va,ku), and GM3(lu,sk,ku) used  $_{0,0}$  and two pairs of pure GMs. We did not use the 2nd order GM  $_{1,1}$  to construct GM3 and GM5 models because it only had a non-zero value when there was a gross difference in ink distribution between opposite corners of a letter, as in a letter “L” ([Figure 1a](#)). Because most of the stimulus characters shown in [Figure 2](#) filled the corners of a square area rather symmetrically, values of  $_{1,1}$  are very close to zero. The average values of  $_{2,0}$  and  $_{0,2}$  of the 70 characters were  $26.2 \pm 0.51$  and  $25.7 \pm 0.50$ , respectively, but the average of the absolute values of  $_{1,1}$  was only  $0.023 \pm 0.003$ . GM7 had all pure GMs up to the 4th order. GM9 added  $_{1,1}$  and  $_{2,2}$  to GM7. GM13 used all GMs up to the 4th order, excluding  $_{1,0}$  and  $_{0,1}$ . GMs higher than the 4th order were not discussed because we found adding 5th-order GMs resulted in little change in fitting empirical CMs.

To quantitatively demonstrate the effectiveness of GM models in predicting human performance, we also implemented three other models: a template-matching model (CSFTM) derived from a CSF ideal-observer model (Chung et al., 2002), a parameter-heavy choice model (CHOICE; Townsend, 1971), and an average of 500 CMs that had the empirical CMs’ diagonal line entries but random off-diagonal line entries (RANDOM). Details of these models were presented in [Appendix A](#). Pearson correlation coefficients were used to quantify the agreement between vectorized empirical and theoretical CMs.

## Results

### Using GM models to predict human confusions

The seven empirical CMs are shown in [Figure 3](#). It was evident that empirical confusions we observed were not random events. This was reflected in the large differences in the values of the off-diagonal line elements (confusions). Some letter pairs seldom got confused (0.00%) and some letter pairs got confused quite frequently (10~20%, pink and blue numbers in [Figure 3](#)). As shown in CM<sub>Sloan</sub>, the well-known confusions in English letters, such as “C”

vs. “O,” “D” vs. “O,” and “N” vs. “H”, were reproduced. These prominent confusions were most likely to be associated with perceptual similarities between characters, and thus could not be the result of random guessing. We constructed several versions of “random confusion” matrices, including Townsend’s (1971) “equiprobable” (every cell had the same value), an “equal legibility” (all diagonal line elements contained the mean legibility of the empirical CM, and all off-diagonal line elements contained mean confusion), and a CM that retained the empirical relative legibility while all incorrect reports were evenly distributed in the nine off-diagonal cells of a column.  $\chi^2$ -tests between the empirical CMs and all these random CMs were conducted, and the results showed that the probability that any of the empirical CMs were produced by random reporting was  $<0.0005$ .

Correlations between whole empirical and theoretical CMs were high. The average correlation across the 7 stimulus groups was  $0.970 \pm 0.006$  for the GM model using 13 GMs. In comparison, for those CMs that had empirical CMs’ diagonal lines but random off-diagonal line entries, the mean whole matrix correlation was  $0.955 \pm 0.012$ . Evidently whole CM correlation provided little information about how well models could predict confusions made by human subjects. Therefore, in this section we ignore the diagonal information and focus on results obtained from fitting the 90 confusion entries.

[Figure 4a](#) shows empirical–theoretical correlation coefficients produced by GM13, GM9, GM7, the average of GM5(lu,va,sk), GM5(lu,va,ku) and GM5(lu,sk,ku), the average of GM3(lu,va), GM3(lu,sk) and GM3(lu,ku), and GM1(lu) (colored symbols). Also shown are correlations produced by the CHOICE model (black squares) and the RANDOM model (black diamonds). These correlation coefficients are shown as the first number in each cell in [Table 1](#). The CHOICE model, which produced a mean correlation of 0.938 with empirical CMs, served as practical upper boundaries of goodness of fit. The CMs without consistent confusion patterns (RANDOM model) produced a mean correlation of 0.180 with empirical CMs and served as the lower boundaries for goodness of fit. [Figure 4b](#) shows scatter plots of the 90 confusions of the CC1 empirical CM against the corresponding 90 theoretical confusions produced by the CHOICE, GM13, GM7, and GM1(lu) models, along with regression lines through the data points. If empirical and theoretical confusions matched perfectly, data points would all fall on a line with a slope of 1.0. Because most of the confusions in each CM had low probabilities except for a few prominent confusions, as shown in [Figure 3](#), the data were scaled and log transformed before regression analyses were performed and plots were made. Regression analyses showed that CHOICE, GM13, and GM7 models all had slopes close to 1.0 (0.898, 0.820, and 0.936), while the GM1(lu) model had a very shallow slope (0.137). In the plots, the data points were scattered widely for the GM1(lu) model but clustered more tightly around the

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models.  
the linear  
0.163, 0.484,  
GM13, and CHOICE  
empirical–theoretical correlation  
number of GMs used in a GM model.  
leaving the mean luminance information  
(0,0), the correlations between GM1(lu)  
empirical CMs were higher than the

lower boundary defined by RANDOM CM's in 5 out of 7 stimulus groups. For example, the theoretical confusions obtained using the mean luminance values of Sloan letters and CC5 characters correlated with corresponding empirical confusions at 0.476 and 0.595, respectively, suggesting that even within these groups of stimuli of relatively uniform spatial complexity, letters of similar mean luminance were more likely to get confused when their sizes were close to acuity limits. With 7 GMs, correlation coefficients were 0.362–0.770. When all 13 GMs up to



4th order (excluding  $_{1,0}$  and  $_{0,1}$ ) were used, the correlation coefficients were at least 0.617. For Chinese characters in CC1, the correlation was about 0.896, approaching the level of performance of the 54-parameter CHOICE model.

Improvement of model performance with increasing number of GMs was more significant with lower order pure GMs. After all pure GMs were used (GM7), adding more GMs caused progressively less performance improvement. As shown in [Figure 4c](#), the improvement saturated at about 9 to 11 GMs. Adding all six 5th-order GMs resulted in less than 0.3% of change in Sloan, CC1, CC2, and CC3 groups, and in 2%, 3%, and 5% improvement in CC4, CC5, and CC6. Therefore, for letter recognition near the acuity limit, pure GMs up to the 4th order explained a large portion of confusions made by human subjects, and adding higher order GMs did not seem to provide additional useful information.

### **Asymmetry of empirical CMs and effect of response biases**

The empirical CMs we obtained were clearly asym-

Without bias adjustments, the theoretical CMs were rather symmetric, with standard deviations of row sums around 0.04–0.08. The correlations between empirical and theoretical row sums were low, from  $-0.367$  to  $0.017$ . Theoretical CMs with bias adjustments had row sums similar to those of the corresponding empirical CMs, and the correlations were high, from  $0.717$  to  $0.907$  ( $p < 0.005$ ), indicating a faithful restoration of the bias observed in empirical CMs. Correlation coefficients between empirical CMs and biased theoretical CMs were shown as the second number in each cell in [Table 1](#). It appeared that biased theoretical CMs generally correlated with empirical CMs better than unbiased, but the improvement was moderate at best.

## Relative legibility

No model based on Euclidean perceptual distances, including the GM models and template matching models, can predict relative legibility directly, because the diagonal line entries of the model similarity matrix ([Equation 7](#)) are all 1.0. However, a model CM defined in [Equation 8](#) did produce diagonal line entries of different values, due to the column-wise normalization. This was because each diagonal line entry was one minus the sum the nine off-diagonal line entries in the same column.

When the whole CM was optimized, the correlation between diagonal line entries of empirical and theoretical

CMs was higher than when only confusions were optimized. This was because whole CM optimization was mainly optimizing diagonal line entries. [Figure 5](#) shows correlation coefficients between diagonal line entries of the 7 empirical CMs and theoretical CMs produced by GM13, GM7, GM1(lu), and CHOICE models. The CHOICE model produced the best correlation, 0.984 on average. The GM models each had two results, that from a whole CM fitting (solid symbol and solid line) and that from a confusion-only fitting (open symbol and dashed line). For Sloan letters, the empirical relative legibility was ROSKDCNHZV. The relative legibility produced by the whole CM fitting GM13 model was OSCRNDKHZV, which correlated with the empirical relative legibility at 0.912. GM models agreed with human subjects in that “R,” “O,” and “S” were more difficult to recognize and “H,” “Z,” and “V” were easier.

## Discussion

### GM as visual features

This study, as far as we know, is the first attempt to use

human subjects use to recognize letters near the acuity limit.

One may expect that some kind of tendency in values (Equation 6) may exist that reflect the intrinsic property of moment analysis, for example, the weights should be lower for higher order moments because they contribute less in low-pass-filtered stimuli. Our results, however, failed to reveal any consistent trend for values. Only in CC5, values decreased with GM order. In CC1, CC4, and CC6, values first increased from 0th to 3rd order of GM, and then dropped at 4th-order GM. In Sloan and CC2, values were the lowest at 2nd-order GM, went up at 3rd order, and then dropped at 4th order. In CC3, values increased steadily from 2nd to 4th order. Our current understanding is that values are very specific to the characteristics of the stimulus group. For example, if characters in a stimulus group all have similar ink pixels, then the 0th-order GM would contribute very little to differentiating characters in the group, and the weight for  $w_{00}$  will be small. This happened in CC6 where the variation of total number of pixels was reduced because a large number of strokes were packed in the same area. As a consequence,  $w_{00}$  did not contribute much to differentiating CC6 characters, and the weight for the 0th-order GM is very small. We have not yet found a satisfying way to explain the observed relationship between model weights and GM order.

## Models with different number of parameters

The correlations produced by various models presented in the Results section only showed one aspect of model fitting. If we wanted to judge relative merits of models, the numbers of free parameters had to be considered, because models with more parameters tend to provide better fit to a set of data. There may not be one simple answer to this question, because the answer may depend on one's view of a balance between the models' abilities to fit data and its complexity, and there are more than one view on this matter. One method that determines a model's goodness of fit while taking its complexity into consideration is the Akaike's Information Criterion (AIC) (Akaike, 1974). The AIC is defined as  $AIC = -2 \ln(L/n) + 2k$ , where  $L/n$  is the number of data points to be fitted (90, if all confusions of a  $10 \times 10$  CM are considered),  $L$  is the residual sum of squares, and  $k$  is the number of free parameters. If A is a simpler model and B is a more complex one, then  $\Delta AIC = AIC_B - AIC_A$  can help to determine the model that explains the data well with fewer free parameters. An evidence ratio, defined as  $1 / e^{-0.5 \Delta AIC}$ , is usually used to quantify how much more correct one model compared to the other. An alternative criterion, Bayesian Information Criterion (BIC), defined as  $BIC = -2 \ln(L/n) + k \ln(n)$ , has a stiffer penalty for parameter usage (Schwarz, 1978). These criteria obviously will pass different judgments on relative merits of models with

different number of parameters. We used both AIC and BIC to give a more comprehensive view. Another advantage of AIC and BIC analyses is that they allow ranking multiple models according to their merits without having to adjust statistical criteria ( $\alpha$ ) like in multiple hypothesis tests.

Because AIC and BIC are related to a specific model fitting results of the specific experiment (N and K), it is difficult to judge whether an individual AIC or BIC value represents a good fit. For example, when the GM13 model was used to fit CC1 empirical CM, the BIC was  $-600.119$ . It is difficult to say how good this fitting is, because there is not a universal best fitting criterion for

GM13 and CSFTM were  $-590.061$  and  $-607.049$ , respectively, and the evidence ratio was 4886.27). However, the evidence was overwhelmingly in favor of the GM13 model in 5 of the 6 CC stimulus groups (evidence ratios  $> 2280$ ) with the exception of CC5 where the GM13 was still in favor, but the evidence was not very persuasive (2.05). Comparisons between CSFTM and GM9 produced the similar results. When the number of moments in GM models was further reduced, the CSFTM model was favored in more and more stimulus groups. It is also interesting to compare the CSFTM model with the 54-parameter CHOICE model. There was only weak evidence that CSFTM is better than CHOICE in Sloan letters (evidence ratio 3.84), but the evidence in favor of the CHOICE model was overwhelming in all CC stimulus groups (evidence ratio  $> 2 \times 10^{11}$ ).

Using BIC, we found overwhelming evidence in favor of the CSFTM model over the GM13 model for the Sloan letters, CC2, CC5, and CC6 groups, and overwhelming evidence in favor of the GM13 model for CC1, CC3, and CC4 groups. When the CSFTM and CHOICE models were compared using BIC, the evidence was overwhelmingly in favor of the CSF model for all stimulus groups.

Therefore, under some situations, like the Sloan letters, the 1-parameter CSFTM model was always superior to other parameter-rich models. In other situations, such as CC1 and CC3, GM13 and GM9 were always superior to the CSFTM models, indicating that the improvement of model performance had outweighed the cost of using more parameters. In other situations, the relative merits of models depended on the criteria used.

The CSFTM model did not seem to be sensitive to the exact shape of the CSF. We simulated the CSFTM model using three front-end filters (see below). There were no significant differences between correlation coefficients produced by different CSFs among the 7 stimulus groups (repeated measures ANOVA,  $F_{2,12} = 1.179$ ,  $p = 0.341$ ).

## The effect of the front-end filter

In the study, we used an empirical CSF as a front-end filter. GM features were extracted from filtered characters. To assess the influence of the front-end filter on the performance of GM models, we repeated the analyses using two additional filters, an empirical CSF obtained from one of our subjects (ZJY CSF, blue squares and curve in Figure A1a), and the 3.8-mm pupil point spread function of Campbell and Gubisch's (1966; CG PSF). The ZJY CSF had a slightly higher peak frequency than the CLT CSF, and a lower cut-off frequency. The CG PSF was fitted with the sum of two Gaussians (Geisler, 1984) and then convolved with bitmaps of the stimuli. The corresponding correlation coefficients produced by the CLT CSF, ZJY CSF, and CG PSF front-end filters agreed with each other very well. An ANOVA showed that

among the 70 sets of model simulations (7 groups  $\times$  10 GM models) there were no significant filter effect ( $F_{2,120} = 0.182$ ,  $p = 0.893$ ) or filter\*model interaction ( $F_{18,120} = 0.419$ ,  $p = 0.982$ ). These results indicated that the GM models are not very sensitive to the details of the front-end filtering. This should not be surprising, because the GM models used only the global features of the characters, which were attenuated to some degree but not eliminated or distorted by these linear filters. The insensitivity of GM model performance to the type of the front-end filter may also be explained by the feature matching process used by the model. We used the feature list extracted from a filtered stimulus character to match a set of stored feature lists that were extracted from identically filtered characters. This approach was appropriate in our study, where subjects had done thousands of trials of recognizing characters close to acuity thresholds. It would be interesting to investigate the effect of front-end filters on GM models when the stimulus feature set is extracted from a filtered character while the store feature set is extracted from unfiltered characters. This situation may occur when the subject has learned the stimuli at very large sizes and is first exposed the stimulus at sizes close to the acuity limits.

## Relative legibility, response bias, and asymmetry of confusion matrices

While studies of letter recognition CM considered the observed asymmetry as the consequence of response bias (Townsend, 1971), which, strictly speaking, is the subject's tendency to report one letter more than others when the stimulus is not legible, relative legibility of the stimulus letters actually plays an important role in determining the magnitudes of pair-wise asymmetries. In our CM<sub>Sloan</sub>, for example, "H" was much more legible than "R" (75% correct vs. 38%). This difference contributed to the large pair-wise asymmetry in which the probability of an "H" being reported as an "R" was 0.012 while an "R" being reported as an "H" was 0.123. Indeed, when we generate random CMs, we could produce substantial asymmetries among confusion entries if large variations in the diagonal line entries were introduced. Therefore, unless the stimuli are truly equally legible, asymmetry of an empirical CM is not a pure measure of subjects' response bias.

## Inter-group variations

It is obvious from Figure 4a that GM models fitted Sloan letters, CC1, CC3, and CC5 better than CC2, CC4, and CC6. It seemed that this fluctuation did not happen only to GM modeling. Although the CHOICE model only concerned with empirical CMs and did not care what stimulus produced them, it echoed the fluctuation. The fluctuation was also in some degree mirrored by the

RANDOM model, which produced higher correlations with empirical CMs when other models produced lower correlations. Therefore, the fluctuation seemed to be related to properties of the empirical CMs. The mean correct rates of the empirical CMs (59.7%, 54.7%, 57.3%, 56.75, 54.4%, 55.0%, and 58.7% for Sloan and CC1–CC6) were similar and did not echo the pattern seen in Figure 4a. It was suggestive that when the RANDOM model performed best, the other models performed worst, for example, at CC4. Because the RANDOM model, after averaging many random confusion entries, had essentially uniform confusion entries, it seemed reasonable to suggest models may fit empirical CMs with more prominent confusion entries better than those with more uniform confusion entries. Indeed, model fitting appeared to be better when confusion entries had larger standard deviations, higher maximum values, and larger ranges. For example, the standard deviations for the confusions of the 7 groups were 0.0493, 0.0583, 0.0447, 0.0529, 0.0418, 0.0424, and 0.0392. Standard deviations, maximum values, and ranges correlated highly with GM13 model performance and were able to account for 78.2%, 76%, and 74.1% of the inter-group variations for this model.

As the complexity of the letter set increases, the standard deviation of the confusion entries decreases, suggesting that confusions became more uniformly distributed. As a consequence, performance of CSFTM and GM models declines. This can be seen in the goodness of fit of both the diagonal line entries and off-diagonal line entries of empirical CMs in Figures 4a and 5. Although GM fitting of human confusions obviously fluctuated across stimulus group, and seemed to have two tiers for goodness of fit, the change among each tier was small. In comparison, the CSFTM fitting, with the exception of CC5 in Figure 4a, decline steadily with stimulus complexity, quantified by the stroke frequency. The less rapid decline of the GM models may be explained by the larger numbers of parameters they used to fit the confusion entries.

## Non-orthogonal GMs vs. orthogonal moments

Because the basis functions of GMs are not orthogonal, GM features have non-zero redundancy, meaning that GMs may not correspond to independent characteristics of the image, from a mathematical point of view. Various orthogonal moment descriptors have been proposed in computer image processing. Legendre moments (LM) defined below were orthogonal and real-valued:

$$L_{ij} = \frac{(2-i+1)(2-j+1)}{(i+j-1)^2} \sum_{x=1}^M \sum_{y=1}^M f(x,y) P_i\left(\frac{x}{M}\right) P_j\left(\frac{y}{M}\right), \quad (9)$$

where  $P_i(\cdot)$  and  $P_j(\cdot)$  are Legendre polynomial of the  $i$ th and  $j$ th orders, and  $x$  and  $y$  are normalized pixel

coordinates in a unit square (Teague, 1980). Computational studies have demonstrated that orthogonal moments, such as  $L_{ij}$ , are more efficient in reconstructing details of images. Ghorbel, Derrode, Dhahbi, and Mezhoud (2005) demonstrated that a  $32 \times 32$  pixel “E” reconstructed from up to 50th-order GM produced 74 pixels that differed from the original. Only up to 8th-order LMs were needed to reach the same level of reconstruction accuracy. Human pattern recognition, on the other hand, typically does not require that much detail. Do LMs explain human recognition of small patterns better than GMs? Correlation coefficients between CMs produced by LM-based feature analysis models and empirical CMs were shown as the third number in cells in Table 1. LM models were slightly better than corresponding GM models in some cases, but the differences were generally small. For the 10 corresponding GM and LM models, the differences in empirical–theoretical correlations averaged across the 7 stimulus groups ranged from +0.019 (GM better than LM) to −0.083 (LM better than GM). Comparing to the dramatically increased efficiency of LM in reconstruction of images (8th order vs. 50th order), the improvement of LM over GM in interpreting human letter confusions near the acuity limit was mediocre. One possible reason is that the basis function of an LM of  $(i+j)$ th order is a linear combination of GM basis functions up to the  $(i+j)$ th order (Teague, 1980). It can be shown that at the lower orders that were most relevant to recognition of letters near the acuity limit, the basis functions of LM are similar to those of GM, and an LM was either the same order GM times a constant or a linear sum of two GMs of equal or lower order. For example,  $L_{0,0} = G_{0,0}$ ,  $L_{2,0} = (5/4)[(3/2)G_{2,0} - (1/2)G_{0,0}]$ ,  $L_{1,1} = (9/4)[(5/2)G_{1,1} - (1/2)G_{0,0}]$ , and so on. Therefore, the difference between LM and GM compositions was relatively small when human recognition of small letters was concerned. It can be seen in Table 1 that GM1(lu) and LM1(lu) models produced identical simulation results. In other models, some LM space dimensions were linear combinations of two GM dimensions, and adjusting weightings on these dimensions might not produce the same results as in the GM space.

## Visual acuity and beyond

Visual acuity is a unique condition where the subject is forced to use global structural properties of stimuli because of the optical and neural filtering. That is probably one of the reasons for the success of the low-order GM models. Recently, Watson and Ahumada (2008) used a CSF template matching ideal observer model to fit visual acuity data obtained under several aberrated conditions. The GM-based feature analysis model may also be used for this purpose. GM features can be extracted from aberrated images



degraded by internal noise and filtered by a neural transfer function. The feature sets can then be matched at different letter sizes in a Monte Carlo simulation to determine threshold letter sizes for different types and amounts of aberrations.

Whether GM-based feature models are applicable to other experimental conditions, such as briefly flashed large and high-contrast letters, or large low contrast letters, remains to be seen. However, there are a few situations where an explicit model for utilizing global properties of visual stimuli is desirable. First, a window of 4 to 8 letters is necessary in order to reach maximum reading speed in normal subjects (Legge, Pelli, Rubin, & Schleske, 1985; Poulton, 1962), and 15 letters to the right of fixation could contribute to normal reading of English (Legge, Hooven, Klitz, Stephen Mansfield, & Tjan, 2002; Legge et al., 1985; Rayner & McConkie, 1976). When reading text whose size is suitable for foveal reading ( $\approx 3$ – $4$  times foveal acuity size), peripheral letters that contribute to reading are likely to be near the acuity size at their locations, because acuity drops sharply with retinal eccentricity. Second, patients who lose central vision due to diseases such as macular degeneration may be trained to read using intact peripheral vision. In such cases, a large text size has to be used, but the room for magnification is quite limited, because of the limited size of a magnifier aperture or a large print page. Therefore, reading is likely to be done near the acuity size of the intact part of the retina. Finally, there is a general consensus that visual patterns are recognized in a global-to-local manner under normal circumstances (Bouma, 1971; Eriksen & Schultz, 1978; Lupker, 1979; Sanocki, 1991; Townsend, Hu, & Kadlec, 1988). While there are debates whether global features can facilitate local feature detection (Lupker, 1979; Sanocki, 1991), there is little doubt that global features of a pattern are extracted and used first. The analog is a “focusing process” where a visual pattern appears as a “blob-like” form first, and more details emerge later (Bouma, 1971; Eriksen & Schultz, 1978; Lupker, 1979; Sanocki, 1991). A universal mathematical description of global characteristics of visual stimuli can be a powerful tool in study human performance under these situations.

## Appendix A: Models and their implementations

### Implementation of GM models

Because we were interested in recognition of letters near the acuity limit, we assumed that GM features were extracted from an internal representation of a stimulus

letter after it was degraded by ocular optics and early neural processing. In previous modeling efforts for human letter recognition, a low-pass filtering (Blommaert, 1988; Loomis, 1990) or a contrast sensitivity function (CSF) filtering (Chung et al., 2002) of the stimulus letters was proposed, the former representing the effects of the ocular optics and the latter representing the effects of early optical/neural processing. We chose to use CSF filtering before GM feature extraction. Specifically, we selected a normal adult CSF function published by Chung et al. (2002; Figure 2). A 3-parameter model (Mannos & Sakrison, 1974)

$$C(F) = \frac{1}{1 + \exp(-\log(F))}, \quad (A1)$$

was used to fit the CSF. The best-fitting parameters were  $\log(F) = 812.3$ ,  $\log(F) = 1.071$ ,  $\log(F) = 0.636$ . The Chung, Legge and Tjan (CLT) CSF data are replotted in Figure A1a with the model fitting. A radial-symmetric 2-D filter in the frequency domain was then created, as shown in Figure A1b. The original stimuli were black-and-white bitmaps of Sloan letters and Chinese characters shown in Figure 2. All stimulus bitmaps were  $50 \times 50$  pixels in size. Because the bitmaps were used as stimuli 0.1 log unit above the acuity sizes shown in Figure 2, the resolutions ranged 700 pixels/deg for the Sloan letters to 398 pixels/deg for CC6. The stimulus bitmaps were pasted on a large black background before being filtered. For each stimulus letter, the Fourier transform of its bitmap was multiplied with the CLT CSF filter, and then the inverse Fourier transform was taken. The result was a highly blurred version of the letter, shown in Figure A1c. The filtered stimulus was cropped to  $1.2 \times$  of original stimulus size to save time in simulation. Cropped sizes of up to  $3 \times$  of original stimulus size were tested, and no significant differences in simulation results were noticed. Procedures defined in Equations 2–5 were used to extract a set of GMs, and a theoretic CM  $\{C_{ij}\}$  with  $+1$  free parameters was generated according to Equations 6–8. An optimization routine was used to look for the best fitting parameters so that the sum of squared differences between a theoretic CM and the corresponding empirical CM was minimal. One of the debatable issues in fitting CMs is how to treat the diagonal line entries. In a typical letter recognition study, the average correct rate is set at 50%–75%, which means that the diagonal line entries are much larger than off-diagonal line entries. If the whole CM is fitted, the diagonal line entries are likely to dominate the fitting and may result in an over-optimistic goodness of fit, in which the fitting of the confusions can be quite poor (LeBlanc & Muise, 1985). In our study, we optimized both the whole CM and confusions entries.

The letter sizes used in the study were 0.1 log unit above acuity sizes shown in Figure 2.



was correlated with 500 such random CMs. The average of the correlation coefficients served as a lower boundary for fitting empirical CMs. Because each random CM still had to satisfy the unit column sum requirement, the average correlations with empirical CMs had positive values (black diamonds in Figure 4a).

## CSF Template-Matching Model (CSFTM)

To compare GM models with alternative models for letter recognition, we derived a CSF template-matching (CSFTM) model from a CSF ideal-observer model (Chung et al., 2002) and applied it to our 7 groups of stimuli. The CSF ideal-observer model was essentially a template-matching model that minimized the sum of squared differences between a stimulus and a template (Tjan et al., 1995). Specifically, the model calculated all sums of squared differences between a CSF filtered stimulus letter and all similarly filtered template letters, and selected as the response the template that had the smallest sum of squared differences from the stimulus. For a CSF filtered stimulus letter  $s$  and a filtered template letter  $t$ , the sum of squared difference is

$$D_{st} = \sum_i \sum_j (I_{st}(i, j) - I_t(i, j))^2. \quad (A3)$$

For a  $N$ -letter recognition experiment,  $\{D_{st}\}$  is a  $N$ -by- $N$ -matrix with zeros on the diagonal, similar to  $\{c_{ij}\}$  in Equation 6. We used procedures similar to Equations 7 and 8 to create a CSF template-matching similarity matrix and a confusion matrix. The CSFTM model has only one free parameter,  $\tau$  in Equation 7.

The implementation of a CSFTM model was similar to that for GM models. The same CSF-filtered letters were used as inputs, and the same optimization procedures were used. Because template matching was sensitive to relative positions between the stimulus and template, we displaced the stimulus relative to the template in 1-pixel step for 5 pixels in both horizontal and vertical directions in calculating  $D_{st}$ . The best result among the 25 relative positions was taken as the  $D_{st}$ . Seven and 9-pixel relative shifts were tested and no significant differences in simulation results were noticed. Loomis (1990) used similar method to study CMs of 26 English letters. Instead of a CSF, Loomis used a low-pass filter to simulate the effect of ocular optics.

In our modeling effort, we computed a theoretical CM for each set of free parameters, calculated the correlation between the theoretical CM and the corresponding empirical CM, and looked for a set of parameters that maximized theoretical/empirical CM correlation. An alternative is a Monte Carlo simulation of a psychophysical experiment, where an idea observer equipped with an optimal decision making strategy tries to recognize

luminance noise degraded characters (Pelli et al., 2006; Tjan & Legge, 1998; Watson & Ahumada, 2008). The outcome of this simulation is also a theoretical CM, which can then be used to compare with an empirical CM. Tjan et al. (1995) gave mathematical proof that the calculation of ideal observer recognition performance of Gaussian noise degraded objects is equivalent to the calculation of template matching. It would be interesting to investigate how the ideal observer decision making would affect GM model performance.

## Reconstruction of a 2-D image with geometric moments

Because a finite spatial function  $f(x, y)$  can be completely specified by geometric moments  $\{M_{ij}\}$  ( $i, j = 0, 1, 2, \dots$ ) (Hu, 1962), one should also be able to reconstruct  $f(x, y)$  from  $\{M_{ij}\}$ . However, reconstruction with GM is not as straightforward as an inverse Fourier transform (Ghorbel et al., 2005), because the basis functions of GM are not orthogonal. Teague (1980) proposed a moment matching method to reconstruct any function  $f(x, y)$  from GMs up to a given order  $N_{\max}$ . The idea is to obtain a continuous function  $\hat{f}(x, y) = M_{00} + M_{10}x + M_{01}y + M_{20}x^2 + M_{11}xy + M_{02}y^2 + \dots$ , whose GM exactly match those of  $f(x, y)$  up to the order  $N_{\max}$ . The constant coefficients of  $\hat{f}(x, y)$  are determined by

$$\int_{-1}^{+1} \int_{-1}^{+1} (M_{00} + M_{10}x + M_{01}y + M_{20}x^2 + M_{11}xy + M_{02}y^2 + \dots) \equiv M_{ij}, \quad (A4)$$

Equation A4 results in a set of linear equations. Solving these equations, which is equivalent to calculating an inversed matrix of known  $M_{ij}$ , uniquely determines all the coefficients of  $\hat{f}(x, y)$ . In theory, exact reconstruction of an  $N_x \times N_y$  image can be made by using moments  $M_{ij}$ , where  $i = 1, 2, \dots, N_x$  and  $j = 1, 2, \dots, N_y$ . We used our implementation of this method in Matlab to create the reconstruction shown in Figure 1b. One inconvenience of moment matching reconstruction is that the coefficients  $c_j$  depend on the order of the moments used in reconstruction. For example,  $c_{22}$  for the same image has different values for  $N_{\max} = 4$  and  $N_{\max} = 5$ . This is because each coefficient  $c_j$  is a linear combination of  $M_{ij}$  up to the  $N_{\max}$  order.

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## References

- Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, 19, 716–723.
- Alt, F. L. (1962). Digital pattern recognition by moments. *IEEE Transactions on Automatic Control*, 7, 240–258.
- Blommaert, F. J. (1988). Early-visual factors in letter confusions. *Journal of Experimental Psychology: Applied*, 3, 199–224. [PubMed]
- Bondarko, V. M., & Danilova, M. V. (1997). What spatial frequency do we use to detect the orientation of a Landolt C? *Journal of Experimental Psychology: Applied*, 3, 2153–2156. [PubMed]
- Bouma, H. (1971). Visual recognition of isolated lower-case letters. *Journal of Experimental Psychology: Applied*, 11, 459–474. [PubMed]
- Campbell, F. W., & Gubisch, R. W. (1966). Optical quality of the human eye. *Journal of the Optical Society of America*, 56, 558–578. [PubMed] [Article]
- Chung, S. T., Legge, G. E., & Tjan, B. S. (2002). Spatial-frequency characteristics of letter identification in central and peripheral vision. *Journal of Experimental Psychology: Applied*, 8, 2137–2152. [PubMed]
- Eriksen, C. W., & Schultz, D. W. (1978). Temporal factors in visual information processing. In J. Requin (Ed.), *Attention* (vol. VII). New York: Academic Press.
- Ferris, F. L., 3rd, Kassoff, A., Bresnick, G. H., & Bailey, I. (1982). New visual acuity charts for clinical research. *Journal of the Optical Society of America*, 72, 91–96. [PubMed]
- Geisler, W. (1984). Physical limits of acuity and hyper-acuity. *Journal of Experimental Psychology: Applied*, 1, 775–782. [PubMed]
- Gervais, M. J., Harvey, L. O., Jr., & Roberts, J. O. (1984). Identification confusions among letters of the alphabet. *Journal of Experimental Psychology: Applied*, 10, 655–666. [PubMed]
- Getty, D. J., Swets, J. A., Swets, J. B., & Green, D. M. (1979). On the prediction of confusion matrices from similarity judgments. *Journal of Experimental Psychology: Applied*, 26, 1–19.
- Geyer, L. H., & DeWald, C. G. (1973). Feature lists and confusion matrices. *Journal of Experimental Psychology: Applied*, 14, 471–482.
- Ghorbel, F., Derrode, S., Dhahbi, S., & Mezhoud, R. (2005). Paper presented at the International Conference on Machine Intelligence (ACIDCA-ICMI'05), Tozeur, Tunisia.
- Gibson, E. J. (1969). *The perception of the visual world*. New York: Appleton-Century-Crofts.
- Ginsburg, A. P. (1977). Unpublished Ph.D., University of Cambridge, Cambridge, England.
- Gold, J., Bennett, P. J., & Sekuler, A. B. (1999). Identification of band-pass filtered letters and faces by human and ideal observers. *Journal of Experimental Psychology: Applied*, 5, 3537–3560. [PubMed]
- Hu, M. K. (1962). Visual pattern recognition by moment invariant. *Journal of Experimental Psychology: Applied*, 8, 179–187.
- International Organization for Standardization (ISO) (1986). Visual acuity testing: Standard optotype and its presentation (No. ISO 8596). International Organization for Standardization.
- Keren, G., & Baggen, S. (1981). Recognition models of alphanumeric characters. *Journal of Experimental Psychology: Applied*, 29, 234–246. [PubMed]
- Laughery, K. R. (1969). Computer simulation of short-term memory: A component decay model. In G. T. Bower & J. T. Spence (Eds.), *Attention* (vol. VI). New York: Academic Press.
- LeBlanc, R. S., & Muise, J. G. (1985). Alphabetic confusion: A clarification. *Journal of Experimental Psychology: Applied*, 3, 588–591. [PubMed]
- Legge, G. E., Hooven, T. A., Klitz, T. S., Stephen Mansfield, J. S., & Tjan, B. S. (2002). Mr. Chips 2002: New insights from an ideal-observer model of reading. *Journal of Experimental Psychology: Applied*, 8, 2219–2234. [PubMed]
- Legge, G. E., Pelli, D. G., Rubin, G. S., & Schleske, M. M. (1985). Psychophysics of reading—I. Normal vision. *Journal of Experimental Psychology: Applied*, 25, 239–252. [PubMed]
- Loomis, J. M. (1990). A model of character recognition and legibility. *Journal of Experimental Psychology: Applied*, 16, 106–120. [PubMed]
- Luce, D. R. (1963a). Detection and recognition. In D. R. Luce, R. R. Bush, & E. Galanter (Eds.), *Handbook of experimental psychology* (vol. I, pp. 103–188). New York: John Wiley and Sons.
- Luce, D. R. (1963b). Psychophysical scaling. In D. R. Luce, R. R. Bush, & E. Galanter (Eds.), *Handbook of experimental psychology* (vol. I, pp. 245–307). New York: John Wiley and Sons.

- Lupker, S. J. (1979). On the nature of perceptual information during letter perception. *Psychological Review*, 86, 25, 303–312. [PubMed]
- Majaj, N. J., Pelli, D. G., Kurshan, P., & Palomares, M. (2002). The role of spatial frequency channels in letter identification. *Journal of Vision*, 2, 42, 1165–1184. [PubMed]
- Mannos, J. L., & Sakrison, D. J. (1974). The effects of a visual fidelity criterion on the encoding of images. *IEEE Transactions on Information Theory*, 20, 525–535.
- Mukundan, R., & Ramakrishnan, K. R. (1998). *Machine Vision: Principles and Methods*. Singapore: World Scientific.
- National Academy of Science National Research Council (NAS-NRC) (1980). Recommended standard procedures for the clinical measurement and specification of visual acuity. Report of working group 39. Committee on vision. *Archives of Ophthalmology*, 98, 41, 103–148. [PubMed]
- Neisser, U. (1967). *Cognition and the Development of Language*. New York: Meredith.
- Parish, D. H., & Sperling, G. (1991). Object spatial frequencies, retinal spatial frequencies, noise, and the efficiency of letter discrimination. *Journal of Vision*, 1, 31, 1399–1415. [PubMed]
- Pelli, D. G., Burns, C. W., Farell, B., & Moore-Page, D. C. (2006). Feature detection and letter identification. *Journal of Vision*, 6, 46, 4646–4674. [PubMed]
- Poulton, E. C. (1962). Peripheral vision, refractoriness and eye movements in fast oral reading. *British Journal of Psychology*, 53, 409–419. [PubMed]
- Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Journal of Experimental Psychology: Human Perception and Performance*, 12, 829–837. [PubMed]
- Sanocki, T. (1991). Effects of early common features on form perception. *Psychological Review*, 98, 50, 490–497. [PubMed]
- Schwarz, G. (1978). Estimating the dimension of a model. *Annals of Statistics*, 6, 461–464.
- Shepard, R. N. (1987). Toward a universal law of generalization for psychological science. *Psychological Review*, 94, 237, 1317–1323. [PubMed]
- Solomon, J. A., & Pelli, D. G. (1994). The visual filter mediating letter identification. *Journal of Vision*, 14, 369, 395–397. [PubMed]
- Teague, M. (1980). Image analysis via the general theory of moments. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 2, 70, 920–930.
- Tjan, B. S., Braje, W. L., Legge, G. E., & Kersten, D. (1995). Human efficiency for recognizing 3-D objects in luminance noise. *Journal of Vision*, 15, 35, 3053–3069. [PubMed]
- Tjan, B. S., & Legge, G. E. (1998). The viewpoint complexity of an object-recognition task. *Journal of Vision*, 18, 38, 2335–2350. [PubMed]
- Townsend, J. T. (1971). Theoretical analysis of an alphabetic confusion matrix. *Psychological Review*, 78, 9, 40–50.
- Townsend, J. T., Hu, G. G., & Kadlec, H. (1988). Feature sensitivity, bias, and interdependencies as a function of energy and payoffs. *Psychological Review*, 95, 43, 575–591. [PubMed]
- Watson, A. B., & Ahumada, A. J., Jr. (2008). Predicting visual acuity from wavefront aberrations. *Journal of Vision*, 8(4):17, 1–19, <http://journalofvision.org/8/4/17/>, doi:10.1167/8.4.17. [PubMed] [Article]
- Zhang, J. Y., Zhang, T., Xue, F., Liu, L., & Yu, C. (2007). Legibility variations of Chinese characters and implications for visual acuity measurement in Chinese reading population. *Journal of Vision*, 7, 48, 2383–2390. [PubMed] [Article]