Available online at www.sciencedirect.com
SCIENCE DIRECT®
Vision Research 45 (2005) 2723–2727
Vision Research
www.elsevier.com/locate/visres

Brief communication

Spatial frequency channels derived from individual differences

William A. Simpson *, Sharon M. McFadden

DRDC Toronto Modelling Section, 1133 Sheppard Avenue West, P.O. Box 2000, Toronto, Ont., Canada M3M 3B9

Received 15 July 2004; received in revised form 12 November 2004

Abstract

Contrast sensitivity functions differ from observer to observer. We propose that these differences arise because each observer has unique weights for the outputs of the neural channels that underlie the contrast sensitivity function. By applying principal components analysis to individual contrast sensitivity functions of 297 observers, estimates of the channel tuning curves were found. We find evidence for three broadly tuned bandpass channels with peaks at 4, 8, and 16 c/deg and bandwidth near 1.3 octaves. These channel tuning curves were reproduced in a cross-validation study of 56 observers.

Keywords: Contrast sensitivity; Spatial frequency channels; Multivariate analysis; Individual differences

The contrast sensitivity function is a useful summary of the spatial performance of the visual system. Electrophysiological recordings show that individual neurons respond to only a limited range of spatial frequencies (DeValois, Albrecht, & Thorell, 1982). Thus the overall contrast sensitivity function must be the net response of a number of neural channels, each tuned to a narrow range of frequencies.

A number of psychophysical paradigms (including adaptation, masking, and summation) have been used in attempts to characterize the tuning curves of the channels that underlie the human contrast sensitivity function (DeValois & DeValois, 1990). An alternative to experimental manipulation is to use the natural variation between subjects to find the channel tuning curves (Billock & Harding, 1996; Mayer, Dougherty, & Hu, 1995; Peterzell & Teller, 1996; Peterzell, Werner, & Kaplan, 1993, 1995; Sekuler, Wilson, & Owsley, 1984). The basic idea is simple: the contrast sensitivity function varies between individuals, and this variation is caused by differences in the relative sensitivity of the underlying neural channels.

Fig. 1 illustrates the idea behind the individual differences approach to spatial frequency channels. Each panel of the figure shows how the contrast sensitivity function for an individual subject is the sum of the outputs of three channels. The relative weighting of the channels differs between subjects. Algebraically, the model is

$$s_i(f) = a_{1i}c_1(f) + a_{2i}c_2(f) + a_{3i}c_3(f) + \cdots + a_{ni}c_n(f), \quad (1)$$

where $s_i(f)$ is the contrast sensitivity function for subject i, $c_1(f)$–$c_n(f)$ are the tuning curves for the n underlying channels, and a_{1i}–a_{ni} are the channel weights for subject i.

There is more than one way to fit such a model. Previous approaches (Peterzell & Teller, 1996; Peterzell et al., 1993, Peterzell, Werner, & Kaplan, 1995; Sekuler et al., 1984) to deriving spatial frequency channels through individual differences have used Factor Analysis (FA) and Structural Equation Modelling (which is allied to FA). Other methods for fitting Eq. (1) include Principal Components Analysis (Mardia, Kent, &

* Corresponding author. Tel.: +1 416 635 2000x3142; fax: +1 416 635 2184.
E-mail address: william.simpson@drdc-rddc.gc.ca (W.A. Simpson).

0042-6989/$ - see front matter.
doi:10.1016/j.visres.2005.01.015

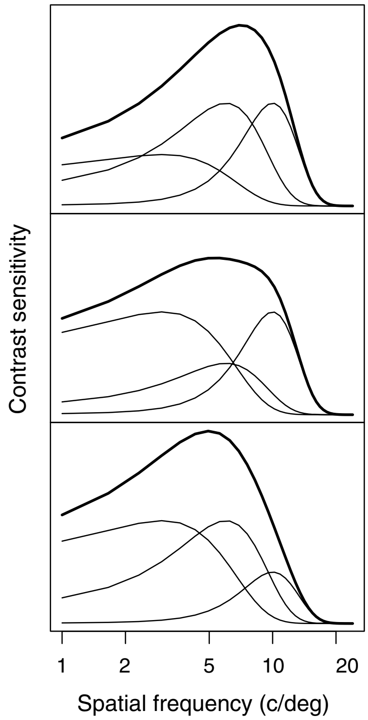

Fig. 1. Hypothetical contrast sensitivity functions (heavy lines) for three observers, each of whom has a different weighting of the underlying channels (thin lines). The y-axis is linear and so the contrast sensitivity at any point is the sum of the heights of the channels.

Bibby, 1979) and Independent Components Analysis (Hyvarinen & Oja, 2000). Our aim in this paper is to derive the channel tuning curves based on the data of 297 normal young adult subjects using PCA. Such an individual differences approach has been used to derive channel tuning curves for infants (Peterzell & Teller, 1996; Peterzell et al., 1993, 1995). Sekuler et al. (1984) used this general approach for adults, but did not present tuning curves.

1. Method

1.1. Subjects

The observers were 297 air crew candidates between the ages of 16 and 28 years. Contrast sensitivity was measured as part of a standard test battery that all air crew candidates undergo. Over a three-day test period the candidates received a complete ophthalmological examination including evaluations of colour vision, visual acuity cycloplegic refraction, visual fields, intraocular pressure, and a general ophthalmological assessment.

A separate sample of 56 air crew candidates, tested a year later, were used to validate the channel tuning curves derived using the larger sample.

1.2. Stimuli

The stimuli were generated by a microprocessor-controlled video system (Nicolet Optronics CS-2000) on loan from the USAF. The same system was used by Ginsberg, Evans, Cannon, Owsley, and Mulvanny (1984) and Sekuler et al. (1984). Stimuli were vertical sinusoidal gratings having spatial frequencies of 1, 2, 4, 8, 16 and 24 c/deg. The display subtended $3° \times 3.6°$ at a viewing distance of 265 cm. The mean luminance of the screen was 70 cd/m^2. In the initial study with 297 air crew candidates, the stimuli were viewed binocularly. In the smaller cross-validation study the stimuli were viewed monocularly.

2. Procedure

The procedure used to measure the contrast sensitivity function was installed on firmware inside the Nicolet Optronics CS-2000, and so the procedure was the same as that used by other authors who used this apparatus (Ginsberg et al., 1984; Sekuler et al., 1984). Each run started with a 3 s presentation of the grating to be detected at 15% contrast, in order to reduce observer uncertainty about the signal parameters. After the preview, the contrast was reduced to zero and remained there for a random duration. Contrast was then increased slowly, and the subject hit a button when it first became visible. This procedure was repeated a minimum of three times for each spatial frequency, and the arithmetic mean was taken Ginsberg (1984). In other studies the geometric mean of contrast sensitivity measurements is typically taken because it is believed that the distribution is positively skewed. We found that the distribution of contrast sensitivity at each spatial frequency was actually symmetric, and that a log transform made the distributions negatively skewed. Before data collection, each subject did a practice run with a grating of 3 c/deg.

3. Results and discussion

The fundamental idea we are trying to establish is that something like Eq. (1) underlies the contrast sensitivity function. The model postulates that all observers have the same channel tuning curves, but differ in how these tuning curves are weighted. Each observed contrast sensitivity function is simply the sum of the channel outputs. Our method of deriving the channel tuning curves is to find the principal components or eigenvectors of the covariance matrix of the measured contrast sensitivities.

In order to validate our approach, we first simulated data that conformed to Eq. (1). This allowed us to explore the effect of using different procedures in the analysis on the derived tuning curves. In the simulation, each observer had three tuning curves measured at six spatial frequencies as shown by the thin solid, dashed, and dotted curves in the top panel of Fig. 2. For each of the 200 observers, each channel had a weight that was uniform random between 0.5 and 1.0. The mean contrast sensitivity function across simulated observers is shown by the squares, and the overall response as reconstructed from Eq. (1) is shown by the heavy curve.

In conducting a PCA one normally first centres the data by subtracting the mean. Another preliminary step that is sometimes taken is to standardize the variates to have unit variance. This amounts to doing PCA on the correlation matrix. The analysis in the middle panel of Fig. 2 was done on centred and scaled data using the function prcomp within the R statistical environment (Ihaka & Gentleman, 1996). After using PCA to derive the tuning curves, a further step is required (rotation) because the tuning curves as derived by PCA and other multivariate methods are not uniquely specified. The situation is directly analogous to that found in colour vision, where the colour matching functions do not uniquely specify the cone absorbance spectra. The true absorbance spectra are some linear combination of the colour matching functions. Similarly, the true spatial frequency channel tuning curves are some linear combination of the eigenvectors produced by PCA. The usual approach in factor analysis is to find a linear combination (rotation) that results in a "simple structure". A rotation producing a simple structure has many eigenvector values that are near zero. We follow Peterzell et al. (1993) in using an oblique rotation that allows the eigenvectors to be nonorthogonal (varimax rotation produced similar results). The middle panel of Fig. 2 shows the reconstructed response from the PCA with centred and scaled data and promax rotation as the heavy curve, along with the tuning curves. (The predicted response for each subject is given by matrix multiplication of the "scores" by the tuning curves, and the average across subjects gives the heavy curve.) It is clear that scaling the variates produces lowpass and highpass tuning curves rather than the three bandpass curves that actually exist.

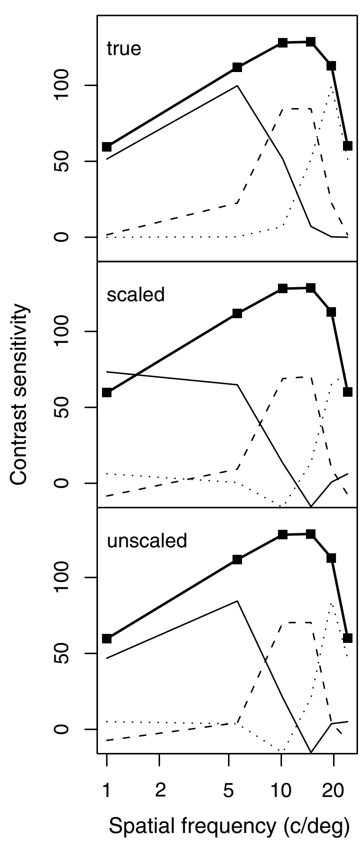

Fig. 2. Results of a simulation where the contrast sensitivities were formed as the sum of three channel outputs (Eq. (1)). The squares show the mean contrast sensitivities, and the heavy curves show the overall performance derived from the three underlying channels (thin, dashed, and dotted curves). The channels derived from Principal Component Analysis (PCA) using the unscaled data (bottom panel) closely matched the true channels (top). Scaling the data prior to PCA (middle panel) produced a lowpass and a highpass channel instead of three bandpass channels.

In the bottom panel of Fig. 2, PCA was done on centred but unscaled data. The derived tuning curves closely resemble the true tuning curves in the top panel. We conclude that if the data truly conform to Eq. (1), then PCA on centered and unscaled data (which amounts to doing PCA on the covariance matrix) followed by promax rotation will give a good picture of the tuning curves.

Before considering the real data, there is one other technical question to discuss: should the logarithm of the contrast sensitivity be taken prior to analysis? We decided against taking logs for three reasons. First, Eq. (1) is a simple linear model, and taking logs would

Table 1
Covariance and correlation matrices and summary statistics for the $n = 297$ study

	Spatial frequency (c/deg)					
	1	2	4	8	16	24
Covariance matrix						
1	701.45	500.62	480.20	289.76	49.31	42.17
2	500.62	1464.36	1200.28	963.87	327.60	128.52
4	480.20	1200.28	2974.94	2412.30	876.76	321.18
8	289.76	963.87	2412.30	3863.47	1423.56	579.53
16	49.31	327.60	876.76	1423.56	963.70	341.93
24	42.17	128.52	321.18	579.53	341.93	245.79
Correlation matrix						
1	1.0000	0.4940	0.3324	0.1760	0.0600	0.1016
2	0.4940	1.0000	0.5751	0.4052	0.2758	0.2142
4	0.3324	0.5751	1.0000	0.7115	0.5178	0.3756
8	0.1760	0.4052	0.7115	1.0000	0.7378	0.5947
16	0.0600	0.2758	0.5178	0.7378	1.0000	0.7026
24	0.1016	0.2142	0.3756	0.5947	0.7026	1.0000
Summary statistics						
Mean	76.16	146.15	197.88	175.47	73.59	31.21
SD	26.48	38.27	54.54	62.16	31.04	15.68

transform it into a nonlinear model. We prefer to try the simpler model as a first step. Second, for our data the distribution of contrast sensitivity at each spatial frequency across observers was approximately symmetric. Taking logs produced distributions that were strongly skewed to the left. Thus, if one wishes to produce symmetric distributions, taking logs will not do it. Finally, if the aim behind taking logs is to make the contrast sensitivities at different spatial frequencies have comparable variances, then the proper way to do this is to scale the data as described previously. We found that PCA on the log contrast sensitivities (scaled or unscaled) produced results similar to those in the middle panel of Fig. 2, and for the very reason mentioned: logging is more or less the same as scaling the data to have unit variance.

The 297 individual contrast sensitivity functions were centred and subjected to PCA. The covariance and correlation matrices and summary statistics are given in Table 1 (the raw data are available upon request from the first author). The first three principal components accounted for 91% of the variance, and so only these were used. Sekuler et al. (1984) compared analyses fitting 2, 3, and 4 channels and they also concluded that three channels gave a good description of the data. The first three principal components were then rotated by promax to give the channel tuning curves. The channel tuning curves are shown by the thin solid, dashed, and dotted curves in the top panel of Fig. 3. The mean contrast sensitivities are shown by the square symbols, and the heavy line shows the fit to the data using the three principal components. The three derived channels have peak frequencies of 2, 4, and 8 c/deg, with full width at half maximum (FWHM) of 1.6, 1.1 and 1.3 octaves. These tuning curves are comparable to those from Wilson and Gelb's (1984) mechanisms B, D, and E that have centres at 1.7, 4.0, and 8.0 c/deg with a FWHM of 1.5 octaves. In an electrophysiological study of macaque V1 cells DeValois et al. (1982) found a wide range of bandwidths, with a median value of 1.4 octaves.

Table 2
Covariance and correlation matrices and summary statistics for the cross-validation study

	Spatial frequency (c/deg)					
	1	2	4	8	16	24
Covariance matrix						
1	405.32	300.03	299.35	164.38	70.12	45.73
2	300.03	745.50	871.17	583.74	190.48	56.00
4	299.35	871.17	2388.07	1610.01	465.63	133.55
8	164.38	583.74	1610.01	1968.53	605.33	174.85
16	70.12	190.48	465.63	605.33	391.41	124.25
24	45.73	56.00	133.55	174.85	124.25	107.53
Correlation matrix						
1	1.0000	0.5458	0.3043	0.1840	0.1761	0.2191
2	0.5458	1.0000	0.6529	0.4819	0.3526	0.1978
4	0.3043	0.6529	1.0000	0.7426	0.4816	0.2635
8	0.1840	0.4819	0.7426	1.0000	0.6896	0.3800
16	0.1761	0.3526	0.4816	0.6896	1.0000	0.6056
24	0.2191	0.1978	0.2635	0.3800	0.6056	1.0000
Summary statistics						
Mean	62.99	116.06	143.62	106.50	42.42	18.79
SD	20.13	27.30	48.87	44.37	19.78	10.37

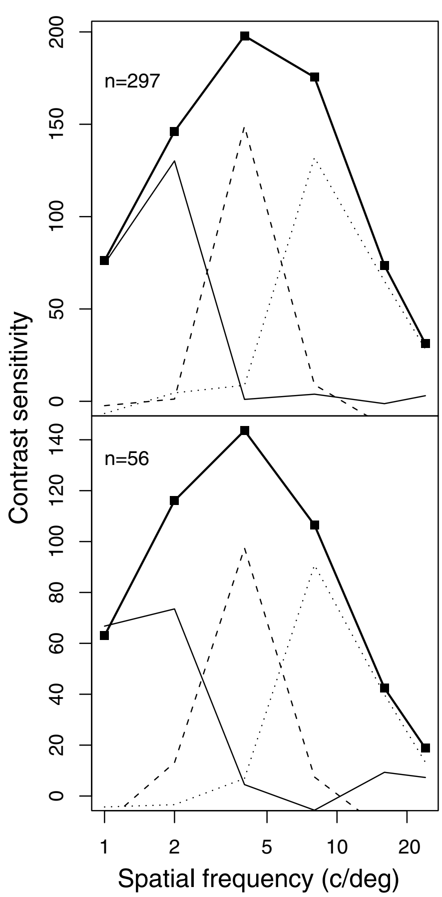

Fig. 3. Top: The contrast sensitivity function averaged across 297 observers is shown by the squares. The fit of Eq. (1) as derived by PCA is shown by the heavy lines. The thin, dashed and dotted lines show the tuning curves of the underlying channels. Bottom. PCA was done on individual contrast sensitivity functions from a different sample of 56 subjects. The fitted tuning curves (thin, dashed, and dotted lines) are similar to those found with the larger sample.

The reader may wonder how reliable the channels derived from multivariate analysis of individual data are. In order to address this question, we repeated our analysis on a set of data collected a year later on a different set of subjects. The covariance and correlation matrices and summary statistics are given in Table 2. The results are shown in the bottom panel of Fig. 3. The channels as estimated by PCA are much the same.

4. Conclusions

The contrast sensitivity functions of individual observers differ. We postulated that these individual differences are due to differences in the relative weighting of the outputs of underlying spatial frequency channels

(Eq. (1)). Principal component analysis of the individual contrast sensitivity functions revealed the tuning curves of three spatial frequency channels. These tuning curves were in substantial agreement with those derived by Wilson and Gelb (1984) using a masking paradigm. Moreover, the tuning curves derived from a measurements on a second sample were essentially the same. The stability of the tuning curves and their agreement with curves derived in other ways gives confidence in the individual differences approach and PCA. We would not, however, draw the strong conclusion that only three channels underlie the contrast sensitivity function. To get a good estimate of the number of channels it would be required to measure contrast sensitivity at a much larger number of frequencies.

Acknowledgments

We thank Warrant Officer Chester Dawes and Sergeant Rex Leyte for obtaining the contrast sensitivity measurements. We also thank the Armstrong Aerospace Medical Research Laboratory for loaning the experimental apparatus.

References

Billock, V. A., & Harding, T. H. (1996). Evidence of spatial and temporal channels in the correlational structure of human spatio-temporal contrast sensitivity. *Journal of Physiology, 490*, 509–517.

DeValois, R. L., Albrecht, D. G., & Thorell, L. G. (1982). Spatial frequency selectivity of cells in the macaque visual cortex. *Vision Research, 22*, 545–559.

DeValois, R. L., & DeValois, K. K. (1990). *Spatial vision*. New York: Oxford University Press.

Ginsberg, A. P. (1984). A new contrast sensitivity chart. *American Journal of Optometry & Physiological Optics, 61*, 403–407.

Ginsberg, A. P., Evans, D. W., Cannon, M. W., Jr., Owsley, C., & Mulvanny, P. (1984). Large-sample norms for contrast sensitivity. *American Journal of Optometry & Physiological Optics, 61*, 80–84.

Hyvarinen, A., & Oja, E. (2000). Independent component analysis: Algorithms and applications. *Neural Networks, 13*, 411–430.

Ihaka, R., & Gentleman, R. (1996). R: A language for data analysis and graphics. *Journal of Computational and Graphical Statistics, 5*, 299–314.

Mardia, K. V., Kent, J. T., Jr., & Bibby, J. M. (1979). *Multivariate analysis*. London: Academic Press.

Mayer, M. J., Dougherty, R. F., & Hu, L. (1995). A covariance structure analysis of flicker sensitivity. *Vision Research, 35*, 1575–1583.

Peterzell, D., & Teller, D. Y. (1996). Individual differences in contrast sensitivity functions: The lowest spatial frequency channels. *Vision Research, 36*, 3077–3085.

Peterzell, D., Werner, J. S., & Kaplan, P. S. (1993). Individual differences in contrast sensitivity functions: The first four months of life in humans. *Vision Research, 33*, 381–396.

Peterzell, D., Werner, J. S., & Kaplan, P. S. (1995). Individual differences in contrast sensitivity functions: Longitudinal study of 4-, 6-, and 8-month old human infants. *Vision Research, 35*, 961–980.

Sekuler, R., Wilson, H. R., & Owsley, C. (1984). Structural modeling of spatial vision. *Vision Research, 24*, 689–700.

Wilson, H. R., & Gelb, D. J. (1984). Modified line element theory for spatial frequency and width discrimination. *Journal of the Optical Society of America A, 1*, 124–131.