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Discovering Sensory Processes Using Individual Differences: A Review and Factor Analytic Manifesto

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Abstract

In the last century, many vision scientists have considered individual variability in data to be "error," thus overlooking a trove of systematic variability that reveals sensory, cognitive, neural and genetic processes. This "manifesto" coincides with old and recent prescriptions of a covariance-based methodology for vision. But the emphasis here is on using small samples to both discover and confirm characteristics of visual processes, and on reanalyzing archival data. This presentation reviews, briefly, 215 years of sporadic and often neglected research on normal individual variability in vision (including 25+ years of my own research). It reviews how others and I have harvested covariance to a) develop computational models of structures and processes underlying human and animal vision, b) analyze and delineate the developing visual system, c) compare typical and abnormal visual systems, d) relate visual behavior, anatomy, physiology and molecular biology, e) interrelate sensory processes and cognitive performance, and f) develop efficient (non-redundant) tests. Some examples are from my factor-analytic research on spatiotemporal, chromatic, stereoscopic, and attentional processing.

Introduction

Here I report research examining individual differences (IDs) in a diverse variety of vision studies, and demonstrate how these differences contain *systematic* variability that elucidates sensory, cognitive, neural and genetic processes.

Most vision science uses "experimental" paradigms, focusing on average differences across stimulus conditions, while treating IDs as "random error variance." But data from many of these experiments contain a separate type of information relevant to studying visual mechanisms. Far less vision science has focused on "correlational" or "factor analytic" approaches which treat normal IDs as systematic and meaningful, reflecting the true variability of underlying processes more than random error.

I propose a more extensive exploration of systematic IDs in visual data to identify "factors" of the visual mind, eye, nervous system and genome. In fact, attempts to understand vision by using IDs, and to understand IDs by modeling visual processes, have been pursued since the 19th century, when Bessel and others [1]-[4] studied IDs in temporal detection among astronomers, and Galton [5]-[6] attempted to link visual performance to general cognitive abilities. This "manifesto" coincides with scattered, oft-neglected prescriptions for a covariance-based methodology for vision, and with recent studies that interrelate IDs in functional organization, anatomy, physiology, heredity, psychophysics, optics, cognition, and multiple visual functions, using normal, clinical, developing and aging populations [7]-[31], [64]-[178], including my own work [32]-[53].

But the primary emphasis here is on analyzing IDs using small samples obtained from typical experiments and archival data, to discover and confirm visual processes.

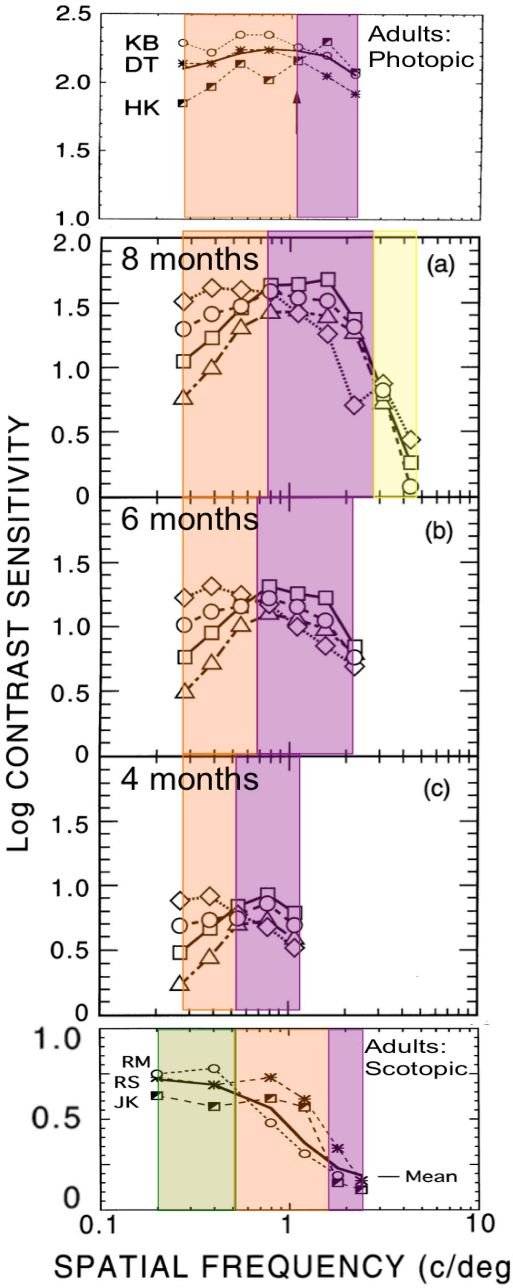

Figure 1. Luminance spatial contrast sensitivity functions (CSFs) for a few individuals selected from larger samples. Upper panel: adults, photopic [38]. Middle panels: infants, photopic [31]-[32], [36]. Lower panel: adults, scotopic [44]-[45], [54]. Solid lines without points show means for complete samples. Orange, purple, green, and yellow delineate separate "factors." Even for small samples, IDs at one SF correlate with IDs at neighboring but not distant SFs.

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1. The variability in visual data is often systematic, not random.

This principle becomes clear when inspecting the spatial contrast sensitivity functions (CSFs) in **Figure 1**, which contains:

(A) Top panels: three CSFs obtained from a larger sample of human adults under photopic conditions [38].

(B) Middle panels: a longitudinal sample of data obtained at photopic light levels from 4 exceptionally consistent infants at 4-, 6, and 8 months of age [31]-[32], [36].

(C) Lower panel: three CSFs obtained from a larger sample of human adults under scotopic conditions [54], [44]-[45].

Even in these small samples, and without correlational or factor analytic statistics, a clear "intuitive factor analysis" is possible. These data were selected to show that IDs at a particular spatial frequency are correlated with IDs at neighboring but not distant spatial frequencies. For instance, in the top panel (orange region), observer KB shows the highest sensitivity for all four spatial frequencies below 1 c/deg, while DT is near the mean, and HK is below the mean for all four. But in the rest of the top panel (purple region), KB's sensitivity regresses to the mean, DT drops below the mean, and HK rises above the mean. While results within a region (orange or purple) inter-correlate, results across larger regions seem not to inter-correlate (between orange, purple). And so, this typical (as I've found) example shows that even with very small samples containing negligible measurement error, systematic and potentially informative differences reside in IDs.

The patterns evident in small samples are often consistent with what is found in much larger sets. For instance, **Figure 2** shows results for larger samples for spatial CSFs obtained for adults using luminance modulated gratings (as in Figure 1). The upper and lower panels are for photopic and scotopic CSFs, respectively. Each square within the matrix of squares represents a scatterplot. Each scatterplot plots log contrast sensitivities obtained for many individuals at one spatial frequency as a function of log contrast sensitivities contrast obtained for many individuals at another spatial frequency. For instance, in the scotopic data [44]-[45], [54], in the second to left top square, the sensitivities of 50 observers obtained using .2 c/deg gratings are plotted as a function the sensitivities of these 50 observers obtained using .4 c/deg gratings, with visibly high correlation. The correlation between .2 c/deg and 1.2 c/deg is also positive, but not as strongly correlated. As such, regions of inter-correlation can be seen in these data. As with Figure 1, regions of inter-correlation are marked by colored boxes, with distinct regions evident. And so again, in these comparatively large samples, a clear "intuitive factor analysis" is possible, even without correlational or factor analytic statistics.

Although the example provided is for spatial contrast sensitivity functions, it is worth noting that such systematic variability with clearly delineated underlying factors is typical of high quality visual data collected using psychophysics (large numbers of trials per point, and relatively bias-free methods such as 2AFC) and many electrophysiological measures (e.g., electroretinograms and visual evoked potentials). (See historical section). This is certainly the case in my own work and collaborations involving human spatial and temporal CSFs, using luminance and chromatic gratings, photopic and scotopic light conditions, psychophysics and VEPs methods, and adults and infants. It is also the case for many other types of data I've investigated, including spectral sensitivity functions in man and (genetically modified) mouse, binocular corrugated gratings, VEP contrast response functions, infant visual attention data, and color naming [32]-[53].

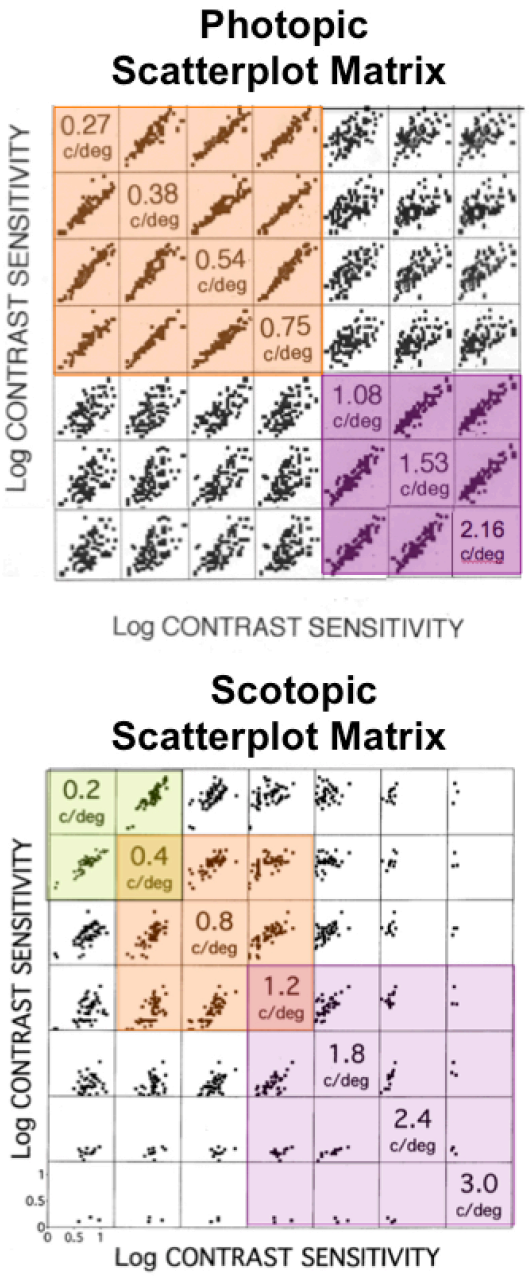

Figure 2. Scatterplot matrices for full sample of individuals' photopic and scotopic CSF data.

2. Systematic variability is usually visible and interpretable in terms of underlying processes, even in data from a few individuals.

When one inspects CSFs from adults, infants, and non-human species, patterns of individual variability consistent with spatiotemporal channels become evident.

Figure 3, for instance, shows spatial frequency tuning curves for six foveal, scotopic processes postulated by Wilson and Gelb after modeling psychophysical masking data [55], [56]. The orange and purple regions from Figures 1 and 2 correspond to regions primarily detected by mechanisms A and B, respectively.

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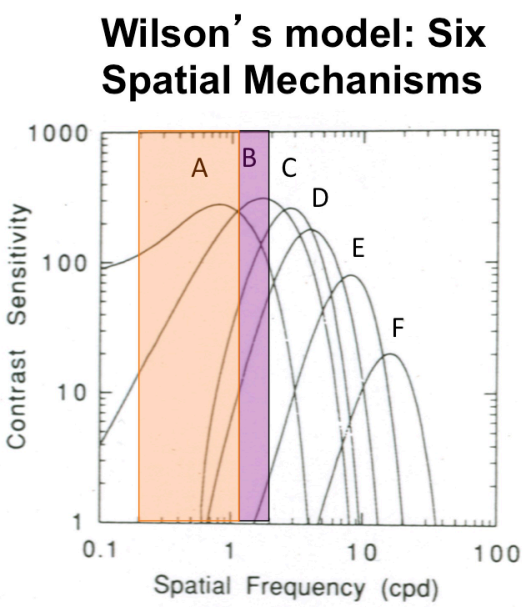

Figure 3. A model of photopic spatial mechanisms based on computational modeling of visual masking functions.[55]-[56]. The orange and purple regions in this figure denote regions primarily determined by Wilson's mechanisms A and B, respectively, and also correspond to the orange and purple factors shown in Figures 1 and 2.

That is, it looks like the "sources of variability" (a term used in factor analysis) in Figures 1 and 2 are explained by, or consistent with, mechanisms A and B from the model of Wilson and Gelb.

Similar indications of underlying mechanisms are visible in IDs for other published functions (e.g. spectral sensitivity, luminous efficiency, color matching, sensitivity of horizontal and vertical corrugations defined by binocular disparity). But visual and perceptual scientists typically focus on average differences across experimental conditions (e.g., average differences in contrast sensitivity for different spatial or temporal conditons, or different ages).

3. Analyses of IDs can be used to confirm what is already "known" about underlying processes, or to discover previously unknown visual processes.

If one has a priori knowledge or a strong theory of the processes underlying a visual function, then confirmatory factor analyses should succeed in recovering those processes from IDs in that function. This type of "confirmatory" analysis is contrasted to "exploratory" analyses, in which one uses individual differences and factor analyses to discover previously unknown processes or sources of variability.

The difference between confirmatory and exploratory factor analyses is illustrated in **Figure 4**, for CSF data. In a *confirmatory analysis* (upper section), one begins (Panel 1) with an a priori model of underlying spatially-tuned processes, and attempts to predict (blue arrow) the pattern of IDs obtained in empirical data (Panel 4, i.e., the types of patterns presented in Figures 1 and 2). In other words, are ID patterns within the data consistent with an existing model of optical, neural or genetic processes? In an *exploratory* analysis (Figure 4, middle section), one uses the pattern of IDs contained in empirical data (Panel 4) to infer or discover (red arrow) optical, neural or genetic processes. In both

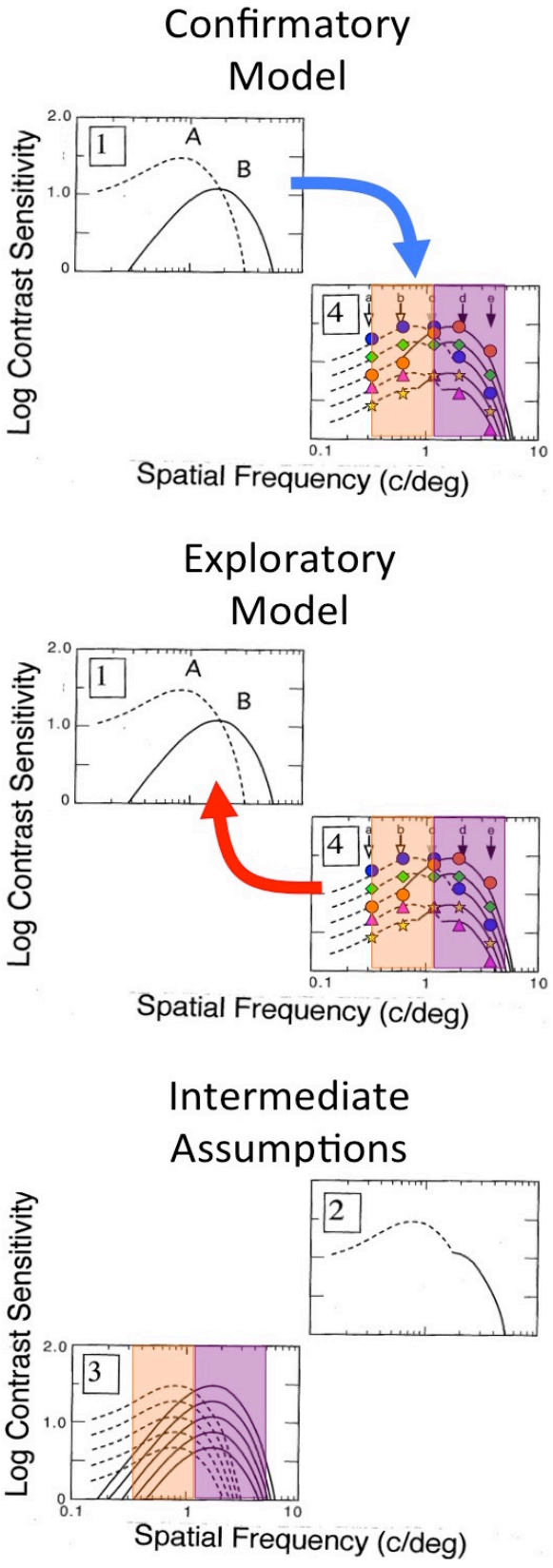

Figure 4. The nature of confirmatory and exploratory factor analytic models, using the example of spatial CSFs. See text for details.

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instances, one makes assumptions (Figure 4, lower section) about how underlying processes combine to determine threshold (Panel 2), and about how underlying processes vary across individuals (Panel 3). In the example, an all-or-none combination rule is shown in Panel 2, and a discrete set of processes of constant shape and tuning vary in sensitivity across individuals. Mechanisms tuned to high and low spatial frequencies are assumed to vary independently in the example.

The terms *confirmatory factor analysis* (CFA) and *exporatory factor analysis* (EFA) are taken from the factor analytic literature. In both types of factor analysis, one might use visual inspection (as in Figures 1 and 2), correlations, factor analytic statistics, structural equation modeling, multidimensional scaling, principal component analyses, independent component analyses, or similar to confirm or explore putative underlying processes. In CFA, the user defines which variables or items are related to the specified constructs or latent factors based on a priori theory, and tests to see if the a priori model fits the data. In EFA, the same statistics may be used to infer the presence of latent factors which are responsible for the shared variance in a set of observed variables. The researcher does not specify a model or structure, and assumes that each variable could be related to each latent factor.

Figure 5 demonstrates what I believe to be a powerful demonstration of a set of confirmatory analyses. Peterzell and Teller [38, 42] predicted that individual differences in their adult CSF data set would be consistent with Wilson's model of spatial channels, mentioned previously. First, they determined that regions of high inter-correlation were found, consistent with the existence of sets of spatial frequencies that are detected by the same underlyng channel (i.e., Figure 2, top section). Statistical factor analyses, which derive variability sources (or factors) from the data, were then used to estimate channel tuning. Two significant factors were found in the data. Both factors showed clear spatial frequency tuning. That is, when principal components or factors were rotated to approximate simple structure using Varimax, the factor loadings varied systematically with spatial frequency.

The tuning of channels was estimated by fitting factor loadings to photopic contrast sensitivities using the following equation:

$$\text{Channel Contrast Sensitivity}_{in} = \frac{\text{mean log contrast sensitivity}_{n}}{\text{abs}\,(1/\text{factor loading}_{in})^{1/Q}} \quad (1)$$

which determines the analyzer contrast sensitivity for factor i at spatial frequency n. Q is the exponent of an often used probability summation equation, consistent with results from photopic masking and channel theory [55, 56]. For each of the factors at each spatial frequency, Equation 1 generated channel sensitivity values that can vary from near-zero (for factor loadings near zero) to the mean log contrast sensitivity (for factor loadings equal to one).

The symbols in Figure 5 represent predicted contrast sensitivities that were calculated using Equation 1. In the lower panel are the results from the initial study of Peterzell and Teller [38[, as well as the results from a second study under slightly different conditions which replicated the initial result [42].

Thus, in an initial study and a replication, Peterzell and Teller confirmed that the channel model of Wilson and Gelb could account for individual differences in the data. That is, the factors obtained from the data were close to matching the predictions of the existing model.

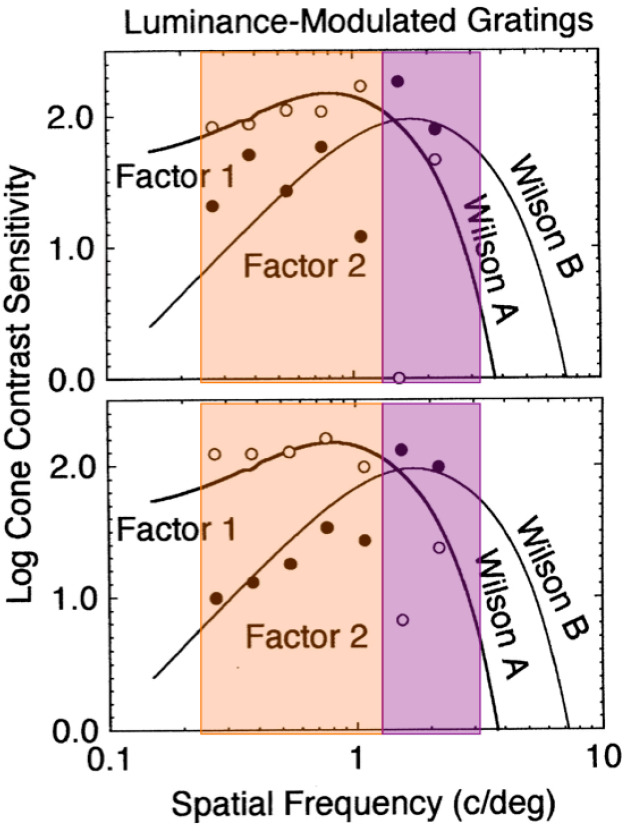

Figure 5. Estimates of the contrast sensitivity of spatial frequency tuned covariance channels plotted as a function of spatial frequency. Estimates in the top panel are for yellow-black sinewave grating stimuli [42], and for white-black gratings from an earlier study [38]. The points denoted by the symbols are derived from Eq. 1, using the mean CSFs obtained, and factor loadings computed from the empirical data. Smooth curves represent the spatial frequency channels A and B of Wilson [55]-[56] (see Figure 3).

Several examples demonstrate the variants of confirmatory analyses in some studies.

A. Monte Carlo simulations of visual models successfully detect known underlying processes.

In simulations, visual functions are created for simulated individuals by combining simulated, independently varying processes defined by existing models. For instance, simulations of various models of spatial channels of adult and infant spatial channels yield statistical factors that accurately recover the known input [22], [34], [36].

B. When individuals are genetically modified to add a visual process, the additional, separable process is detectable in patterns of IDs.

As perhaps the only example of this confirmatory approach, IDs in chromatic sensitivity functions of transgenic mice (expressing a functional long wavelength [L] photo-pigment, in addition to S and M photo-pigments) were compared to unmodified wild type mice (expressing S and M photo-pigments only) [52]. Using the archival data of Shabaan et al. [57] Peterzell and Crognale verified the existence of an additional ID factor in the data from 5 transgenic mice compared to 5 wild type mice.

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C. "Known" processes can be recovered from archival data.

In the most sophisticated factor analysis of visual data to date, MacLeod and Webster [23]-[24], for example, examined IDs in the color matches of normal human observers from the archival data of Stiles and Burch. Independent sources of IDs included the following identifiable factors: macular pigment density, lens pigment density, the spectral positions of three cone types, the covarying densities of the photo-pigments, and rod intrusion. Their factor analyses produced direct estimates the M- and L-pigment absorption spectra that matched, nearly, previously identified spectra. Thus they confirmed an established model using the previously unexplored variability in archival data.

4. Studies of IDs can test competing models of visual processes.

The development of infants' CSFs for luminance and chromatic gratings provides an example. Two classes of models, both based on the emergence of multiple spatial channels, have been proposed to account for CSF development. One class suggests that each spatial frequency channel is fixed in spatial scale, but grows in sensitivity (i.e., a vertical shift) with age, with channels tuned to higher frequencies achieving measurable sensitivity only at later ages [58]. The second class suggests that multiple channels exist at birth, and that with age each individual channel shifts both in sensitivity (vertically) and in spatial scale (horizontally) toward higher spatial frequencies [59]-[61]. The observed developmental changes in the CSF, and psychophysical masking and adaptation data, can be fit by either model.

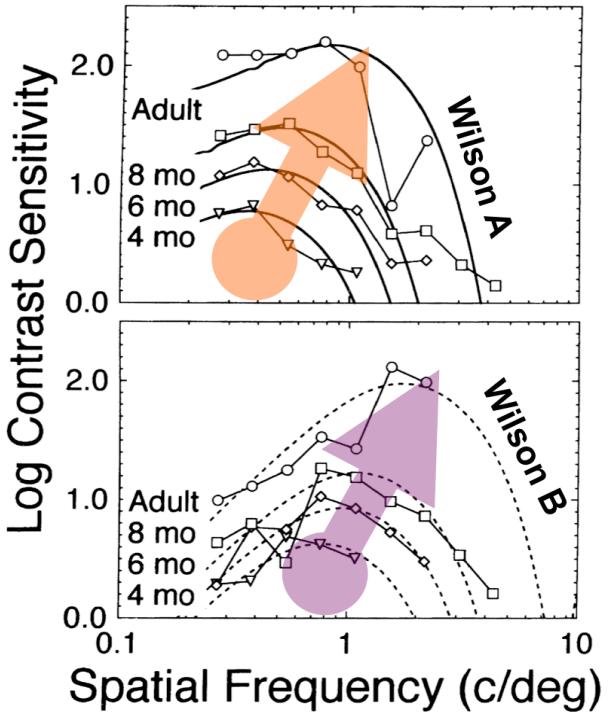

Figure 6. Estimates of the contrast sensitivity of spatially tuned covariance channels plotted as a function of spatial frequency [38], [32], [33], [36]. Comparison of covariance channels obtained from IDs to the predictions derived from Wilson's [61], [62] computational model of the development of spatial frequency channels (smooth curves). As mean foveal cone spacing decreases and eye size increases with age, the peak sensitivity of each channel shifts from lower spatial frequencies to its adult value. The covariance channels are superimposed on Wilson's channels A and B {upper and lower). The covariance channels shift rightward to higher spatial frequencies with age, consistent with developmental scale change.

Possible shifts in spatial scale of the individual channels were examined by applying ID theory and methodology to luminance and chromatic CSFs of human infants in a series of psychophysical and VEP experiments [32]-[34], [36-37], [39], [41], [43]. Data were analyzed in the same manner as with adults (Figure 5), and in each study revealed factors that appeared to shift as predicted by the scale-change model. **Figure 6** shows results from a longitudinal psychophysical study using luminance-modulated gratings [32], [33], [36], along with results from adults under comparable conditions [38]. IDs suggest the presence of at least two channels by 2 months of age. The spatial scale of these covariance channels shifts with age, in support of the scale-change hypothesis, and specifically Wilson's [61]-[62] model.

5. Studies of IDs can discover previously unknown visual processes.

Exploratory (vs. confirmatory) factor analyses are conducted when a priori knowledge of the underlying processes is absent. In general, covariance in IDs is interpreted to indicate a univariant process, though alternatives possible.

As an example, Peterzell, Schefrin, Tregear and Werner [44] , [45] examined the covariance structure of IDs underlying 50 scotopic CSFs, using archival data [54]. The factor analysis was "exploratory" because little was known about scotopic spatial channels.

The process underlying photopic CSFs had been modeled in terms of multiple channels selective for spatial frequency, with the lowest frequency channel obtained "foveally" using stationary sinusoidal gratings typically had its peak sensitivity near 1 c/deg [38], [42], [60]. But less was known about the processes underlying the scotopic CSF. The channels could vary considerably. Hess and Howell demonstrated that the CSF peaks near 0.2 c/deg when stimuli were presented scotopic luminances [63]. This low-frequency peak was unexplainable using only a band-pass channel peaking near 1 c/deg. Hence, the researchers concluded that several spatial frequency channels exist at very low spatial frequencies but may operate as scotopic luminances only (or, similarly, the peak of a channel might shift to lower spatial frequencies at low light levels, due, perhaps, to a reduction of the influence of the surrounds of receptive fields). At the same time, Greenlee et al. [60] determined that the lowest adaptable frequency channel obtained using scotopic stationary gratings occurred well below 1 c/deg (as measured in rod monochromats). They concluded that rod monochromats differed from normals. Equally likely from their results, though, was the possibility that scotopic vision, unlike photopic vision, contains multiple spatial frequency channels below 1 c/deg.

And so an exploratory factor analysis was conducted in an attempt to estimate the number and nature of spatial channels mediating scotopic contrast sensitivity. First, individual data (e.g., Figure 1, lower panel) and correlation matrices (i.e., Figure 2, lower panel scatterplot matrix) were examined, revealing evidence consistent with discrete multiple channels. Factor analyses using the same methods as with photopic adult and infant data provided the results shown in **Figure 7**.

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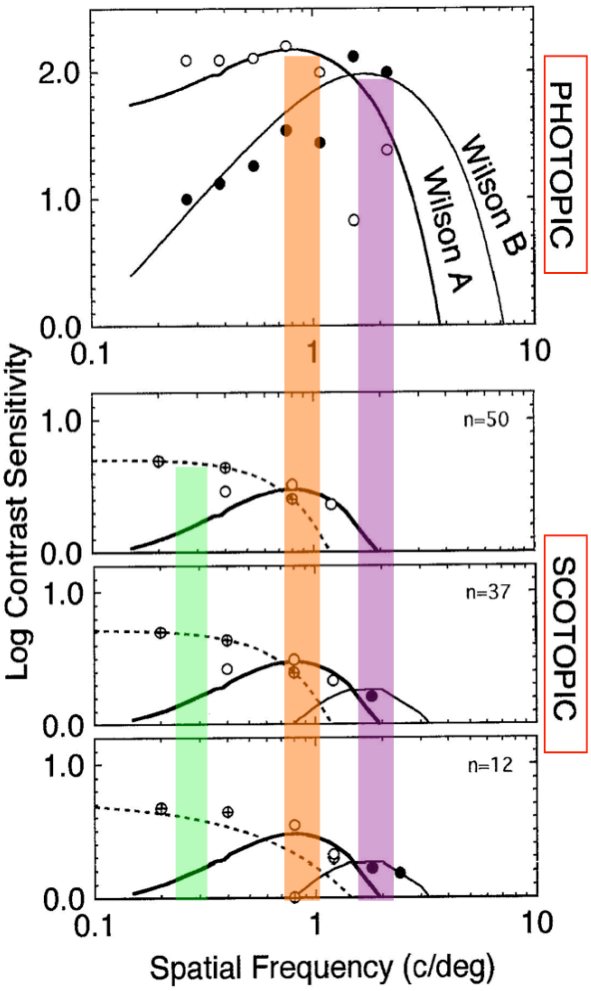

Figure 7. Estimates (lower panels), for scotopic vision, of the contrast sensitivity of spatial frequency tuned covariance channels plotted as a function of spatial frequency. See text for details. The points denoted by the symbols are derived from Eq. 1, using the mean scotopic CSFs obtained, and factor loadings computed from the empirical data. Smooth solid curves represent the spatial frequency channels A and B of Wilson [55]-[56]. Upper panel re-plots results for photopic vision from Figure 5, lower panel.

The symbols in Figure 7 (lower panels) represent predicted contrast sensitivities that were calculated using Eq. 1, the mean log scotopic CSF (Figure 1, lower panel), and the factor loadings from the factor analyses on either 12, 37, or 50 subjects (with only 12 participants providing data at all 6 spatial frequencies).

Three discrete factors were obtained from the IDs. For the two scotopic channels tuned to the highest spatial frequencies, we discovered (Figure 7, lower panels) that the tuning functions resemble those obtained for photopic vision, both from our own factor analytic studies, and from the aforementioned spatiotemporal model of Wilson ([55]-[56], as shown in Figure 5). That is, the symbols obtained from our data map onto the "A" and "B" spatial channels specified in the computational model. In contrast to the photopic data, however, we *discovered* a single covariance channel in the scotopic data that is tuned to very low spatial frequencies (with a dashed line drawn through the points). Of course, this "discovery" is offered with caution. Further research is needed to validate the existence of this channel.

6. Conclusion.

The history of studying individual differences in vision has not been reviewed here in much detail. And yet it seems fair to say that the history is richer than most current researchers realize. At various points in history, researchers have used factor analytic approaches and individual differences in attempts to elucidate vision and visual processes. The groups interested in such research have included astronomers developing "personal equations" and "personal scales," psychometricians studying human abilities, military researchers hoping developing screens, social and cultural psychologists studying situational perception, as well as visual psychophysicists and neuroscientists studying visual processes. And topics in the visual literature include investigations into such diverse topics as dark adaptation, acuities (including vernier acuity), spectral efficiency (vλ), contrast sensitivity, illusions, Rorschach responses, imagery, gestalt factors (e.g., "closure"), aesthetic preference, field dependence, spatial tests, visual memory, color preference, face recognition, electrophysiology vs psychophysics vs. other domains, synesthesia, eyewitness perceptual abilities, global and local processing, pupil size, visual memory, and more. A more detailed summary of factor analytic research into visual processes remains to be attempted.

In sum, other researchers and I have harvested covariance to a) identify structures and processes underlying vision, b) analyze and delineate the developing visual system, c) compare typical and abnormal visual systems, d) relate visual behavior, anatomy, physiology and molecular biology, and e) interrelate sensory processes and cognitive performance. **Results may suggest a framework for inferring processes from data, and perhaps a map for future discoveries.**

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