Introduction

Paradigms for attacking the problem of how vision works continue to develop and mutate, and the boundary between them can be indistinct. Nonetheless, this bibliography represents an attempt to delineate one such paradigm: Visual Psychophysics. Unlike, for example, anatomical paradigms, the psychophysical paradigm requires a complete organism. Most of the studies discussed below involve human beings, but psychophysics can be used to study the vision of other organisms too. At minimum, the organism must be told or taught how to respond to some sort of stimulus. (Studies of reflexes such as the knee-jerk response are not psychophysical.) It is the decision processes preceding those responses that are of primary interest to a psychophysicist. The word "psychophysics" comes from Fechner's *Elemente der Psychophysik* (see Theory), in which the paradigm was initially codified. Fechner himself was not particularly interested in vision. All sensory processes are amenable to psychophysical examination. Consequently, several of the key advances in the both the theory and the practice of psychophysics were made by scientists trying to understand something else. Much of that work will be ignored here. What this bibliography does contain, after brief discussion of Theory and Practice, is a catalogue of psychophysical investigation, loosely organized according to stimulus properties ("features") that are unquestionably encoded at a very low level in the hierarchy of visual processing: luminance, spectral content, contrast, and spatio-temporal position. Discussion will focus on how visual stimuli differing in these feature contents are detected, discriminated, and appear to human observers. Separate sections describe the criteria necessary for a stimulus property to be considered a visual feature (feature criteria and current debates) and the effects of spatial and temporal context on detection and appearance. Some related areas of investigation and their relationship to visual psychophysics are described at the end.

Theory

The impact of Fechner's (1966) empirical attitude toward mental events cannot be overstated. Prior to *Elemente*, psychological science was based either on physiology or philosophy. Although Fechner explicitly refused credit for inventing any psychophysical methods, he did classify each one as either a method of just-noticeable difference, a method of average error, or a method of right and wrong cases. The first two of these methods survive today as the method of limits and the method of adjustment. However, more recent assays of the field invariably suggest new taxonomies, encompassing new methodologies and better distinguishing between certain flavors of the classic ones. The most important types of psychophysical measurement not considered by Fechner are response times (reviewed by Luce 1986), confidence ratings (analyzed by Galvin, et al. 2003), and magnitude estimations (popularized by Stevens 1961; criticized by Laming 1997). However, advances in the field of statistics have proven to be even more valuable for contemporary psychophysicists. This is because organisms do not always respond in the same way to the same stimuli. Thurston (1994) was among the first researchers to characterize the stochastic nature of psychophysical responses, but the mathematical tools for summarizing this variability are still being developed today. Two particularly noteworthy summaries of advances in this regard are those by Green & Swets (1966) and Macmillan & Creelman (2005).

Fechner, Gustav T. *Elements of Psychophysics, Vol. 1*. Translated by Helmut E. Adler. New York, NY: Holt, Rinehart & Winston, 1966. English translation of *Elemente der Psychophysik*, first published in 1860.
According to Fechner, the whole of *Elemente* "evolved on the basis of and in connection with" an idealistic interpretation of immortality. Fechner may not have had an undying soul, but his influence refuses to disappear. His greatest contribution to psychology was the notion that mental events can be measured in terms of the stimuli that elicit them.

Galvin, Susan J., John V. Podd, Vit Drga, & John Whitmore. 2003. Type 2 tasks in the theory of signal detectability: Discrimination between correct and incorrect decisions. *Psychonomic Bulletin and Review* 10:843–876.
Distinguishes between confidence in stimulus characteristics and confidence in response accuracy, and thoroughly models both from the perspective of Signal-Detection Theory.

Green, David M., & John A. Swets. 1966. *Signal Detection Theory and Psychophysics*. New York, NY: Wiley.
With very few and explicit assumptions regarding the sources of response variability, the authors develop a mathematical framework for characterizing sensory computations with what was then revolutionary precision. It has become the cornerstone of contemporary psychophysical analyses.

Laming, Donald. 1997. *The Measurement of Sensation*. Oxford University Press.
Trenchant critique of magnitude estimation and related techniques. Also contains refinements of and amendments to the author's idiosyncratic theories of visual discrimination from previous publications. The empirical support is selective but persuasive.

Luce, R. Duncan. 1986. *Response Times: Their Role in Inferring Elementary Mental Organization*. Oxford, UK: Oxford University Press.
A compendium of analytical tools, tricks for getting sensible data, and caveats about over-interpretation.

Macmillan, Neil A. & C. Douglas Creelman. *Detection Theory: A User's Guide*, 2nd edition (2005). Mahwah, NJ: Lawrence Erlbaum Associates.
Textbook and methodological handbook for all types of psychophysical measurement.

Stevens, Stanley S. 1961. To honor Fechner and repeal his law. *Science* 133:80–68.
Whereas Fechner was interested in sensory intensity, what he measured was the ability to discriminate between similar sensations. Stevens introduced magnitude estimation as a way to actually measure apparent intensities. This paper may be his most accessible. It contains a succinct compendium of magnitude estimation's "applications and validations."

Thurstone, Louis L. 1994. A law of comparative judgment. *Psychological Review* 101:266–270, first published in 1927.
The five "cases" introduced in this short essay are collections of increasingly restrictive assumptions about the sources of response variability. Read this to

understand why it makes sense to call a 21st-century psychophysical model "Thurstone Case V."

Practical Guides

Computers have had a profound influence in the field. The vast majority of today's experiments use stimuli created and displayed on computer screens, keyboards are often used to collect responses, and results are routinely subjected to statistical analyses that were logistically implausible before the advent of the personal computer. Consequently, some of the recent advances in the general practice and theory of psychophysics have been described in conjunction with computer programs for their implementation. Noteworthy works in this area include those by Kingdom & Prins (2010) and Knoblauch & Maloney (2012). These works and others are catalogued in H. Strasburger's regularly updated website: Software for visual psychophysics, which in turn appears on visionscience.com . Continually updated, this latter resource has well-organized links to almost every aspect of visual science as it is practiced today, including over 100 books on the topic (of these, Graham 1989 may be the only one that is wholly restricted to the psychophysical paradigm).

Kingdom, Frederick A.A., & Nicolaas Prins. 2010. *Psychophysics: A Practical Introduction*. London: Elsevier.
Yet another taxonomy for psychophysical methods (cf. Theory) plus MATLAB routines for controlling and analyzing psychophysical experiments.

Knoblauch, Kenneth, & Laurence T. Maloney. 2012. *Modeling Psychophysical Data in R*. New York, NY: Springer.
Focuses on the Generalized Linear Model and associated analytical frameworks, which have proven uniquely valuable for explaining response variability on a trial-by-trial basis (i.e. rather than statistically).

Software for visual psychophysics[http://www.hans.strasburger.de/psy_soft.html]. Edited by Hans Strasburger.
Not just all the software written by Strasburger, but *all* of the software, or hotlinks to it, sensibly organized and succinctly described.

Vision Science[http://visionscience.com].
From here, it's no more than two clicks to virtually every laboratory, researcher, product, journal, conference, job or bibliography in the field.

Luminance

Given that there would be no vision without light, it should not be surprising that the visual measurement of luminance (i.e. the amount of light) was among the first phenomena investigated using a psychophysical method. Indeed, it may be that the method of limits was invented by Bouguer (1961) when he increased the distance between one of two candles and reflecting screen until the shadow formed by an intervening rod disappeared. From the two candles' distances, Bouguer inferred what would be known today as the Weber faction. Specifically, the ratio between a just-noticeable-increment ΔI and the baseline or pedestal I to which it is added turned out to be about 0.015. Weber fractions can be surprisingly invariant over large domains of pedestal intensity. Fechner (1966) formulated this invariance as $\Delta I/I = k$, and coined it Weber's Law. However, when (as in Bouguer's experiment) the psychophysical task merely requires perceiving a border between stimuli having luminances I and $I + \Delta I$, empirical adherence to Weber's Law is poor. Bartlett (1942) was among the first to note that this type of *increment detection* was fundamentally different from tasks in which the two stimuli do not share a spatial or temporal border (e.g. when each appears against a dark background). In this latter paradigm of *difference discrimination*, the Weber fraction remains invariant over several magnitudes (at least five, according to Cornsweet & Pinsker 1965) of pedestal intensity. Whittle (1986) noted that Weber's Law also holds for pedestal *decrements* of up to half a bright background's luminance. Although observers can be very accurate when deciding which of two surfaces under different illumination has greater overall reflectance, they exhibit systematic biases when attempting to compare the total amounts of reflected light from differently illuminated surfaces (Arend & Goldstein, 1987). This "phenomenal regression to the real object" is why contemporary psychophysicists (e.g. Gilchrist 2013 and MacLeod 2013) consider brightness (i.e. apparent luminance) to be a relatively artificial visual feature; one that observers construct from their more biologically relevant estimates of lightness (i.e. apparent reflectance). Exactly how observers assemble that construction and many other related topics have been recently reviewed by Kingdom (2011).

Arend, Lawrence E. & R. Goldstein 1987. Simultaneous constancy, lightness, and brightness. *Journal of the Optical Society of America A* 4:2281–2285.
Contains oft-modeled data for two different tasks using the same stimuli: 1) adjust the 'test' luminance, so that it has the same brightness as the 'standard' and 2) adjust the 'test,' so that it looks as if it were cut from the same piece of paper as the 'standard.' Data from this second task demonstrate phenomenal regression even though there was no real object; all images were computerized.

Bartlett, N.R. 1942. The discrimination of two simultaneously displayed brightnesses. *Journal of Experimental Psychology* 31:380–392.
Although this paper represents a pivotal demonstration of Weber's Law for discriminating luminances in the dark, Bartlett was primarily interested in the effect of display duration. His data confirm Bloch's Law ($\Delta I \times t = k$) for durations (t) less than about 0.1 s.

Bouguer, Pierre *Optical Treatise on the Gradation of Light*. Translated by W.E. Knowles Middleton. Toronto: University of Toronto Press, 1961. English translation of *Essai d'optique sur la gradation de la lumière*, first published in 1729.
Firmly established the method of limits for measuring increment thresholds in the luminance domain. Bouguer understood that visual sensitivity might not be constant and wrote, "We can only judge directly the strength of two sensations when they affect us at the same instant."

Cornsweet, Tom. N., & Pinsker, Harold. M. 1965. Luminance discrimination of brief flashes under various conditions of adaptation. *Journal of Physiology* 176:294–310.
Often replicated and often modeled, not only do these data provide strong support for Weber's Law above the detection threshold, they also show that ΔI actually decreases with small values of I. A similar 'dip' (a.k.a. negative masking) has been found near

the detection thresholds of other stimulus features (e.g. Suprathreshold Contrast) besides luminance.

Gilchrist, Alan. "Objective and Subjective Sides of Perception." In *Visual Experience: Sensation, Cognition and Constancy,* Edited by Gary Hatfield and Sarah Allred. Oxford, UK: Oxford University Press, 2012.
Gilchrist is an expert on the way we experience luminance, and in this chapter uses ammunition from his field of study against the notion that (brightness) sensations can be disentangled from (lightness) perception, which he dismisses as a 19th-century idea that had a brief afterlife with behavioral fetishists in the 20th.

Kingdom, Frederick A.A. 2011. Lightness, brightness and transparency: A quarter century of new ideas, captivating demonstrations and unrelenting controversy. *Vision Research* 51:657–673.
A well-balanced and thorough review on the last 25 years of research into the perception of luminance, by one of the aforementioned "fetishists."

MacLeod, Donald I.A. "A mechanistic perspective on the 'given.'" In *Visual Experience: Sensation, Cognition and Constancy,* Edited by Gary Hatfield and Sarah Allred. Oxford, UK: Oxford University Press, 2012.
Covers much of the same ground as Gilchrist (above), using equally colorful language. He compares early sensory signals with the "releasing stimuli" of ethology. That is, they simply serve as a trigger for one of the various interpretations that the visual system can produce.

Whittle, Paul. 1986. Increments and decrements: luminance discrimination. *Vision Research* 26:1677–1691.
The data herein are particularly valuable for computing a perceptual gamut, i.e. the total number of just-noticeable differences between two luminances.

Spectral content

Newton (1730) understood that color was not a physical property. He wrote, "The Rays to speak properly are not coloured. In them there is nothing else than a certain Power and Disposition to stir up a Sensation of this or that Colour." Today we know that Newton's Power and Disposition are differences in wavelength. Color-mixing experiments (e.g. Maxwell 1855) formed the backbone of trichromatic theory, which posited three types of physiological receptor with different preferences for wavelength. An organism's ability to detect changes in a light's collection of wavelengths (or *spectrum*) depends on the relative output of these three types of receptor. Hurvich and Jameson (1957) proposed a highly influential "dual-process" theory, which explains how the three receptoral outputs may be combined to produce Hering's (1964) two chromatic dimensions and one achromatic one. Today's students of color vision require two textbooks. Boynton (1979) provides history, personality and succinct explanations for all the major findings. Wyszecki and Stiles (1982) provide all the formulae, data sets, and references in the field. Since the publication of these standard texts, one particular question has received more psychophysical scrutiny than any others concerning how visual systems process light spectra. The question is why differently colored lights don't cause huge changes in the colors of the surfaces that reflect them. See Foster (2011) for a recent review of this color constancy and related phenomena. Finally, to learn what is happening right now in color science, all over the world, consult http://www.aic-colour.org or one of the regional satellites it lists.

Association Internationale de la Couleur[http://www.aic-colour.org].
Despite the title this website is in English. It is not merely an association, it is an association of associations. See their "members" page for a color group near you.

Boynton, Robert. M. 1979. *Human Color Vision*. New York, NY: Holt, Rinehant and Winston.
A concise and readable textbook.

Foster, David H. 2011. Color constancy. *Vision Research* 51:674-700.
Currently, the definitive review.

Hering, Ewald. *Outlines of a theory of the light sense*. Translated by Leo M. Hurvich and Dorothea Jameson. Cambridge, MA: Harvard University Press, 1964. The material was first published in separate sections (1905, 1907, 1911) and was later published as a unit in 1920 and again in 1925. English translation online at http://www.scribd.com/doc/55305772/Hering-Outline-of-a-Theory-of-Light-Sense .
According to Hering, "Redness and greenness, or yellowness and blueness are never simultaneously evident in any other colour." In the foreword, the translators make a convincing argument that this observation of Hering's should be included amongst the most profound in all of vision science.

Hurvich, Leo M. and Jameson Dorothea. 1957. An opponent process theory of colour vision. *Psychological Review* 64:384-404.
They developed the hue-cancellation technique and fused what seemed to be mutually exclusive ideas into a single, largely correct "dual-process" theory of color vision.

Maxwell, James C. and Jameson Dorothea. 1855. Experiments on colour, as perceived by the eye, with remarks on colour blindness. *Transactions of the Royal Society of Edinburgh* 21:275-299.
Purely psychophysical methods developed independently and contemporaneously of Fechner (1966). One of several pieces of evidence supporting human trichromacy.

Newton, Isaac. *Opticks: Or, A Treatise of the Reflections, Refractions, Inflections and Colours of Light*, 4th edition (1730). Free at http://books.google.co.uk/books?id=GnAFAAAAQAAJ&redir_esc=y .
In this treatise, Newton demonstrates the composite nature of white light, and argues that color should not be considered a physical property.

Wyszeki, Günther and Stiles W.S. *Colour Science*, 2nd edition. 1982. New York, NY: Wiley
A handbook that requires two hands. Key psychophysical data appear in Chapters 5 and 7, on visual equivalence and visual thresholds, respectively. The influence of other stimulus factors (e.g. luminance) is discussed therein.

Contrast

Above it was suggested that veridical estimates of stimulus luminance would be of relatively small practical value to an organism. Gilchrist (2013) says, "Light is not information; it is the vehicle on which the information rides." Useful information (and I quote again), "comes in the form of modulations in light energy." Contrast is a quantity that describes the size of those modulations, but there are at least three different mathematical formulations of it. The Michelson formula has become particularly popular because it applies to stimuli in which the minimum luminance and maximum luminance take up roughly similar areas, and this includes the sinusoidal luminance gratings that are used to measure contrast sensitivity functions. The contrast of a sinusoidal luminance grating is proportional to the amplitude of the sinusoid that describes its luminances. This proportionality allows people to use the terms “amplitude” and “contrast” interchangeably. The term “amplitude” makes perfect sense when describing the Michelson contrast of a sinusoidal luminance grating. It makes pretty good sense when describing other contrasts too.

Detecting Contrast

One problem with Bouguer's (1961) method of limits for detecting contrast is that it is subjective. An alternative method that is not subjective is the *m*-alternative, forced-choice (*m*AFC) detection experiment, in which the observer must decide which of *m* observation intervals is accompanied by a faint visual stimulus. Swets et al (1961) investigated why observers sometimes make errors in *m*AFC detection. If it were simply a matter of not seeing anything, then performances should be no better than chance when given a second opportunity following an incorrect first response. In fact, performance on second opportunities is much better than chance. Swets et al ascribed *m*AFC errors to random fluctuations in sensory intensity. The standard deviation of this "noise" is the fundamental unit of Signal-Detection Theory (SDT; Green & Swets, 1966). Swets et al found that their data were consistent with a noise whose variance increased with its mean. Solomon (2007) noted other possibilities equally consistent with the aforementioned data. One of these was Tanner's (1961) notion of intrinsic uncertainty, which posits that detection is governed by the maximum activity in several independent mechanisms, only one of which is actually sensitive to the stimulus. The mathematics of uncertainty were worked out by Pelli (1985). Inconsistent with uncertainty theory, Legge et al (1987) found a decrease in the slope of the *psychometric function* mapping contrast to *m*AFC accuracy when random luminance fluctuations were added to the grating their observers were attempting to detect. Nonetheless, the notion of a visual noise with increasing variance has yet to be accepted by the field at large (see Georgeson & Meese 2006 for a review). Finally, it must be noted that psychophysical techniques are also used to probe how the visual system detects modulation (i.e. contrasts) in stimulus features other than luminance. For example, Krauskopf and Gegenfurtner (1992) report a 4AFC detection experiment for chromatic contrasts.

Georgeson, Mark A. and Tim S. Meese. 2006. Fixed or variable noise in contrast discrimination? The jury's still out... *Vision Research* 46:4294-4303.
A brief review of arguments for and against the increasing variance hypothesis, as it relates to the visual processing of contrast.

Krauskopf, John and Karl Gegenfurtner. 1992. Color discrimination and adaptation. *Vision Research* 32:2165-2175.

The authors modulate chromaticity without modulating luminance, and provide measurements of detectability and discriminability.

Legge, Gordon E., Daniel Kersten, and Arthur E. Burgess. 1987. Contrast discrimination in noise. *Journal of the Optical Society of America A* 4:391-404.
Measured detection and discrimination in the presence of luminance noise. Results favor models of increasing variance over models of intrinsic uncertainty.

Pelli, Denis G. 1985. Uncertainty explains many aspects of visual contrast detection and discrimination. *Journal of the Optical Society of America A* 2:1508-1532.
Thorough analysis of Tanner's theory, and its application to a wide range of data.

Solomon, Joshua A. 2007. Intrinsic uncertainty explains second responses. *Spatial Vision* 20:45-60.
Re-analysis of data from Swets et al. Also a primer on Signal-Detection Theory.

Swets, John, Wilson P. Tanner Jr., and Ted G. Birdsall 1961. Decision processes in perception. *Psychological Review* 68:301–340.
A key paper in the formulation of Signal-Detection Theory for psychophysics.

Tanner, Wilson P., Jr. 1961. Physiological implications of psychophysical data. *Annals of the New York Academy of Sciences* 89:752–765.
All his empirical data were acoustical rather than visual, but Signal-Detection Theory applies to both. Among other notions, this paper introduced the idea of observer uncertainty.

Suprathreshold Contrast

Usually the first question psychophysicists ask about modulation discrimination is whether Weber's Law holds. For the case of luminance modulation (i.e. contrast), it does not. The just-noticeable difference ΔI between two easily detectable contrasts (I and $I + \Delta I$) is best described as a power function of the pedestal: $\Delta I = kI^p, p < 1$ (e.g. Laming, 1986). Departures from Weber's Law can be even more pronounced near the threshold for detection, where just-noticeable difference actually decreases (it "dips") with pedestal contrast (e.g. Foley, 1994). Chen et al (2000) provide similar discrimination functions for chromatic contrast. On the other hand, when ΔI is defined with respect to energy (proportional to the squared contrast), then there is no dip, and Weber's Law holds for easily detectable pedestals (Legge & Viemeiseter, 1988). Solomon (2009) provides a review of contrast-discrimination. Stimuli known as *textures* have been used to investigate how visual systems discriminate between shapes (rather than the size) of luminance modulation (Chubb et al, 2007). The appearance of easily discriminable contrasts has been assessed using magnitude estimation and matching paradigms. Georgeson and Sullivan (1975) offered an explanation for why apparent contrast does not change with its distance from the observer. Cannon (1995) provides the most comprehensive review of work on the nature of contrast appearance.

Cannon, Mark W. "A multiple spatial filter model for suprathreshold contrast perception." In *Vision Models for Target Detection and Recognition: In Memory of Arthur Menedez,* Edited by Eli Peli. Singapore: World Scientific Publishing Company, 1995.

Reviews magnitude estimation data, and why different studies often arrive at different conclusions. Describes an image-based model for contrast appearance.

Chen, Chien-Chung, John M. Foley, and David H. Brainard. 2000. Detection of chromoluminance patterns on chromoluminance pedestals I: threshold measurements. *Vision Research* 40:773-788.
Not only do they measure just-noticeable differences between luminance modulations and between chromatic modulations, they also measure the detectability of luminance modulations when added to chromatic modulations, and vice versa. A model for their results appears in the companion paper.

Chubb, Charles, Jong-Ho Nam, Daniel R. Bindman, & George Sperling. 2007. The three dimensions of human visual sensitivity to first-order contrast statistics. *Vision Research* 47: 2237–2248.
Measurement and model of discriminating between texture "scrambles," each of which is defined by the distribution of its pixels' luminances.

Foley, John M. 1994. Human luminance pattern mechanisms: masking experiments require a new model *Journal of the Optical Society of America A* 11:1710–1719.
In addition to providing carefully measured dipper functions, Foley compares three simple models of contrast-gain control. In each model, the presence of one luminance grating causes an attenuation in sensitivity to the contrast of another luminance grating. Very influential.

Georgeson, Mark A. and G.D. Sullivan. 1975. Contrast constancy: Deblurring in human vision by spatial frequency channels. *Journal of Physiology* 252:627-656.
Gratings of different frequency appear to have the same suprathreshold contrast when their physical contrasts are nearly identical, despite observers' different sensitivities to these gratings, as ascertained from contrast detection. They called this phenomenon "contrast constancy."

Laming, Donald. 1986. *Sensory Analysis*. London: Academic Press.
A thorough and opinionated review of psychophysical discrimination in general. Controversially traces observer variability in a variety of visual tasks to the stochastic properties of light.

Legge, Gordon. E., & Neal F. Viemeister 1988. Sensory analysis in vision and audition: A commentary on Sensory analysis by Donald Laming. Behavioral & Brain Sciences, 11, 301-302.
Legge and Viemeister were merely two of a large group of scientists appearing in this special issue full of appreciation for and criticism of Laming 1986.

Solomon, Joshua A. 2009. The history of dipper functions. *Attention, Perception & Psychophysics* 71:435-443.
A tutorial review. Includes tips for collecting and plotting contrast-discrimination functions.

Position

If an organism is to compare the luminances or spectra of two stimuli (and thus possibly notice a contrast), those stimuli cannot be in the same place at the same time. They need to be separated at least a little bit, and this raises the question of exactly how far is necessary for the organism to detect the separation, and given that the separation can be detected, how well can different separations be discriminated?

Detecting Separation

Like non-biological optical systems, the eye's ability to resolve laterally separated sources of light is limited by aberration and diffraction, and can be characterized by its point-spread function. The point-spread function, in turn, can be inferred from the modulation-transfer function, which describes how well different spatial frequencies can be transmitted through the optical system. There are physical techniques for measuring an eye's modulation-transfer function, but these techniques only quantify the eye, not the organism as a whole. One way to quantify how well different frequencies are processed in complete organisms is to measure the just-detectable contrasts for gratings having those frequencies. Campbell & Green (1965) were amongst the first to do this, using vertical gratings at fixation. Somewhat different results have been obtained with other orientations (Campbell et al 1966) and other retinal eccentricities (Rovamo et al 1978), and it should be noted that the visual system's representation of spatial frequencies at suprathreshold contrast is totally different (Georgeson & Sullivan 1975). Resolution of temporally separated sources of light have been quantified in an analogous manner (see Watson 1986 for a review of *linear systems* analysis in the time domain), though care must be taken to prevent involuntary eye-movements from introducing a spatial component to temporal modulations, because sensitivity to spatio-temporal modulation (i.e. motion) can be up to twice as high as that for purely temporal modulations (Levinson & Sekuler, 1975). This latter result suggests that detection of temporal modulations is mediated by directionally selective mechanisms, such as the elaborated Reichardt detectors posited by van Santen and Sperling (1984). Analytical methods developed for linear systems have also been used to quantify sensitivity to modulations in depth (i.e. distance from the organism), when these modulations are combined with modulations in space (producing inclination or slant, e.g. Tyler 1973) and time (producing stereomotion, e.g. Tyler 1971; both these latter articles have been reviewed by Howard & Rogers, 2012).

Campbell, Fergus W. and David G. Green. 1965. Optical and retinal factors affecting visual resolution. *Journal of Physiology* 181:576-593.
Contains measurements of the human spatial contrast sensitivity function, made both with naturally viewed gratings and interference fringes created directly on the retina.

Campbell, Fergus W., Janus J. Kulikowski, & J. Levinson. 1966. The effect of orientation on the visual resolution of gratings. *Journal of Physiology* 187:427-436.
Repeats the aforementioned measurements with obliquely oriented stimuli. The following paper (starting on page 437) is also noteworthy for investigating interactions between vertical and oblique gratings.

Howard, Ian P. and Brian J. Rogers. 2012. *Perceiving in Depth Vol. 2* Oxford University Press.
So comprehensive and current is this review of all things binocular, it precludes any further summary of these matters herein. Accordingly, the dimension of depth will

simply be ignored in the remainder of this bibliography. Also highly recommended is Volume 1 in this series. It includes a complete history and analysis of the psychophysics of depth perception.

Levinson, Eugene and Robert Sekuler. 1975. The independence of channels in human vision selective for direction of movement. *Journal of Physiology* 250:347-366.
A luminance grating whose contrast reverses in time is the sum of two otherwise identical luminance gratings drifting in opposite directions. Data in this paper suggest that one of the latter must be detected in order for the former to be seen.

Tyler, Christopher W. 1971. Stereoscopic depth movement: Two eyes less sensitive than one. *Science* 174:958-961.
For points and lines, it is their positions on the retina that determine whether their separation can be detected. This is also true for depth. Movement toward (or away) will cause image motions in opposite directions on the observer's two retinae. Tyler found that very subtle motion in these directions was visible only when his observers closed one eye.

Tyler, Christopher W. 1973. Stereoscopic Vision: Cortical limitations and a disparity scaling effect. *Science* 181:276-278.
Amplitude sensitivity for depth as a function of lateral displacement.

van Santen, Jan P. H. and George Sperling. 1984. Temporal covariance model of human motion perception. *Journal of the Optical Society of America A* 1:451-473.
Motion perception was a hot topic amongst psychophysicists in the mid-1980's. This is the first of many papers offering a model for exactly which spatio-temporal separations should be visible, and which should not.

Watson. 1986. "Temporal sensitivity." In *Handbook of Perception and Human Performance,* Edited by Kenneth R. Boff, Lloyd Kaufman, and James P. Thomas. New York, NY: Wiley.
A thorough review of sensitivity to temporal changes in luminance, including mathematical and empirical comparisons between the various types of measurement.

Separations in One Dimension
Weber (1996) found that “it makes no difference” whether two lines were approximately 1 or 2 inches long; the ease with which the larger could be selected depended only on the ratio of their lengths. Subsequent measurements reported by Fechner (1966) support Weber's Law for easily detected lateral separations. Whitaker and Latham 1997 de-confounded lateral separation from retinal eccentricity, and Morgan et al (2012) reported Weber-like just-noticeable differences between irregularities in the separation of spots arrayed along an iso-eccentric circle. Separations in dimensions other than the fronto-parallel image plane, however, do not appear to support Weber's Law. For example, Ogle (1953) reported that the just-noticeable difference for stereoscopic depth increased exponentially with small depth pedestals, and binocular fusion fails altogether when pedestals are large. The Weber fraction for temporal separations falls steadily with pedestal separations up to 2 or 4 seconds (Grondin 2003) and is notably larger when assessed with visual (as opposed to auditory) stimuli. Even when the physical separation between two stimuli is fixed, their apparent separation can depend both on their relative orientation with respect to

various frames of reference, as well as the position of either endpoint in that frame. For example, Fick (1851, cited in Coren & Girgus, 1978) reported that the line connecting two horizontally displaced points appeared shorter than a line of equal length connecting their midpoint to a point above. When two stimuli are separated in time, most observers have a slight tendency to prefer the second, whatever the task. This Time-Order Error complicates but does not preclude assessing how temporal order affects perceived temporal separation (Grondin 2010). Nor can it explain the surprising influence of temporal separation between a ruler-like comparison and a flashed point of light on the latter's apparent distance from fixation (Müsseler et al 1999).

Coren, Stanley and Joan S. Girgus. 1978. *Seeing is Deceiving: The Psychology of Visual Illusions* Hillsdale, N.J.:Erlbaum.
This book focuses on the geometrical illusions such as the Müller-Lyer and the aforementioned Fick, which might have been the first ever reported.

Grondin, Simon. 2003. "Sensory modalities and temporal processing." In *Time and Mind II: Information Processing Perspectives,* Edited by Hede Helfrich. Göttingen, Germany: Hogrefe.
This chapter boasts a large collection of Weber fractions for temporal separation in vision, audition and between stimuli in those two modalities.

Grondin, Simon. 2010. Timing and time perception: A review of recent behavioral and neuroscience findings and theoretical directions. *Attention, Perception, & Psychophysics* 72:561-582.
As this article is both a review and a tutorial, it is essential reading for anyone preparing to measure either the sensitivity to or the appearance of temporal separations.

Morgan, Michael J., Isabelle Mareschal, and Joshua A. Solomon 2012. Perceived pattern regularity computed as a summary statistic: implications for camouflage. *Proceedings of the Royal Society B: Biological Sciences* 279:2754-2760
They measured detection and discrimination between amounts of irregularity in the separation of stimuli in one and two dimensions of the fronto-parallel image plane, and explained why Weber's Law for these separations is to be expected from an ideal discriminator.

Müsseler, Jochen, A. H. C. van der Heijden, S. H. Mahmud, Heiner Deubel, and Samar Ertsey 1999. Relative mislocalization of briefly presented stimuli in the retinal periphery. *Perception & Psychophysics* 61:1646-1661
Seven experiments lead to the surprising conclusion that apparent spatial relationships depend on how observers prepare for their next eye movement.

Ogle, Kenneth N. 1953. Precision and validity of stereoscopic depth perception from double images. *Journal of the Optical Society of America* 43:906-913
An early, systematic investigation of the relationship between stereoscopic depth and the just-noticeable difference in stereoscopic depth.

Weber, E. H. (1851). Der Tastsinn und das Gemeingefuhl (p. 559); quoted in Ross, H. E., & Murray, D. J. (1996). E. H. Weber on the tactile senses (p. 211). Hove, UK: Erlbaum, Taylor & Francis.
Although his primary evidence came from weight discrimination, it was the seemingly more general applicability of Weber's conclusions that earned them the epithet "Law" and spurred Fechner (1966) to codify the fundamentals of psychophysical investigation.

Whitaker, David & Keziah Latham. 1997. Disentangling the role of spatial scale, separation, and eccentricity in Weber's Law for position. *Vision Research* 37:515-524.
The authors confirmed Weber's Law for separations along an iso-eccentric circle and concluded that this relationship should not be ascribed to the channels discussed immediately below, because their measurements were independent of the contrast and frequency content of the separated stimuli.

Separations in two fronto-parallel dimensions: orientation processing.

Our current understanding of orientation discrimination rests on the discovery (Hubel & Wiesel, 1959) of neurons with different preferences for orientation. Like the receptors subserving wavelength discrimination (e.g. Maxwell, 1855), the neurons subserving orientation discrimination are broadly tuned. Each responds well to a wide variety of orientations. Unlike photoreceptors, which have maximal preference for one of usually only three wavelengths, cortical neurons can have maximal preference for any orientation. Graham (1989) details three psychophysical techniques (summation, masking, and adaptation; see **Context**) for inferring the tuning properties of individual orientation analyzers (a.k.a. channels), and these correspond well to estimates from single-cell physiology (DeValois & DeValois, 1988). Nonetheless, there are more than a few computations the visual system could perform for converting the activity in a population of differently tuned neurons into a psychophysical response. These are listed in Chapter 3 of Dayan & Abbot (2001). Howard (1982) provides an extensive review of the psychophysical limits of orientation discrimination and how these depend on orientation and retinal position. Westheimer (2010) offers a more succinct and up-to-date review, explicitly linking the "hyperacuity" for 2-D fronto-parallel separations with the (ordinary) acuity for 1-D separations.

Dayan, Peter and L.F. Abbott (2001) *Theoretical Neuroscience: Computational and Mathematical Modeling of Neural Systems*. Cambridge, MA: The MIT Press
Introductory textbook for the study of computational neuroscience, one major goal of which is to understand how activity in individual neurons and groups thereof can be used to predict measurable behavior.

DeValois, Russell L. and Karen K. DeValois (1988) *Spatial Vision*. Oxford University Press
Not psychophysics, but even a rudimentary understanding of orientation processing requires an appreciation for how individual neurons selectively respond to different orientations. This text provides an extensive review.

Graham, Norma V. S. (1989) *Visual Pattern Analyzers*. Oxford University Press

Impressively organized review of psychophysical experiments designed to measure channel bandwidth. Not just their results, but also the (often implicit) assumptions required to deduce meaningful estimates from them.

Howard, Ian P. (1982) *Human Visual Orientation*. New York, NY:Wiley
Extensive review of mostly psychophysical investigations, with a focus on which computations could and could not underlie the perception of orientation in the fronto-parallel image plane.

Hubel, David H. & Torsten N. Wiesel. 1959. Receptive fields of single neurones in the cat's striate cortex. *Journal of Physiology* 148:574-591.
Not psychophysics, but these physiological experiments had such a profound effect on all studies of vision, its authors remain the only vision scientists to have been awarded the Nobel Prize.

Westheimer, Gerald. "Visual acuity and hyperacuity." In *Handbook of Optics, Vol. III,* 3rd edition (2010). New York, NY: McGraw-Hill.
A succinct introduction how human observers distinguish between positions and the relationships between positions in an image.

Separations in space and time: motion processing.
Although the just-detectable spatio-temporal separation of two point (or line) stimuli is thought to convey a sense of motion, the visual mechanism responsible for that sensation need not estimate the position of either stimulus. Therefore, just like the detection of orientation in the fronto-parallel plane, the detection of orientation in space-time qualifies as a hyperacuity (Westheimer 1979). The 1980's enjoyed a massive increase in the popularity of experiments on motion perception amongst psychophysicists. This can be attributed to three highly influential descriptions of the computations subserving motion perception (Adelson & Bergen, 1985; van Santen & Sperling, 1984, 1985; and Watson & Ahumada, 1985). Although there are no textbooks on visual perception that are exclusively devoted to psychophysical studies, virtually all contemporary ones contain a chapter devoted to these motion models, but perhaps the most succinct description of them can be found in the first few pages of Burr and Thompson's (2011) up-to-date history. Contemporaneous with their review is Nishida's (2011), which provides detail on how various stimulus factors (including spatial position and orientation) affect aspects of motion perception including speed discrimination and acceleration detection.

Adelson, Edward H. and James R. Bergen 1985. Spatiotemporal energy models for the perception of motion. *Journal of the Optical Society of America A* 2:284-299.
Their model shows how phase-invariant, opponent *motion energy* can be computed from the output of eight physiologically plausible neuron-type filters, whose receptive fields are oriented in space and time.

Burr, David and Peter Thompson 2011. Motion psychophysics: 1985–2010. *Vision Research* 51:1431–1456.
Given the extreme comprehensiveness of both this review and that of Nishida (2011), it is surprising how little overlap there is. In other words, both are highly recommended and neither supersedes the other. This one uses the influential 1980's models as a springboard, and consequently has a more intense focus on modeling.

Nishida, Shin'ya 2011. Advancement of motion psychophysics: Review 2001–2010. *Journal of Vision* 11(5):11, 1–53.
This one (cf. Burr & Thompson, 2011) has a more intense focus on empirical results, and boasts a whopping 15 pages of references.

van Santen, Jan P. H. and George Sperling. 1985. Elaborated Reichardt detectors. *Journal of the Optical Society of America A* 2:300-320.
Whereas van Santen & Sperling's (1984) previous publication introduced their motion model, this one compares it with Adelson & Bergen's (1985) and Watson & Ahumada's (1985) and identifies the conditions under which all three can be considered formally equivalent.

Watson, Andrew B. and Albert J. Ahumada, Jr. 1985. Model of human visual-motion sensing. *Journal of the Optical Society of America A* 2:322-342.
Systematic consideration of prior empirical results led these authors to construct a motion-detection model only subtly different from those proposed by Adelson & Bergen (1985) and van Santen & Sperling (1984).

Westheimer, Gerald. 1979. The spatial sense of the eye. *Investigative Ophthalmology and Visual Science* 18:893-912.
From motion psychophysics' pre-history, this review article on psychophysical measurements of position squarely puts 2-D (spatio-temporal) motion processing on the same footing as 2-D (spatial-spatial) orientation processing. Both should be considered hyperacuities, whereas the more general "spatial acuity" can be used to describe 1-D separations. This section of this Bibliography has been organized accordingly.

Feature criteria and current debates
Luminance, spectral content, position, and modulations thereof unquestionably qualify as input upon which visual computations are based, but the list is not exhaustive. For example, we can be reasonably confident that spatial scale (or, equivalently, spatial-frequency content) is another (e.g. DeValois & DeValois, 1988; Graham, 1989), but there are some notable controversies. For example, some authors (e.g. Burr & Ross, 2008, cf. Tibber et al. 2012) contend that numerosity should be considered a primary visual property, similar to (but distinct from) spatial scale and texture density. The primacy of image blur also has proponents (e.g. Georgeson et al, 2007; Watt & Morgan, 1983) and detractors (e.g. Watson & Ahumada, 2011). There is, perhaps, an even greater lack of consensus regarding the criteria necessary and sufficient for an image attribute to be considered as a primary visual feature. Adelson and Bergen (1991) suggested a number of possible hierarchies based on the physical content of visual input. Wolfe and Horowitz's (2004) has a more empirical basis. The most recent consideration of these factors, accompanied by yet another proposed set of criteria is contained in Morgan's (2011) review of visual features.

Adelson, Edward H. and James R. Bergen. "The plenoptic function and the elements of early vision." In *Computational Models of Visual Processing,* Edited by Michael S. Landy and J. Anthony Movshon. Cambridge, MA: MIT Press, 1991.

The nature of input filtering, unquestionably performed early in the visual pathway, is discussed and organized into "periodic tables" of visual features.

Burr, David and John Ross. 2008. A visual sense of number. *Current Biology* 18:425-428.
Opening remark in the numerosity debate. An after-effect of numerosity adaptation is measured.

Georgeson, Mark A., Keith A. May, Tom C. A. Freeman, and Gillian S. Hesse. 2007. From filters to features: Scale–space analysis of edge and blur coding in human vision. *Journal of Vision* 7(13):7 1-21.
In this model, blur is a more fundamental feature than contrast. The latter is inferred from the frequency preference and activity in the most active channel.

Morgan, Michael. 2011. Features and the 'primal sketch.' *Vision Research* 51:738-753.
The one criterion for inclusion in this review of evidence for and theory regarding primary visual features is their localizability within the stimulus, as filtered by neurones early in the visual pathway.

Tibber, Marc S., John A. Greenwood, & Steven C. Dakin. 2012. Number and density rely on a common metric: Similar psychophysical effects of size, contrast, and divided attention. *Journal of Vision* 12(6):8 1-19.
Recent evidence suggesting that the purportedly distinct visual primitives of numerosity and density are in fact identical.

Watson, Andrew B. and Albert J. Ahumada, Jr. 2011. Blur clarified: A review and synthesis of blur discrimination. *Journal of Vision* 11(5):10 1-23.
The authors contend that all previous measurements of blur discrimination, including those used to support the notion of image blur as a primary visual feature, could have been predicted on the basis of what is known regarding the discriminability of image contrast.

Watt, Roger J. and Michael J. Morgan 1983. The recognition and representation of edge blur: evidence for spatial primitives in human vision. *Vision Research* 23:1465-1478.
Data from three experiments lead the authors to suggest that some positional information is irretrievably lost when different images are compared on the basis of apparent blur, and this loss can be taken as concrete evidence for the explicit computation of blur, early in the visual pathway.

Wolfe, Jeremy M. and Todd S. Horowitz 2004. What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience* 5:495-501.
Empirical evidence consistent with the attentional guidance Wolfe and Horowitz would like to use as criteria for feature primacy includes a) little effect of distractors on speed and accuracy when searching for a target identified by its feature content and b) more effect of distractors on searches for targets identified by their lack of that feature.

Context

Graham (1989) reviewed the three methods psychophysicists use to reveal the spatial frequency and orientation selectivity of channels in the visual system. All three methods require a stimulus that the organism can detect, and all three involve adding some stuff to a basic contrast-detection experiment. For example, consider a baseline detection threshold, as determined using 2AFC (see Detecting Contrast). In the summation paradigm, some stuff is added to the detection target, making it easier to see. Consequently, detection threshold drops. The more selective the channel is for the extra stuff, the more detection threshold should drop. In the masking paradigm, extra stuff is added to both observation intervals, not just the target's. This manipulation usually makes the target harder to detect, and consequently threshold rises (see Suprathreshold Contrast). Method #3 is called adaptation. It is a lot like masking except the extra stuff is added before the observation intervals. This manipulation also elevates detection thresholds, but, perhaps more famously, it can distort the appearance of suprathreshold targets. These distortions and those caused by spatial (rather than temporal) context are the focus of the next subsection.

Repulsion

It is well known that the visual system exaggerates the differences between spatially and temporally adjacent textures. For example, the simultaneous contrast illusion exaggerates the difference between textures having different luminances (Mach, 1914) and the tilt after-effect (and tilt illusion) exaggerate the differences between temporally separated (and spatially separated) textures having different orientations (Gibson & Radner, 1937). Given the ubiquity of contextually induced repulsion, most investigators focus either on a specific type of context (e.g. Webster 2011, who reviews temporal context) or a specific dimension of repulsion (e.g. Schwartz et al 2007, who focus on orientation). One notable exception takes the form of a book by Purves & Lotto (2003), in which the authors argue that most illusions of context (not just those consistent with the similar surfaces reflecting different sources of illumination discussed by Gilchrist 2013 and MacLeod 2013) can be understood in terms of biological relevance. The exaggeration of feature differences is so widespread in sensory systems that you might expect there to be a general trait for the susceptibility to repulsion. Boston & Mollon (2010) measured repulsion along 10 visual dimensions (e.g. luminance, chromaticity, tilt, etc.) in a pool of 100 normally sighted observers and found large individual differences in various types of repulsion, but with one exception there were no significant between-observer correlations. The exciting implication of Bosten & Mollon's result is that correlations between repulsion susceptibility and other psychiatric (e.g. Dakin et al 2005) and physiological (e.g. Schwartzkopf et al 2011) factors are likely due to mechanisms more specific than previously thought.

Bosten, Jennifer M. and John D. Mollon 2010. Is there a general trait of susceptibility to simultaneous contrast? *Vision Research* 50:1656–1664.

Too often failures of correlation crop up in "control" experiments, designed to show that a study's "main result" is not artifactual. That is why Bosten & Mollon's results should please skeptics. Despite extensive measurements, an elegant experimental design, and the clear desire to find between-observer correlations, they just aren't there.

Dakin, Steven, Patricia Carlin, and David Helmsley 2005. Weak suppression of visual context in chronic schizophrenia. *Current Biology* 15:R822-R824.
Short and to the point. Contains results from 11 forensic inpatients for whom the contextually induced repulsion of perceived contrast intensity was weak or absent. All 11 of these observers suffered from schizophrenia. Even uninterested readers will recognize that this may prove to be a medical breakthrough.

Gibson, James J. and Minnie Radner 1937. Adaptation, after-effect and contrast in the perception of tilted lines. I. Quantitative studies. *Journal of Experimental Psychology* 20:453-467.
First in a series of two papers describing the bias (which here is given the physical term *contrast*) in an observer's perception of an oriented stimulus when neighboring or superimposed stimuli have a different orientation in the fronto-parallel plane.

Mach, Ernst. *The analysis of sensations and the relation of the physical to the psychical*. Translated by C. M. Williams. Chicago, Il: Open Court Publishing Company, 1914. English translation of *Die Analyse der Empfindungen und das Verhaltniss des physischen zum psychischen*, first published in 1897. http://archive.org/details/analysisofsensat00mach
Herein (p. 216 and 217) Mach repeats his earlier theory that the brightness of any stimulus depends upon the ratio between its luminance and that of surrounding stimuli.

Purves, Dale, R. Beau Lotto (2003) *Why we see what we do: An empirical theory of vision*. Sunderland, MA:Sinauer Associates
Explanations for some contextual effects based on image statistics and biological relevance, and color plates containing the most striking examples of these illusions.

Schwartz, Odelia, Anne Hsu and Peter Dayan 2007. Space and time in visual context. *Nature Reviews Neuroscience* 8:522-535.
Comprehensive review (empirical results and theory) of the tilt illusion and tilt after-effect.

Schwarzkopf, D. Samuel, Chen Song and Geraint Rees 2011. The surface area of human V1 predicts the subjective experience of object size. *Nature Neuroscience* 14:28-30.
The authors report estimates of visual cortex (from magnetic resonance images) that correlate with contextually induced distortions in the perceived size of circles.

Webster, Michael A. 2011. Adaptation and visual coding. *Journal of Vision* 11(5):3 1-23.
Massive and readable overview of after-effects in all visual dimensions and the explanations thereof.

Assimilation

In the absence of sufficiently high temporal and/or spatial frequencies on the retina, even relatively high contrasts can go undetected. Troxler fading is but one example of this, in which the appearance of a small, peripheral part of the visual field matches that of the surrounding, larger part (see Spillman 2011, for a brief overview). Ramachandran and Gregory (1991) demonstrated that this filling-in is not limited to the dimensions of luminance and chromaticity, but encompassed textural properties such as spatio-temporal frequency content as well. Parkes et al (2001) reported that the orientation of a peripherally viewed patch of grating came to resemble the average of similarly oriented gratings in the region, even when the boundaries between them remained distinct. They suggested this assimilation to the regional average was a form of compulsory texture perception, and might form the basis of the crowding phenomenon, which can prohibit the identification of small alphanumeric characters in the visual periphery (see Pelli & Tillman 2008 and Levi 2008 for recent reviews). The inherently statistical basis of texture perception can be traced back to Attneave (1954) who was profoundly influenced by Information Theory (cf. Laming 2010 for an entertaining critique on the place of Information Theory in psychophysics). Attneave assumed that sensory systems must have limited capacity, and therefore summary statistics (e.g. average brightness and the dispersion of brightnesses) must underlie texture perception. Recently this idea has been resuscitated, and researchers such as Freeman and Simoncelli (2011) are working to understand exactly which summary statistics form the basis of texture perception, and how they are computed.

Attneave, Fred. 1954. Some informational aspects of visual perception. *Psychological Review* 61 183-193.
Arguably the first publication linking texture perception to summary statistics.

Freeman, Jeremy and Eero P. Simoncelli. 2011. Metamers of the ventral stream. *Nature Neuroscience* 61 183-193.
A follow-up study, this paper synthesizes "metamers," that look identical to original images, from otherwise random texture constrained to have the same values over a set of statistics the earlier study established could form the basis of discrimination. The size of statistically homogenous image regions their observers would tolerate increased with retinal eccentricity at a rate similar to the receptive fields in visual area V2.

Laming, Donald. 2010. Statistical information and uncertainty: A critique of applications in experimental psychology. *Entropy* 12, 720-771.
Lucid review of Information Theory in experimental psychology. According to Bayesian interpretations thereof, psychophysical responses are based on the best estimate of stimulus parameters, incorporating the “prior” probabilities of various types of stimulation. Laming argues that response frequencies match presentation probabilities, rather than minimizing estimation error or anything like that.

Levi, Dennis. 2008. Crowding—An essential bottleneck for object recognition: A mini-review. *Vision Research* 48, 635–654.
Summary statistics are merely one theory discussed in this review. Evidence supporting it and various alternatives has appeared since its publication, but no new theories have.

Parkes, Laura, Jennifer Lund, Alessandra Angelucci, Joshua A. Solomon and Michel Morgan. 2001. Compulsory averaging of crowded orientation signals in human vision. *Nature Neuroscience* 4, 739–744.
Psychophysical experiments confirming orientation assimilation between neighboring Gabor patterns in the visual periphery. They describe crowding as "texture perception, when we do not wish it to occur."

Pelli, Denis and Katherine A. Tillman. 2008. The uncrowded window of object recognition. *Nature Neuroscience* 11, 1129–1135.
Whereas Levi's (2008) review is comprehensive, these authors make a concerted effort to understand many disparate results within a single conceptual framework. Contains compelling demonstrations.

Ramachandran, Vilayanur S. and Richard L. Gregory. 1991. Perceptual filling in of artificially induced scotomas in human vision. *Nature* 350, 699–702.
The authors demonstrate that fixation causes disappearance of the border between texture having a broad spatio-temporal spectrum and a peripherally viewed patch of uniform gray. Retinal input even seemed to be homogenous when the texture's spectrum was narrowed to include only horizontal orientations. Also noteworthy was the lingering impression of dynamic texture in the unchanging region when the physical texture was replaced by uniform gray.

Spillman, Lothar. 2011. Fading, Perceptual Filling-in, and Motion-Induced Blindness: Phenomenology, Psychophysics, and Neurophysiology. *Chinese Journal of Psychology* 53, 393-397.
Introduction to a special issue on spatial and temporal filling-in. Cites key historical papers.

Related areas of investigation

In many psychophysical experiments, observers are required to compare one visual stimulus with their memory of another. Indeed, previously seen stimuli can affect psychophysical performance even when observers are not required to remember them. Thus, a full understanding of sensory comparisons requires some understanding of memory for visual stimuli. Visual memory is a research topic in its own right, and psychophysical techniques are often employed to quantify its capacity (see Brady et al 2011, for a review). Similarly, as noted in the introduction, all psychophysical experiments require observers to be told or taught how to respond to visual stimuli. In many cases, performance continues to improve long after observers understand the instructions. Research into perceptual learning is thus a natural outgrowth of basic psychophysics, and it is increasing in popularity (see Lu et al 2011, and Sagi 2011 for reviews). Finally, acting to modulate all sensory experiences, there is attention. Observers frequently attend where they are looking (i.e. at fixation), but not always, and there are some tasks that they simply cannot perform if they were attending to the wrong location at the wrong time. Moreover, many researchers have reported that suprathreshold appearances can change with the focus of attention. Carrasco (2011) reviews recent activity in this vibrant area of research.

Brady, Timothy F., Talia Konkle, and George A. Alvarez 2011. A review of visual memory capacity: Beyond individual items and toward structured representations. *Journal of Vision* 11(5):4, 1–34.
Comprehensive overview of recent research on visual memory.

Carrasco, Marisa 2011. Visual attention: The past 25 years. *Vision Research* 51 1484–1525.

Comprehensive overview of recent research on visual attention, with a particular focus on how attention affects appearance.

Lu, Zhong-Lin, Tianmiao Hua, Chang-Bing Huang, Yifeng Zhou, and Barbara A. Dosher 2011. Visual perceptual learning. *Neurobiology of Learning and Memory* 95 145–151.
A brief review, focusing on how practice affects basic psychophysical discriminations (e.g. between orientations and contrasts).

Sagi, Dov 2011. Visual perceptual learning. *Vision Research* 51 1552-1566.
Both a comprehensive overview of empirical findings and a theoretical framework for understanding them.