Perceiving the Intensity of Light

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The relationship between luminance (i.e., the photometric intensity of light) and its perception (i.e., sensations of lightness or brightness) has long been a puzzle. In addition to the mystery of why these perceptual qualities do not scale with luminance in any simple way, “illusions” such as simultaneous brightness contrast, Mach bands, Craik-O’Brien-Cornsweet edge effects, and the Chubb-Sperling-Solomon illusion have all generated much interest but no generally accepted explanation. The authors review evidence that the full range of this perceptual phenomenology can be rationalized in terms of an empirical theory of vision. The implication of these observations is that perceptions of lightness and brightness are generated according to the probability distributions of the possible sources of luminance values in stimuli that are inevitably ambiguous.

A fundamental problem in vision (and perception generally) was recognized at the beginning of the 18th century by George Berkeley (1709/1975), who pointed out that the sources underlying visual stimuli are unknowable in any direct sense. The light that falls on the eye from any region of a scene confounds the contributions of reflectance, illumination, and transmittance (as well as a host of subsidiary factors that affect these parameters). As a result, the physical provenance of light reaching the eye—and therefore the significance of the stimulus for visually guided behavior—is profoundly uncertain. This fundamental fact presents a biological quandary. Successful behavior in a complex and potentially hostile environment clearly depends on responding appropriately to the physical sources of visual stimuli rather than to the stimuli as such. If, however, the retinal images generated by light cannot uniquely define the underlying reality the observer must deal with, how then does the visual system produce behavior that is generally successful?

The purpose of this review is thus to consider evidence, much of it derived from our own experiments over the last few years, about the way the uncertain relationship between the physical world and the perceptual world is resolved by the nervous system (see Purves & Lotto, 2003). The gist of this body of work is that what one sees at any moment appears to be fully determined by the probability distributions of the possible sources of the stimulus rather than the physical qualities of the stimulus (which are ambiguous) or the properties of the objects and conditions that generated the stimulus (which cannot be known directly). Although this framework has several important precedents (see below), it differs from most mainstream neurobiological thinking in recent decades and suggests other ways of conceptualizing the purposes served by the known physiology of visual system circuitry. The context here for exploring the merits of this conception of vision is sensations of lightness and brightness, which are arguably the most fundamental qualities of human visual experience.

Luminance, Brightness, and Lightness

Luminance is an objective measurement of the overall intensity of a stimulus expressed in candelas/m² (photometers used for this purpose measure radiant energy with a filter that mimics the sensitivity of the average human observer, thus specifically measuring light). The resulting sensations are called lightness and brightness. Like all sensations, lightness and brightness are not subject to direct measurement and can only be evaluated by asking an observer to report the appearance of one stimulus relative to that of another. Although in ordinary usage the term brightness often refers inclusively to sensations of light intensity, in visual psychophysics brightness indicates the extent to which the apparent intensity of light coming from a given portion of a scene is attributable to the region in question being a primary source of light. Lightness, conversely, refers to the apparent intensity as a consequence of surface reflectance: that is, the extent to which an object appears as it does because it reflects more (or less) light to the eye than other surfaces in the scene.

Enigma of Simultaneous Brightness Contrast

A common sense presumption is that an objective measure of light intensity (i.e., luminance) and the ensuing sensations of lightness or brightness should be directly proportional because increasing the luminance of a target stimulus increases the number of photons captured by photoreceptors and thus the output activity of the retina at any given level of background light (Sakmann & Creutzfeldt, 1969). A corollary is that two objects in a scene that return the same measured amount of light to the eye should appear equally light or bright. It has long been known, however, that perceptions of brightness or lightness often fail to meet these expectations. For example, two patches of the same photometric intensity look different when they are presented on different backgrounds. Thus, the patch on the background of relatively low luminance in Figure 1A appears lighter (or brighter) than the same patch on a background of higher luminance, a phenomenon called simultaneous brightness contrast (or in some accounts, brightness induction). The standard illusion shown
here is actually a relatively weak example of this general phenomenon compared with some of those we show below or with other more complex stimuli in the literature, for reasons that will become apparent as the argument here develops.

The explanation of this effect most often offered is based on the properties of neurons at the input level of the visual system (e.g., neurons in the retina) and the lateral interactions among them, which are clearly an important aspect of retinal function. The foundation of such models is evidence that, presumably as a means of enhancing the detection of contrasting luminance boundaries (edges), the central region of the receptive fields of lower order visual neurons has a surround of opposite polarity (Hartline, 1940; Hartline & Graham, 1932; Kuffler, 1953, 1973; Wiesel & Hubel, 1966). The firing rate of neurons whose receptive fields intersect a contrast boundary will therefore differ from the activity of neurons whose receptive fields fall entirely on one side of the boundary or the other (see Figure 1B). Thus, neurons whose receptive field centers are excited by light and that lie just within the diamond on the dark background in Figure 1A will fire at a higher rate than the neurons whose receptive field centers lie just within the diamond on the light background (because the former are less inhibited by their oppositely disposed receptive field surrounds than the latter; see Figure 1B). As a result, so the argument goes, the patch on the dark background looks lighter or brighter than the patch on the lighter background.

Reasons for Doubting This Conventional Explanation

As many workers in this field have recognized, there are reasons for being suspicious of the idea that the different appearance of the equiluminant targets in Figure 1A is simply an incidental consequence of the organization of retinal circuitry illustrated in Figure 1B. Consider, for instance, the classical Wertheimer–Benary stimulus, in which two equally luminant targets identically embedded in a darker cross differ in brightness despite the absence of any differences in local luminance contrast (Benary, 1924; Wertheimer, 1912/1950). Even more remarkable is the stimulus illustrated in Figure 2, in which the target patches on the left are surrounded by a greater area of higher luminance territory than lower and yet appear lighter and/or brighter than the targets on the right, which are surrounded by less lower luminance territory than higher (the converse argument applies to the

Figure 1. Standard demonstration of simultaneous brightness contrast and the conventional explanation of this effect. A: A target (the diamond) on a less luminant background (left) is perceived as being brighter or lighter than the same target on a more luminant background (right), even though the two targets are physically identical and appear so if both are presented on the same background (inset). B: Diagram of the usual explanation of this phenomenon, based on the center-surround receptive field properties of retinal ganglion cells. The top diagram shows a series of ganglion cell receptive fields (A–E) arrayed across a contrast boundary; the bottom diagram shows the associated neural activity as a result of this placement (see the text for details). From Neuroscience (p. 246), by D. Purves et al., 2001, Sunderland, MA: Sinauer. Copyright 2001 by Sinauer. Adapted with permission.

Figure 2. Evidence that distorted neuronal responses to local contrast (see Figure 1B) cannot explain simultaneous brightness contrast. White’s (1979) stimulus, illustrated here, is a particularly interesting example because it generates a perception of a series of identical test patches (see inset) that is similar to the sensations of lightness and/or brightness elicited in Figure 1A, even though the local contrast of the patches is essentially opposite that of the standard brightness contrast stimulus. That is, the targets that appear lighter and/or brighter (the gray patches on the left) are surrounded mainly by areas of higher luminance, whereas the targets that appear darker (the patches on the right) are surrounded mainly by areas of lower luminance.
patches on the right; White, 1979). Although the disposition of the
surrounds in White’s (1979) stimulus is effectively opposite that in
Figure 1A, the apparent lightness and/or brightness difference be-
tween the left and right targets is about the same as that elicited by
the standard simultaneous brightness contrast stimulus.

Indeed, many stimuli have been constructed over the years that are
difficult to explain in terms of the conventional ideas about brightness
contrast effects illustrated in Figure 1B (e.g., Adelson, 1993; Corn-
sweet, 1970; Gilchrist, 1977, 1994; Knill & Kersten, 1991; Land,
1986; Lotto & Purves, 1999, 2001; O’Brien, 1959; Purves & Lotto,
2003; Purves, Shimpi, & Lotto, 1999; Todorovic, 1997; Williams,
McCoy, & Purves, 1998a, 1998b). Although the creators of some of
these stimuli have persisted in the idea that the related perceptual
effects are epiphenomena of the input or midlevel stages of visual
processing (e.g., Blakeslee & McCourt, 1997, 1999, 2001; Cornsweet,
1970; Todorovic, 1997), others have argued that this sort of rational-
ization is inadequate (e.g., Adelson, 1993, 2000; Gilchrist, 1977;
Lotto & Purves, 1999, 2001; Purves & Lotto, 2003; Purves et al.,
1999; Williams et al., 1998a, 1998b).

Evidence That Lightness and Brightness Correspond to
the Empirical Significance of Stimulus Luminances

If the receptive field properties of input level neurons fail to
account for the subjective experiences of lightness and brightness
elicited by stimuli such as those in Figures 1 and 2, how are these
phenomena to be understood? The key to rationalizing the perceived
intensity of light is the inherent ambiguity of these—and indeed all—visual stimuli. As already noted, the perceptual significance of
the intensity of the light returned to the eye from any part of the scene
is uncertain. This conclusion follows from the fact that luminance is
determined by at least three fundamental aspects of the physical
world: the illumination of objects, the reflectance of object surfaces,
and the transmittance of the space between objects and observer (a
long list of other factors are influential but are for the most part
subsidiary to these three; see Figure 3). Changing any of these
real-world variables will necessarily change the relative intensity of
the light reaching the eye. As a result of this conflation (an infinite
number of different combinations of illumination, reflectance, and
transmittance can give rise to the same luminance), there is no definite
relationship between a given stimulus element and its sources. Ac-
cordingly, there is no way for the visual system to directly determine
how these factors have been combined to generate the pattern of
luminance values in a retinal image. Because appropriate behavior
requires responses that accord with the provenance of the stimulus
rather than the parameters of the stimulus per se, percepts determined
by luminance values as such would be a poor guide to behavior.

Given the inherent ambiguity of any luminance value in a scene, a
more effective visual strategy would be to generate percepts accord-
ing to the behavioral success or failure experienced when observers
respond to stimuli generated by different combinations of illumina-

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Figure 3. Conflation of illumination, reflectance, and transmittance, the primary factors that determine the
luminance of any portion of a visual stimulus. See the text for further explanation.
tion, reflectance, and transmittance. If vision indeed operates in this way, then perceptions of relative lightness or brightness should vary predictably according to the degree to which a given luminance value in a visual stimulus is more (or less) consistent with the possible combinations of illumination, reflectance, and transmittance that have given rise to the same or a similar stimulus in the past.

Some Simple Tests of This Prediction

In accord with this conceptual framework, the relative lightness and/or brightness of two identical targets is indeed changed when the probable sources of the stimulus are altered by experimental manipulation of the stimulus, even if the luminance contrast between the targets and their immediate surrounds remains unchanged. Thus, when the dark and light surrounds in the standard brightness contrast stimulus in Figure 1A are depicted in a manner consistent with the target diamonds being under different illuminants (as in Figure 4A), the apparent difference in the brightness of the targets is greater than in a depiction of the targets and their surrounds under the same illuminant (as in Figure 4B; Williams et al., 1998a, 1998b). The immediate reason for the different appearance of the physically identical targets in these presentations is that empirically an object under weak illumination that reflects the same amount of light to the eye as another object under more intense illumination would typically have signified a more reflective object. The corresponding biological rationale that explains why it is advantageous to see the targets in this way is taken up in the next section.

If this interpretation is correct, then any change relevant to the probable contributions of illumination, reflectance, and transmittance—no matter how subtle—should influence the apparent brightness and/or lightness of the elements in the scene. An aspect of illumination that can be readily manipulated to test this point is penumbras, the hazy borders that are to a greater or lesser degree found at the edges of all shadows cast by the obstruction of light from the sun and most other sources. Because light sources are generally extended, the rays reaching the shadow-casting object do not arise from a single point in space. As a result, the edges of shadows are blurred to a degree that depends on the extent of the source, the distance of the shadow-casting object from the shadowed surface, the clarity of the atmosphere, and a variety of other factors (Lynch & Livingston, 1995; Minnaert, 1937/1992). Thus, penumbras not only indicate that a particular luminance profile is a shadow (rather than, say, the result of a gradient of surface reflectance) but also convey a range of additional empirical information about the illumination of a scene (see, for example, Rock, 1995, p. 47). Because cast shadows will, in the past, almost always have been adorned by penumbras (only point sources of light fail to generate them), a luminance gradient associated with a contrast boundary should also change the relative probabilities of the possible sources of the stimulus and thus the perceived lightness and/or brightness of an associated target. This is indeed what happens: The presence of a depicted penumbra, which enhances the likelihood of a shadow, further increases the apparent lightness and/or brightness difference of the equiluminant test targets (see Figure 6 in Williams et al., 1998a). Indeed, differences in lightness and/or brightness can be elicited by identical targets when all differences in local contrast are eliminated, as long as the empirical information in the image indicates the likelihood of differently reflective sources (see Figure 3 in Williams et al., 1998b).

The point has already been made that the different appearance of identical targets in a variety of stimuli in which local contrast is

Figure 4. Effect of changing the probable illumination of test targets while maintaining the luminance values of both the targets and their immediate surrounds. A: Test targets and surrounds from Figure 1A presented such that the left diamond lies in an apparent shadow cast by an object between the light source and the surface. B: Test targets and surrounds presented as intrinsic components of a uniformly illuminated surface. C: Difference in the perceived brightness of the two identical test targets reported by observers in psychophysical testing of the response to these stimuli. The upper bar in the graph shows the average brightness adjustments made to equate the brightness of the diamond on the dark surround with that of the diamond on the light surround in the scene shown in A (as indicated on the left). The lower bar shows the adjustment made to equalize the appearance of the two diamonds on the unshadowed card (B). From “The Influence of Depicted Illumination on Perceived Brightness,” by S. M. Williams, A. N. McCoy, and D. Purves, 1998, Proceedings of the National Academy of Sciences, USA, 95, p. 13297. Copyright 1998 by the National Academy of Sciences. Adapted with permission.
much the same makes it difficult or impossible to rationalize simultaneous brightness contrast effects in terms of the opposing center-surround organization of the receptive fields of retinal, thalamic, or primary visual cortical neurons (see above). These further demonstrations, as others in the literature (see, e.g., Adelson, 1993; Benary, 1924; Gilchrist, 1977; Schirillo, 1999a, 1999b; Wertheimer, 1912/1950), suggest that the apparent lightness or brightness of any given target is actually determined by the probable contributions of illumination, reflectance, and transmittance to the same or a similar stimulus experienced in the past.

**Biological Rationale for Simultaneous Brightness Contrast in These Terms**

How, then, can the standard simultaneous brightness contrast effect demonstrated in Figure 1A be rationalized in terms of this empirical framework, and what biological purpose is served by such “distorted” perceptions? The stimulus in Figure 5A, like the similar stimulus pattern in Figure 1A, is, on empirical grounds, consistent with the two equiluminant targets being similarly reflective surfaces under similar illuminants (see Figure 5B) and/or differently reflective surfaces under different illuminants (see Figure 5C). In terms of the framework being considered here, both these categorical possibilities would be incorporated into the resulting percept in proportion to their respective frequencies of occurrence in the past experience of both the species and the individual observer. Because the latter category (differently reflective objects in different illuminants) will have been a common source of such a stimulus and because things that are different should—to be useful guides to behavior—look different, the two identical targets appear differently bright.

The biological rationale for this peculiar way of seeing is thus that by using the probability distributions of stimulus sources accumulated by trial and error during phylogenetic and ontogenetic experience (i.e., by molding visual circuitry, and thus perception, solely according to the past successes and failures of visually guided behavior), observers will entertain percepts and generate behaviors in response to ambiguous retinal images that have a better (indeed, increasingly better) chance of being successful. Put more generally, allowing objects that would typically have been different (or the same) to look different (or the same) optimizes behavioral responses to the inevitably uncertain sources of naturally occurring visual stimuli (see Purves & Lotto, 2003, for the application of this argument to other aspects of vision).

Although this strategy may seem maladaptive in presenting perceptual appearances that fail to accord with physical measurements of real-world objects and conditions (as indicated here and elsewhere by often striking visual “illusions”), the resulting anomalies are simply the signature of the biologically useful way the visual system solves the problem of promoting successful behavior in response to stimuli whose sources cannot be apprehended directly. In consequence, a standard simultaneous brightness stimulus is experienced, quite literally, as the empirical significance of the stimulus rather than as a representation of the physical intensities of the pattern of light falling on the retina (or as the output of the retinal ganglion cells, a metric that would be no less ambiguous than the stimulus itself).

Of course, observers need not be cognitively aware of the accumulated experience with past sources that has molded any given perception. On the contrary, the effects are elicited as reflexes that are presumably no different from simpler reflex responses to sensory stimuli generated in other parts of the nervous system. Like spinal cord reflexes, and for the same reasons, they are outside the realm of cognition.

**Some Other Perceptual Puzzles Explained by This Empirical Framework**

If this framework is correct, then this explanation of simultaneous brightness contrast should also account for a diversity of
other well-known perceptual enigmas that entail discrepancies between luminance and perceptions of lightness and/or brightness. There are many such puzzles of this sort in vision science, often dating back to the 19th century. Here, we examine three such challenges: the Cornsweet edge effect, the perception of Mach bands, and the Chubb–Sperling–Solomon illusion. The purpose is to consider the evidence that the effects of each of these quite different stimuli can also be explained in wholly empirical terms.

**Cornsweet Edge Effect**

The perceptual response to the Cornsweet stimulus is an instance of a broad class of edge effects first described by Kenneth Craik in the 1940s (Craik, 1948/1966; see also O’Brien, 1959). Like the stimuli used to elicit simultaneous brightness contrast, the Cornsweet edge generates sensations of lightness and/or brightness that fail to tally with photometric measurements; it is, however, quite different in structure from standard brightness contrast stimuli.

In the usual presentation shown in Figures 6A and 6B, the territory that adjoins the step edge and the light gradient appears brighter than the territory adjoining the dark gradient (see Figure 6C; note that this stimulus again belies explanations based on distorted retinal output arising from local contrast because the territory that looks darker is next to the darker gradient and vice versa; cf. Figure 1A). The basis of the effect is clearly the nature of the step edge and gradients that separate the two territories that look differently bright because blocking this portion of the stimulus abolishes the striking perceptual difference between the flanking regions (see Figure 6D). There is no generally accepted explanation of this phenomenon.

The explanation originally suggested by Cornsweet (1970) was based on filtering effects generated by lateral interactions among visual input neurons. A simpler possibility is that the Cornsweet effect, like the standard simultaneous brightness contrast effects described in the previous section, arises as a consequence of experience with what such stimuli have turned out to be in the past (Purves et al., 1999). Like the more conventional stimuli already considered, the Cornsweet edge is ambiguous; that is, there are different possible sources of the step and gradients separating the two adjacent targets. Luminance gradients are generated in one of two general ways: (a) from changes in the reflectance properties of surfaces (see Figure 7, top) or (b) from changes in the illumination of surfaces (see Figure 7, bottom). Whatever the specific sources of such stimuli, a luminance gradient arising from illumination generally signifies a variation in the amount of light reaching the eye from the object in question:

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*Figure 6 (opposite).* The Cornsweet edge effect. A: Diagram of the spinning disk used by Cornsweet (1970) to show that when two equiluminant regions are separated by an edge associated with a pair of oppositely disposed luminance gradients, the adjoining territories elicit different perceptions of lightness and/or brightness. B: Standard presentation of the Cornsweet stimulus, shown here as a blowup of a portion of the rotating disk. C: Comparison of the photometric and perceptual profiles of the stimulus in B. Despite the equal luminances of the territories adjoining the two gradients, the territory (1) to the left of the dark gradient (2) looks darker than the territory (4) to the right of the light gradient (3). D: This effect is abolished by covering up the step edge and the opposing luminance gradients, as indicated by the inset. From “An Empirical Explanation of the Cornsweet Effect” by D. Purves, A. Shinpi, and R. B. Lotto, 1999, *Journal of Neuroscience, 19*, p. 8544. Copyright 1999 by the Society for Neuroscience. Adapted with permission.
adjacent territories at the beginning and the end of the gradient will be
differently illuminated. As a result, when two territories adjoining a
gradient return the same amount of light to the eye, the territory
(target) flanking the lighter edge of the luminance gradient would, in
past experience, typically have been under stronger illumination (and
therefore have been a less reflective surface) than the equiluminant
territory flanking the darker edge. A luminance gradient arising from
the reflectance properties of an object, conversely, does not imply this
difference in illumination or the corresponding differences in the
reflectance properties of the adjoining territories. In consequence, the
luminances of the territories adjoining a gradient based on illumina-
tion usually have a different empirical significance than the territories
adjoining a luminance gradient based on reflectances. With respect to
the Cornsweet stimulus (or stimuli like it), the pattern of light that falls
on the eye is therefore consistent with either of these major categories
of experience with luminance gradients (see Figure 7).

If perceptions of brightness indeed correspond to the empirical
significance of the stimulus in question, then it should be possible to
predict the consequences of any change in the presentation of the
Cornsweet edge according to how it affects the probable source of the
ambiguous stimulus. For instance, if the elements in the surrounding
scene are made more consistent with the Cornsweet gradients arising
from changes in reflectance (see the upper panel in Figure 7), then
increasing the probability that the flanking regions are uniformly
illuminated, then the perceived difference in brightness of the equi-
luminant regions should decrease. The diminishment occurs because
the equiluminance of the adjoining territories will, in past experience,
usually have arisen from two surfaces with the same material prop-
erties under more or less the same amount of light. This prediction can
be evaluated by embedding the standard Cornsweet stimulus in a
surround identical in luminance to the surfaces adjoining the gradients
(see Figure 8). Manipulating the presentation in this way increases the
probability that the elements of the stimulus are in the same plane, a
circumstance consistent with the gradients arising from a transition in
reflectance. As a result, observers indeed find the Cornsweet effect
greatly reduced or abolished, even though the luminance relationships
in the stimulus itself remain the same (see Figure 8B; the psycho-
physical results obtained in this and other manipulations outlined in
the following paragraphs are fully described in Purves et al., 1999).

It is equally possible to generate the opposite effect. Thus, if the
information in the scene makes the Cornsweet stimulus more
consistent with changes in illumination than reflectance, the per-
ceived difference in lightness and/or brightness of the adjoining
territories should increase. In empirical terms, the increase occurs

Figure 8. Diminishing the Cornsweet effect by removing the background
contrast. A: The standard Cornsweet stimulus (see dotted outline in B)
presented such that the equiluminant territories adjoining the gradients
now extend around the Cornsweet stimulus as such. When the stimulus
is embedded in this way, observers see the territories adjoining the Cornsweet
dge as having about the same lightness and/or brightness. B: Perspective
view to indicate the source made more likely by this presentation of the
stimulus (i.e., a largely or wholly flat surface with the territories adjoining
the Cornsweet edge receiving the same amount of illumination). From “An
Empirical Explanation of the Cornsweet Effect” by D. Purves, A. Shimp, and
R. B. Lotto, 1999, Journal of Neuroscience, 19, p. 8546. Copyright 1999 by the
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because equiluminant territories adjoining the gradients in this
case more frequently have signified differently reflective surfaces
under different illuminants. For example, increasing the probabil-
ity that the source of the opposing gradients is a doubly curved
surface and that the flanking regions therefore lie in different
planes increases the likelihood that the two territories are a less
reflective surface in light and a more reflective surface in shadow
(see Figure 6 in Purves et al., 1999); this altered probability causes
an increase in the perceived difference in the target territories
compared with the effect of the standard presentation.

Combining the effects of several empirical manipulations such that
total information in a scene is mutually consistent with the source
of the stimulus being differently reflective surfaces in different illumi-
nants should enhance the Cornsweet edge even more. An example of
such mutually supportive empirical information is shown in Figure 9.
The perceived lightness and/or brightness difference between the
territories adjoining the Cornsweet edge is much greater than in the
standard presentation in Figure 6 and is increased well beyond the
changes induced by manipulations of orientation, direction of illumination, and perspective alone (see www.purveslab.net for an interactive demonstration).

All these observations suggest that the Cornsweet edge effect is based wholly on statistical information gleaned from past experience.

Mach Bands

An especially intriguing challenge to any theory of the way humans perceive light intensity is the illusory bands of increased darkness or lightness induced by linear luminance gradients. The original stimulus used by Ernst Mach, who first reported these phenomena in 1865, was a disk with black and white sectors that, when spun, generated a linear gradient linking a uniformly lighter region occupying the center of the disk with a uniformly darker region occupying the periphery (see Figure 10). In response to this presentation, observers perceive an illusory band of maximum lightness at the initiation of the gradient and a band of maximum darkness at its termination. Explaining these bands has long been a touchstone of attempts to rationalize perceptions of brightness (reviewed in Ratliff, 1965).

Mach (1865) proposed that the perception of these illusory bands is a direct consequence of physiological interactions in the retina and elaborated a detailed mathematical model of this process based on reciprocal inhibition between neighboring retinal points, a theory that he continued to modify and improve over several decades (Mach, 1866, 1868, 1914/1959). Despite a great deal of additional work during the subsequent century, Mach’s reasoning, at least in general terms, has remained the conventional explanation of this striking effect (e.g., Arend & Goldstein, 1987; Coren, Porac, & Ward, 1999, p. 110; Cornsweet, 1970, 1985; Goldstein, 2002, p. 66; Grossberg, 1987; Ratliff, 1965). Could it be, however, that Mach bands arise because a stimulus such as that in Figure 10 triggers a perceptual response determined by past experience with further subtleties that characterize the sources of luminance gradients?

In considering this possibility, recall that there are two general sources of luminance gradients: transitions in reflectance and transitions in illumination (see Figure 7). Mach bands, like the Cornsweet effect, appear to arise as a result of experience with a subset of these luminance gradients, namely with the characteristics of gradients generated by the illumination of curved surfaces (see Figure 11). Whereas a flat surface with uniform properties reflects a constant proportion of the light falling on it, a curved surface gives rise to a luminance gradient: Whatever the angle of incidence, a diminishing amount of light reaches each unit area of the surface as it curves away from the source of illumination (see Figure 11A). The resulting gradient, however, does not fully represent the stimulus that is typically generated by a curved surface. Because the surfaces of most natural objects are in varying degrees specular, meaning that the intensity of reflected light is greatest at the angle of incidence, a maximum in the luminance
Figure 10. Mach bands. A: Diagram of the painted disk used by Mach (1865). When the disk is spun, a luminance gradient is established between the uniformly lighter center of the disk and the uniformly darker region at its periphery. B: Blowup of a portion of the spinning stimulus in A, indicating the nature and position of Mach bands. As can be seen, a band of maximum lightness is apparent at Position 2 and a band of maximum darkness at Position 3, neither of which is present in the photometric measurements shown in C. C: Because the portion of the black sector between Positions 2 and 3 in A is a segment of an Archimedean spiral, the luminance gradient generated between the corresponding points on the spinning disk is linear, as indicated by this photometric measurement along the line in B. D: A similar graph illustrating the illusory lightness maximum that is perceived at the initiation of the gradient (Position 2) and the illusory minimum at its termination (Position 3). From “An Empirical Basis for Mach Bands,” by R. B. Lotto, S. M. Williams, and D. Purves, 1999, Proceedings of the National Academy of Sciences, USA, 96, p. 5240. Copyright 1999 by the National Academy of Sciences. Adapted with permission.

Figure 11. The generation of highlights. A: Because light is reflected most efficiently at the angle of incidence, a luminance maximum will occur for any eye position (indicated by the icon) when a curved surface is to some degree specular. B: Luminance profile for a perfectly specular surface seen from the viewpoint in A. In this circumstance, the only light that reaches the observer is from the portion of the curved surface that reflects the incident rays directly toward the eye. C: Luminance profile for a perfectly Lambertian surface (surface that reflects light equally in all directions). D: Luminance profile derived by combining the curves in B and C (determined from the image of the rendered cube shown here). Because most natural surfaces have specular as well as Lambertian properties, the luminance gradients generated by curved surfaces are typically adorned by a view-dependent highlight at the onset of the gradient from the better lit to the shadowed surface. From “An Empirical Basis for Mach Bands,” by R. B. Lotto, S. M. Williams, and D. Purves, 1999, Proceedings of the National Academy of Sciences, USA, 96, p. 5242. Copyright 1999 by the National Academy of Sciences. Adapted with permission.
profile occurs at or near the onset of the gradient (see Figure 11B–11D). These so-called highlights occur so routinely that people take them for granted.

Gradients of illumination on curved surface will also exhibit a lowlight. Lowlights arise because natural objects are typically illuminated by indirect light (e.g., sunlight reflected from the atmosphere or objects on the surface of the earth) in addition to light coming directly from the sun. The major source of indirect light from the sun is skylight, which, because of the physical properties of the atmosphere, is approximately isotropic. Light reflected from objects on the surface of the earth, however, is anisotropic—most such light being opposite in direction to the primary source (because surfaces orthogonal to the direction of the primary light source will be most strongly illuminated and therefore the source of most directionally specific reflected light).

The result of these typical conditions of illumination in natural visual environments (or most artificially lit environments for that matter) is a region of minimum light reflected from a curved surface near the termination of the luminance gradient generated by the direct light (see Lotto, Williams, & Purves, 1999b, for a more detailed explanation). As a consequence of these fundamental properties of light and its interaction with objects, luminance gradients generated by curved surfaces (either convex or concave) are typically adorned with a photometric highlight at the onset of the gradient and a lowlight at its termination (see Figure 12).

How, then, can these facts about naturally occurring luminance gradients explain Mach bands? When presented with any luminance gradient in a stimulus, observers will have experienced a variety of different sources: curved surfaces, penumbras (which of course do not have highlights and lowlights), and gradients generated by surface reflectance properties (e.g., the Mach stimulus in Figure 10A). Thus, the source of a Mach stimulus, like the sources of simultaneous brightness contrast stimuli and the Cornsweet edge, is ambiguous. Although the gradient in the Mach stimulus lacks a highlight and lowlight, it is nonetheless similar to stimuli that normally have these adornments. If the visual system has evolved to see luminance gradients in the stimulus is made more consistent with a gradient arising from a curved surface (which routinely has highlights and lowlights) and diminished when the stimulus is made more consistent with penumbral gradients (which lack highlights and lowlights). Third, the salience of the bands in response to a given luminance gradient is changed by ancillary cues that indicate whether the gradient pertains to a curved or a flat surface.

Thus Mach bands, rather than being an incidental manifestation of lateral interactions among the retinal ganglion cells or other lower order visual neurons as often proposed, provide further evidence for a fundamentally empirical strategy of vision.

Chubb–Sperling–Solomon Illusion

A final challenge considered here is the Chubb–Sperling–Solomon illusion (Chubb, Sperling, & Solomon, 1989). In this phenomenon, the differential brightness of randomly arranged elements is reduced when the target is embedded in a pattern of the same spatial frequency but higher luminance contrast (see Figure 13). Although the effect is not particularly strong, the apparent contrast between the elements of the circular target in Figure 13A is appreciably lower than that in Figure 13B.

![Figure 12](image_url). Digital photograph of an aluminum cube on a moderately reflecting surface in sunlight that shows in both the picture (left) and the accompanying photometric measurement (right) the highlight and lowlight that adorn most curved surfaces in viewing real-world objects. Numbers indicate corresponding points on the surface of the cube and the photometric profile. Note the similarity of the luminance profile here to the perceptual profile in Figure 10D. From “An Empirical Basis for Mach Bands,” by R. B. Lotto, S. M. Williams, and D. Purves, 1999, Proceedings of the National Academy of Sciences, USA, 96, p. 5243. Copyright 1999 by the National Academy of Sciences. Adapted with permission.
same when presented without their respective surrounds. The contrast between the patterned elements of the two identical targets appears the same average luminance (B). The inset below shows that the contrast contrast than when the same pattern is placed in a uniform surround of the bedded in a surround of higher luminance contrast (A) appears to have less. Thus, an imperfectly transmitting medium, irrespective of its particular properties, typically reduces the differences in the amount of light returned from differently reflective surfaces seen through it.

An empirical explanation of the Chubb–Sperling–Solomon effect rests on these facts about imperfectly transmitting media (Lotto & Purves, 2001). The stimulus in Figure 13A is consistent with a contribution of transmittance to the light returned from the target for two empirical reasons: (a) The borders between the patterned elements of the surround are continuous with the borders within the target and are thus consistent with occlusion of the central area by an imperfectly transmitting medium, and (b) the luminances of the target elements accord with values that would have arisen if the pattern of the surround were occluded in this way. The uniform background in Figure 13B is, by comparison, inconsistent (or less consistent) with this stimulus source. As a result, the perception elicited by the target in Figure 13A should, if the empirical theory of perception advocated here is correct, manifest the consequences of imperfect transmittance to a greater degree than the perception elicited by Figure 13B (simply because the stimulus is more likely to signify a contribution of imperfect transmittance to the amount of light reaching the eye from the different parts of the stimulus). It follows that the elements of the target in Figure 13A should appear more similar in brightness and/or lightness than the target elements in Figure 13B, as they do.

In keeping with this explanation, when the Chubb–Sperling–Solomon stimulus is made less consistent with the experience of viewing textures through imperfectly transmitting media, the effect is reduced (see Lotto & Purves, 2001). One way this can be achieved is to slowly and continuously rotate the textured surround of the Chubb–Sperling–Solomon stimulus in Figure 13A (see www.purveslab.net for a demonstration of this effect). Although this manipulation changes neither the luminance nor the spatial frequency of the stimulus, the motion of the target with respect to the surround makes it much less likely that the central target is being viewed through an imperfectly transmitting medium that is not applied to the surround. Although this effect has no obvious explanation in terms of lateral interactions among cortical neurons similarly tuned to spatial frequency (see above), it is predicted by the different empirical significance of the moving and stationary components of the modified stimulus. Another simple way to make the Chubb–Sperling–Solomon stimulus less consistent with the experience of viewing a textured surface through an imperfectly transmitting medium is changing the luminance relationships between target and surround (see Figure 4 in Lotto & Purves, 2001). Although the outcome of such manipulations is again predicted on empirical grounds, it is difficult to rationalize in other terms.

These several observations contradict explanations of the Chubb–Sperling–Solomon effect based on the anomalous activation of inhibitory connections between neurons similarly tuned to spatial contrast frequencies in the stimulus. The common denominator of the way these stimuli behave is simply a probabilistic incorporation into perception of the empirical consequences of imperfect transmittance.

The physical effects of imperfect transmittance on the light that reaches the eye are straightforward. If, for example, two target surfaces reflect, respectively, 80% and 30% of the incident light, the return from the more reflective surface in perfectly transmitting conditions will be greater than the return from the less reflective surface in the ratio of 8:3. If, however, the same surfaces are viewed through an imperfectly transmitting medium, this ratio is typically reduced. Although the interposition of such a medium reduces the overall amount of light reaching the eye from the surfaces in question, light is added to the luminances attributable to the surfaces because the transmitting medium also reflects light to the eye. Because this reflected light is added equally to any return from a surface viewed through the medium, the relative luminance attributable to the less reflective target surface will always be increased to a greater degree than the luminance associated with the more reflective surface. As a result, the difference in the luminance of the two target surfaces is reduced, in this example from a ratio of 8:3 in perfect transmittance to about 7:5 (see also Metelli, 1970, 1974; Metelli, da Pos, & Cavedon, 1985). Thus, an imperfectly transmitting medium, irrespective of its particular properties, typically reduces the differences in the amount of light returned from differently reflective surfaces seen through it.

Figure 13. The Chubb–Sperling–Solomon illusion. A target pattern embedded in a surround of higher luminance contrast (A) appears to have less contrast than when the same pattern is placed in a uniform surround of the same average luminance (B). The inset below shows that the contrast between the patterned elements of the two identical targets appears the same when presented without their respective surrounds.

The original interpretation of this effect was based on the idea of inhibitory interactions between cortical neurons tuned to similar spatial frequencies (Chubb et al., 1989; see also Olzak & Laurinen, 1999). Thus, the response of neurons to the contrasting target elements in Figure 13A is taken to be diminished with respect to the appearance of the target in Figure 13B because the high-contrast elements in the surround in Figure 13A more vigorously activate inhibitory connections between the relevant neurons than the uniform surround in Figure 13B. If it is assumed that perceptions of contrast are a more or less direct manifestation of the relative activity of spatial contrast frequency detectors in the visual cortex, then the contrast between the elements of the target in Figure 13A should be less than the contrast in Figure 13B, as is the case.

As with the Cornsweet edge and Mach band stimuli, however, an empirical explanation of the Chubb–Sperling–Solomon illusion is more consistent with the perceptual phenomenology elicited by this sort of stimulus. In this case, the pertinent empirical facts concern transmittance, which is defined as the ratio of the amount of light that reaches a detector compared with the amount of light actually reflected from an object surface. All scenes viewed at the surface of the earth are seen through media that to a greater or lesser degree affect the amount of light that reaches the eye from objects. Although the relative clarity of the atmosphere minimizes the effects of transmittance in most circumstances, viewing objects at a distance, viewing nearby objects in fog or smog, and viewing objects through semi-transparent liquids or solids (e.g., water or glass) are all frequent—and consequential—factors in determining the quality of the light that ultimately falls on the retina and initiates perception.

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These several observations contradict explanations of the Chubb–Sperling–Solomon effect based on the anomalous activation of inhibitory connections between neurons similarly tuned to spatial contrast frequencies in the stimulus. The common denominator of the way these stimuli behave is simply a probabilistic incorporation into perception of the empirical consequences of imperfect transmittance.
General Framework for Understanding the Relationship of Luminance and Lightness and/or Brightness in Empirical Terms

The ability to rationalize a variety of otherwise puzzling effects in empirical terms suggests that it should be possible to apply this conceptual framework to the relationship of luminance and its perceptual consequences more generally. The attempt to determine such scaling relationships in quantitative terms was first taken up in the 19th century by Ernst Weber (1834/1996) and Gustav Fechner (1860/1966) and was carried forward in the 20th century by a number of investigators, preeminently Stanley Stevens (1966, 1975). Although intuition suggests that the perception of lightness or brightness should scale linearly with the intensity of light that activates retinal receptors, this is, of course, not the case (as the phenomenology already described makes plain). Stevens showed that even when isolated test stimuli are viewed against a neutral background, doubling the luminance of the stimulus does not simply double the perceived brightness (see Figure 14). For increments of the test target above the background luminance (the portions of the functions to the right of each of the pertinent vertical lines in Figure 14), the brightness is greater than expected for relatively small increases in the target luminance but less than expected for greater values of target luminance. This aspect of the relationship between luminance and brightness measured under standard conditions in the laboratory is usually referred to as Stevens’s law.

Several other features of the luminance–brightness relationship have been noted over the years. First, the exponent of Stevens’s law varies as a function of the test circumstances. When, for instance, test targets are presented as a series of milky surfaces on a dark background, the exponent of the scaling function is about 0.5; if, however, the target series is shown as different pieces of gray paper in ambient light, then the exponent of the function approaches 1. Other anomalies apparent in Figure 14 are (a) that the shape of the scaling function is more or less opposite for increments and decrements (decrements of the target with respect to any given background being the portion of the functions to the left of the vertical line pertinent to each one of the three scaling functions shown), (b) that the relationship between luminance and brightness varies dramatically as a function of the background luminance, and (c) that the slope of the relationship is greatest when the luminance of the test target is similar to the luminance of the background. No generally accepted explanation for any of this phenomenology has been forthcoming, although several theories have been advanced (see discussion in Nundy & Purves, 2002).

A general framework for rationalizing this otherwise perplexing set of observations in empirical terms is shown in Figure 15. For any luminance (L) there is a set of all the possible pairs of luminance levels (L') for which the perceived brightness (B) is equal. The general relationship between luminance and perceptions of lightness and/or brightness (called brightness scaling) summarizing the major features that have been described in a range of studies over the years. The graph shows scaling tests at three levels of background luminance, indicated by the three vertical dashed lines. The features to note include (a) the nonlinearity of the relationship, (b) the more or less opposite form of the function for increments and decrements (the relationship for increments of the test target above background has been called Stevens’s law, the different shape of the relationship as a function of the background luminance), and (c) the steeper slope of the relationship when the luminance of the target is near that of the background. The units are arbitrary but linearly scaled. From “A Probabilistic Explanation of Brightness Scaling,” by S. Nundy and D. Purves, 2002, Proceedings of the National Academy of Sciences, USA, 99, p. 14483. Copyright 2002 by the National Academy of Sciences. Adapted with permission.
A simple probabilistic framework for rationalizing the phenomenology of lightness and/or brightness scaling. A: Space defined by all the possible combinations of illumination and reflectance that could have generated particular values of luminance. The reflectance efficiency functions (x-axis) and illuminant intensities (y-axis) are given in arbitrary units relative to the average values of these parameters in any scene. The three differently colored lines show the effects on brightness scaling that would be expected when the empirical significance of the stimulus is varied (i.e., when the probability distribution of the possible illumination–reflectance combinations for any given luminance is altered). B: Different scaling relationships predicted by the empirical considerations in A. If the information in a stimulus is consistent with the generative source of the target luminance being predominantly either illumination or reflectance, the exponent of the function should approach 1.0; if, conversely, the information is consistent with a roughly equal contribution from these sources, the exponent should be about 0.5. As indicated in the text and in Figure 14, these expectations are evident in the results of psychophysical tests of scaling. From “A Probabilistic Explanation of Brightness Scaling,” by S. Nundy and D. Purves, 2002, Proceedings of the National Academy of Sciences, USA, 99, p. 14483. Copyright 2002 by the National Academy of Sciences. Adapted with permission.
illumination (I) and reflectance (R) values that could have given rise to the stimulus in question (for the sake of simplicity, the contribution of transmittance and other factors here is assumed to be negligible). Figure 15A shows the possible I and R values that give rise to luminances that are 10%, 20%, . . ., 100% as intense as the maximum possible luminance. The distribution of the possible I–R combinations that could have given rise to any particular value of luminance (which can be thought of as a third dimension of this space) thus describes, to a first approximation, human experience with the relative contributions of these underlying factors to luminance.

The “space” illustrated in Figure 15 thus provides a simple didactic scheme in which to explore how the luminance/lightness–brightness relationship would be expected to change in any circumstances as a function of its possible sources. For example, if the conditions for a given test of brightness scaling were to change the probable contribution of illumination and/or reflectance to the luminance values presented, then the probability distribution of the possible I and R values along any isoluminance line would also change. More specifically, if in any scene the change in experimental conditions increased the probability that the changes in target luminance derived predominantly from changes in reflectance, then the central tendency (e.g., the mean) of the probability distribution of the possible I–R combinations that could have given rise to a particular target luminance would shift toward the blue line in Figure 15A. By the same token, if the experimental conditions increased the probability that the changes in luminance values in the scene derived predominantly from changes in surface illumination, then the central tendency of probability distributions of the I and R values would shift toward the green line. Conversely, if the experimental conditions provided little or no information about the generative sources of the luminances in the scene (or if the information was consistent with the contributions of illumination and reflectance being equal), then the distribution of the possible I–R combinations underlying the luminance values would be more centrally located along any particular isoluminance line, as indicated by the red line.

Notice that the distance between physically proportional luminances in this space varies according to these several general circumstances. For instance, the distance between the 10% line and the 20% isoluminance line is the same as the distance between the 70% and 80% lines when distances are measured along a line parallel to either the reflectance or illumination axis (see dots along the blue and green lines in Figure 15A). If, however, the distance between isoluminance lines is measured along a line equidistant from the axes of reflectance and illumination, then the distance between the 10% and 20% isoluminance lines is greater than the distance between the 70% and 80% lines (see dots along the red line). As a result, if the information in a scene was to bias the probable sources of the luminance values in the retinal image toward either the illumination or the reflectance axis—and if the relative sensations elicited by any two luminance values were a consequence of the distances between the probable I and R sources in this empirical space—then differences in the perceived brightness of the targets in a scene should vary according to the distance along a line running more nearly parallel to the axes of illumination or reflectance (i.e., nearer to the blue or green lines in Figure 15A). If, conversely, the information in the scene biased the central tendency of the probability distributions of the possible sources of luminance values toward I–R combinations in the middle of this space, then the brightness difference elicited by different luminances should be proportional to the distance along the red line in Figure 15A. The scaling relationships expected on this basis for targets shown as increments above background are illustrated in Figure 15B.

One way to test these predictions is to ask subjects to adjust the luminances of a series of test patches such that brightness of adjacent patches increases in perceptually equal steps when there is only a minimum of information about the relative contribution of illumination and/or reflectance to the stimulus. These conditions are thus similar to a standard scaling test. Subjects can then be asked to perform the same task, but with the test patches presented in a scene rich in empirical information consistent with the patches signifying different reflectances under the same illuminant. The point of the comparison is to determine if the scaling relationship changes in the manner predicted by the empirical framework illustrated in Figure 15. If the information in a scene makes it more likely that the source of the target luminances in the test series is predominantly due to either changes in surface reflectance or the illumination, the possible I–R combinations giving rise to that luminance will necessarily fall closer to one axis or the other of this empirical space. Perceptual responses to the luminance values presented should therefore track along a line that is closer to the relevant axis (e.g., the blue line or the green line). Conversely, if the stimulus makes it less likely that the generative I–R combination is dominated by changes in either surface reflectance or illumination, then the perceptual responses to the presented luminances should track more centrally in this space (i.e., along the red line). The results obtained by psychophysical testing are in accord with these expectations (Nundy & Purves, 2002).

These observations support the conclusion that the peculiarities of lightness and/or brightness scaling that have been reported over the years (see Figure 14) are also explainable in wholly empirical terms: the parameters of the scaling function changing predictably in a manner dictated by the influence of all the information in the scene on the probability distribution of all the possible sources of a particular value of target luminance. Understood in this way, the discrepancies between lightness and lightness and/or brightness, whether in tests of scaling or any other circumstance, are simply the signature of the empirical strategy of vision.

Conclusion

A variety of perceptual phenomena pertinent to the way humans perceive the physical intensity of light stimuli, including standard illusions of simultaneous brightness contrast, Craik–O’Brien–Cornsweet edge effects, Mach bands, the Chubb–Sperling–Solomon illusion, and brightness scaling, can all be explained in terms of a visual strategy that generates perceptions of luminance (i.e., the sensations of lightness and brightness) as reflex responses determined by the relative probabilities of the possible sources of inevitably ambiguous stimuli. The ability of this empirical framework to explain a wide range of perceptual phenomenology supports this novel way of understanding what people actually see. If correct, the functional role of the neural circuitry underlying light-
ness and/or brightness percepts will also need to be understood in these terms.

References


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