An Empirical Explanation of the Chubb Illusion

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Abstract

■ The perceived difference in brightness between elements of a patterned target is diminished when the target is embedded in a similar surround of higher luminance contrast (the Chubb illusion). Here we show that this puzzling effect can be explained by the degree to which imperfect transmittance is likely to have affected the light that reaches the eye. These observations indicate that this 'illusion' is yet another signature of the fundamentally empirical strategy of visual perception, in this case generated by the typical influence of transmittance on inherently ambiguous stimuli. ■

INTRODUCTION

The brightness of any luminant stimulus varies, often quite markedly, as a function of the context in which it is presented. An especially intriguing example of this phenomenon is the illusion described by Chubb, Sperling, and Solomon (1989), in which the differential brightness of randomly patterned elements of a target (Figure 1A) is reduced when the target is embedded in a pattern of similar spatial frequency but higher luminance contrast (Figure 1B). Thus the apparent contrast between the elements of the circular target in Figure 1A is lower than that in Figure 1B, even though the overall luminance of the two surrounds is the same.

Illusory percepts of brightness, including this one, are usually explained as epiphenomenal consequences of lateral inhibitory interactions between neurons tuned to the same attributes of the stimulus (see, e.g., Adelson, 2000; Palmer, 1999, p. 116 ff). In this interpretation, the response of neurons to the contrasting target elements in Figure 1A is diminished in Figure 1B because the higher contrast but otherwise similar surround more vigorously activates inhibitory connections between neurons similarly tuned to spatial frequency than does the uniform surround in Figure 1A (Olzak & Laurinen, 1999; Chubb et al., 1989). If perceptions of contrast are a more or less direct manifestation of the relative activity of spatial contrast frequency detectors, then the brightnesses of the targets should appear more similar in Figure 1B than in Figure 1A, as is indeed the case (cf. Figure 1A and B). In support of this hypothesis, the apparent difference in the brightness of the target elements in Figure 1A is largely unaffected by the surround in Figure 1C, which has a lower spatial contrast frequency than the target (cf. Figure 1B and C). Since neurons 'tuned' to the different spatial frequencies of the target and surround are presumably not laterally connected to the same degree, this result is expected.

Despite the simplicity of interpreting these percepts as incidental consequences of the lateral interactions between similarly tuned neurons, this reasoning is undermined by the fact that the apparent contrast between the elements of the target pattern in Figure 1D is largely unaffected by the surround in Figure 1F. Because the luminance contrasts and spatial frequencies of the stimuli in Figure 1E and F are identical, the absence of much effect in this instance cannot be explained in terms of the receptive field properties of neurons 'tuned' to spatial-contrast-frequency.

Given this discrepancy, we here consider the possibility that the range of otherwise puzzling effects in Figure 1 might arise in quite a different way, namely from past experience with the sources underlying such stimuli. The rationale for exploring this way of understanding the Chubb effect is evidence that a number of brightness illusions have recently been shown to accord with what the same or similar stimuli have typically turned out to be in the experience of the species and the individual (Purves et al., 2001; Lotto & Purves, 1999; Lotto, Williams, & Purves, 1999a, 1999b; Purves, Shimpi, & Lotto, 1999; Williams, McCoy, & Purves, 1998a, 1998b). The evidence we present indicates that the Chubb illusion can, like other illusions of brightness, be understood in wholly empirical terms, in this case with the typical consequences of seeing surfaces through imperfectly transmitting media.

RESULTS

The source of any light that falls on the retina is inherently ambiguous: A given stimulus can signify any of an infinite number of combinations of illumination, reflectance, and transmittance. As a consequence of this ambiguity, we have argued that the visual system may

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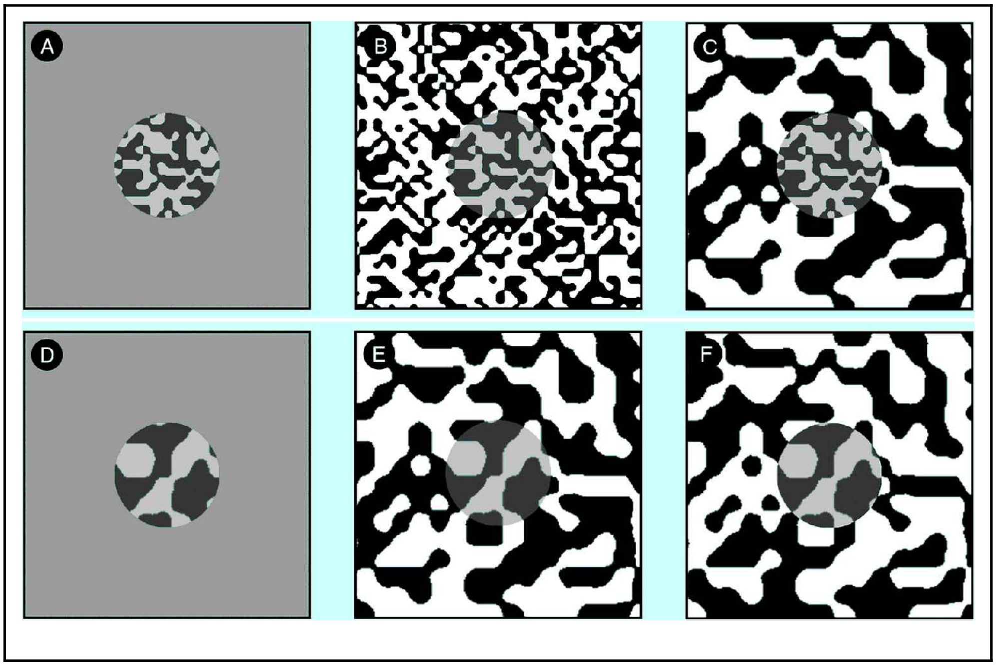

Figure 1. The Chubb effect. A 'target' pattern embedded in a surround of higher luminance contrast (A) appears to have more contrast than when the same pattern is placed in a uniform surround of the same average luminance (B). This effect does not occur, however, if the spatial frequency of the surround is made lower than that of the spatial frequency of the target (C). Nonetheless, lower spatial frequency patterns are perfectly capable of inducing the Chubb effect (cf. D and E), as long as the patterns are continuous across the target surround boundary (cf. E and F).

generate successfully guided behavior in a wholly empirical manner (see review by Purves et al., 2001). Consistent with this hypothesis, the brightness, saturation, and/or hue of identical targets can be changed dramatically by making the overall stimulus more consistent with the targets being different objects under the different illuminants, or, conversely, by making the stimulus more consistent with similar objects under similar illuminants (Lotto & Purves, 1999; Purves et al., 2001; Williams et al., 1998a, 1998b).

These demonstrations and their interpretation have focused on the effects of changing the probable contribution of reflectance and/or illumination to the stimulus. Here we test whether changing the probable contribution of transmittance to stimuli affects perception in a similarly predictable manner. The reason for considering the Chubb effect in this argument, in addition to its intrinsic interest, is the similarity of the Chubb stimulus to the stimuli used by Metelli (1970, 1974) and Metelli, da Pos, and Cavedon (1985) to induce illusory perceptions of 'transparency'. The following experiments therefore test whether the Chubb and related stimuli can be successfully explained in terms of experience with the effects of transmittance on light stimuli.

The Empirical Consequences of Imperfect Transmittance

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 the relevant objects. Although the relative clarity of the atmosphere minimizes the effects of transmittance in most circumstances, viewing objects at a distance, nearby objects in fog or smog, or through semitransparent liquids or solids (e.g., water or glass) are all frequent and consequential factors in determining the spectral properties of the light that ultimately falls on the retina and initiates perception.

The effects of imperfect transmittance are illustrated in Figure 2. If, for example, two target surfaces reflect, respectively, 80% and 30% of the incident light (Figure 2A), the return from the more reflective surface in perfectly transmitting conditions will be greater than the return from the less reflective surface by a ratio of 8:3 ("Ratio-1" in Figure 2A). If, however, the same surfaces are viewed through an imperfectly transmitting medium, this ratio is reduced ("Ratio-2" in Figure 2A). Although the interposition of such a medium reduces the amount of light coming from the affected surfaces proportionally, some light is also added to the luminances attributable to the two surfaces in question. The latter effect occurs because the medium also reflects light to the eye (see Figure 2A). Since this reflected light is added equally to any return from a surface viewed through the medium, the luminance attributable to the less reflective target surface is always 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 et al., 1985).

In short, an imperfectly transmitting medium, irrespective of its particular properties, always reduces the luminance differences between differently reflective surfaces seen through the medium. If perceptions are

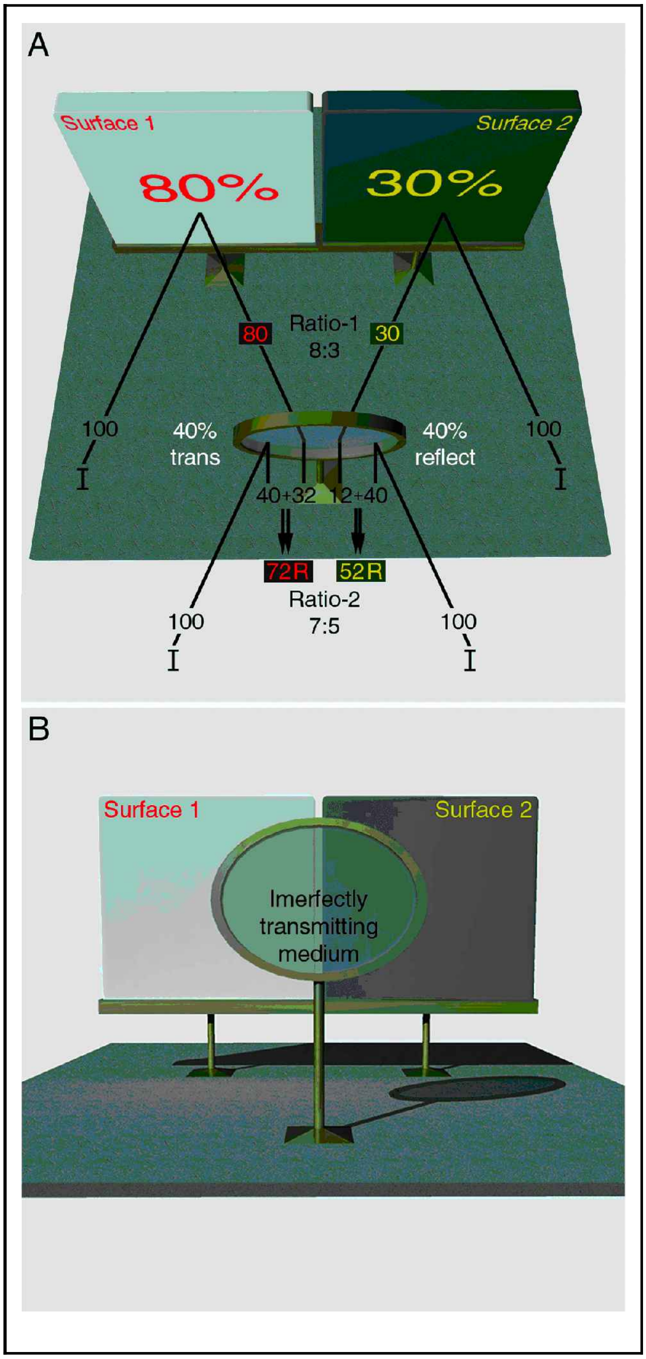

Figure 2. Effects of imperfect transmittance. (A) An imperfectly transmitting medium interposed between object and observer reduces the luminance differences of returns corresponding to the surfaces that would be seen through the medium (see text for further explanation). (B) Illustration showing how the effects diagrammed in (A) would appear.

generated empirically, then to the extent that a stimulus is consistent with a contribution of imperfect transmittance, this influence will be 'incorporated' into the perception of the target. As a result, the apparent brightness difference between differently luminant elements of a target should decrease when imperfect transmittance is likely to have contributed to the light being returned from it.

An Empirical Explanation of the Chubb Effect

The Chubb stimulus in Figure 1B is empirically consistent with a contribution of transmittance to the light returned from the target for two reasons: (1) the borders between the patterned elements of the surround in Figure 1B are continuous with the patterned boundaries in the target; and (2) the luminances of the target elements accord with the values that would arise if the pattern of the surround were viewed through an imperfectly transmitting medium. Because a uniform background is, by comparison, more ambiguous in these respects, imperfect transmittance is more likely to have contributed to the return from the target in Figure 1B than in Figure 1A. As a result, the perception elicited by the target in Figure 1B incorporates the consequences of imperfect transmittance to a greater degree than the perception elicited by Figure 1A, causing the elements of the target in Figure 1B to appear more similar in brightness than the target elements in Figure 1A.

Evidence for An Empirical Explanation of the Chubb Effect

This explanation of the Chubb effect predicts that changing the stimulus in Figure 1B in any manner that makes it less consistent with the experience of viewing a texture through imperfectly transmitting media should decrease (or even reverse) the effect. The apparent difference in the brightness of the target elements should increase in any such circumstance, even though the luminance ratios in the stimulus and spatial frequencies of the surround and target remain unchanged. The following experiments were undertaken to test this prediction.

Altering the Probable Contribution of Imperfect Transmittance by Manipulating Motion

In a first test of this prediction, subjects were asked to compare the stationary stimulus in Figure 3A to the stimulus in Figure 3B, in which the same surround rotated slowly around the stationary target (this comparison can be viewed at http://www.purveslab.net). Since rotating the surround does not change the luminance contrasts or spatial frequencies in the stimulus, the targets should continue to appear identical. Nineteen out of the twenty subjects tested, however, judged the brightness difference between the target elements in Figure 3B to be greater than in Figure 3A ($p < .01$). Although this result has no obvious explanation in terms of lateral interactions among neurons similarly tuned to spatial frequency (see above), it accords with the difference in the empirical significance of the stationary and moving stimuli. Thus, whereas the stimulus in Figure 3A is consistent with the central target being viewed through an imperfectly transmitting medium, the mo-

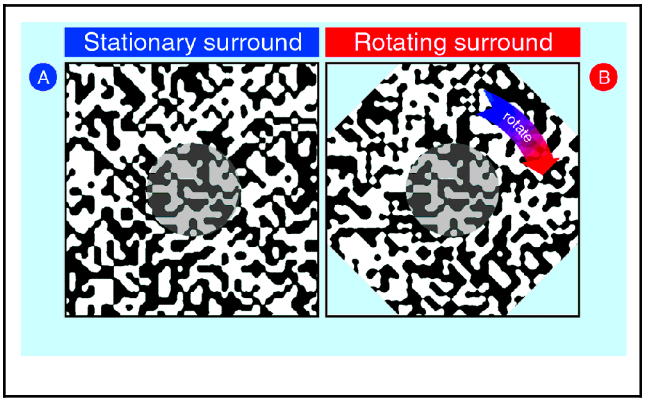

Figure 3. Altering the brightness contrast of the target elements in a stationary presentation (A) by slowly rotating the surround (B) (see text for explanation).

tion of the surround introduced in the stimulus illustrated in Figure 3B makes this possibility less likely.

Altering the Probable Contribution of Transmittance by Manipulating Luminance

In a second test of an empirical explanation for the class of stimuli exemplified by the Chubb effect, subjects were presented with the stimuli in Figure 4. In Figure 4B, the luminance difference between the elements of the surround is three times greater than the luminance difference between the elements of the target. This luminance ratio, together with the continuity of the patterned elements across the boundary of the target and surround, are consistent with the stimulus arising from imperfectly transmitting medium interposed between the observer and the target. As a result, 19 out of 20 subjects judged the apparent contrast of the target on the patterned surround in Figure 4B to be less than that of the target pattern on the uniform surround in Figure 4A, much as in the comparison of Figure 1A and B ($p < .01$).

A quite different result was obtained, however, when the subjects were presented with the stimuli in Figure 4C and D. In these stimuli the luminances of the surrounds in Figure 4A and B have each been decreased by a factor of four, without changing either the patterns or their contrast ratios (i.e., the luminance contrast of the surround remains three times greater than that of the target). This manipulation does, however, change the empirical significance of the stimuli in that the presentation in Figure 4D is now less consistent (indeed incompatible) with a contribution of transmittance to the target. This inconsistency arises because an imperfectly transmitting medium overlying the central region of the surrounding pattern could not increase the luminances of *both* the light and dark elements in the surround to produce the luminances that are actually returned from the target in the figure (although it could produce one or the other of these values).

In accord with this change in the empirical significance of the target, 15 out of 20 subjects perceived the contrast of the target on the patterned surround in Figure 4D to be higher than that of the same target on the uniform surround in Figure 4C ($p < .05$). Although this result is predicted on empirical grounds, it is difficult to rationalize in other terms; indeed, the perception elicited is the opposite of that elicited by comparing the otherwise similar stimuli in Figure 4A and B, which contradicts explanations of the Chubb illusion in terms of an incidental consequence of lateral interactions between spatially tuned neurons in the cortex.

Altering the Probable Contribution of Transmittance by Manipulating Color Information

In addition to affecting luminance, imperfect transmittance also alters the spectral distribution of returns in quite specific ways. When chromatic returns pass through an imperfectly transmitting but achromatic medium, their spectral characteristics are always shifted toward neutrality—i.e., the spectral distribution broadens (see Figure 5A,B). This effect occurs because the light reflected by an imperfectly transmitting medium of this sort adds uniformly to the distribution of wavelengths in each of the transmitted returns from the surfaces seen through it, thereby decreasing the differences in their perceived saturation (cf. profiles 2 and $2'$ with 5 and $5'$ in Figure 5B). Similarly, when surfaces are viewed through an imperfectly transmitting chromatic medium, both returns are shifted towards the spectral characteristics of the medium (cf. profiles 2 and $2'$ with 5 and $5'$ in Figure 5D). This influence arises because

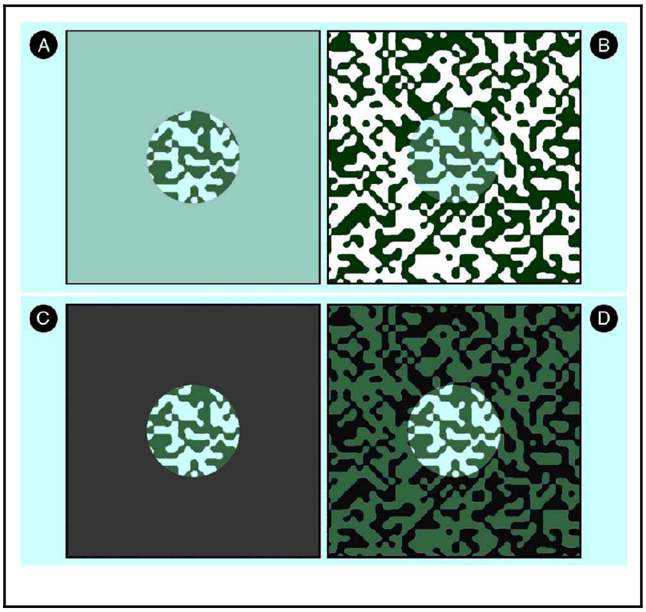

Figure 4. Altering the apparent contrast of the target elements by manipulating the luminance ratios of the surrounds (see text for explanation).

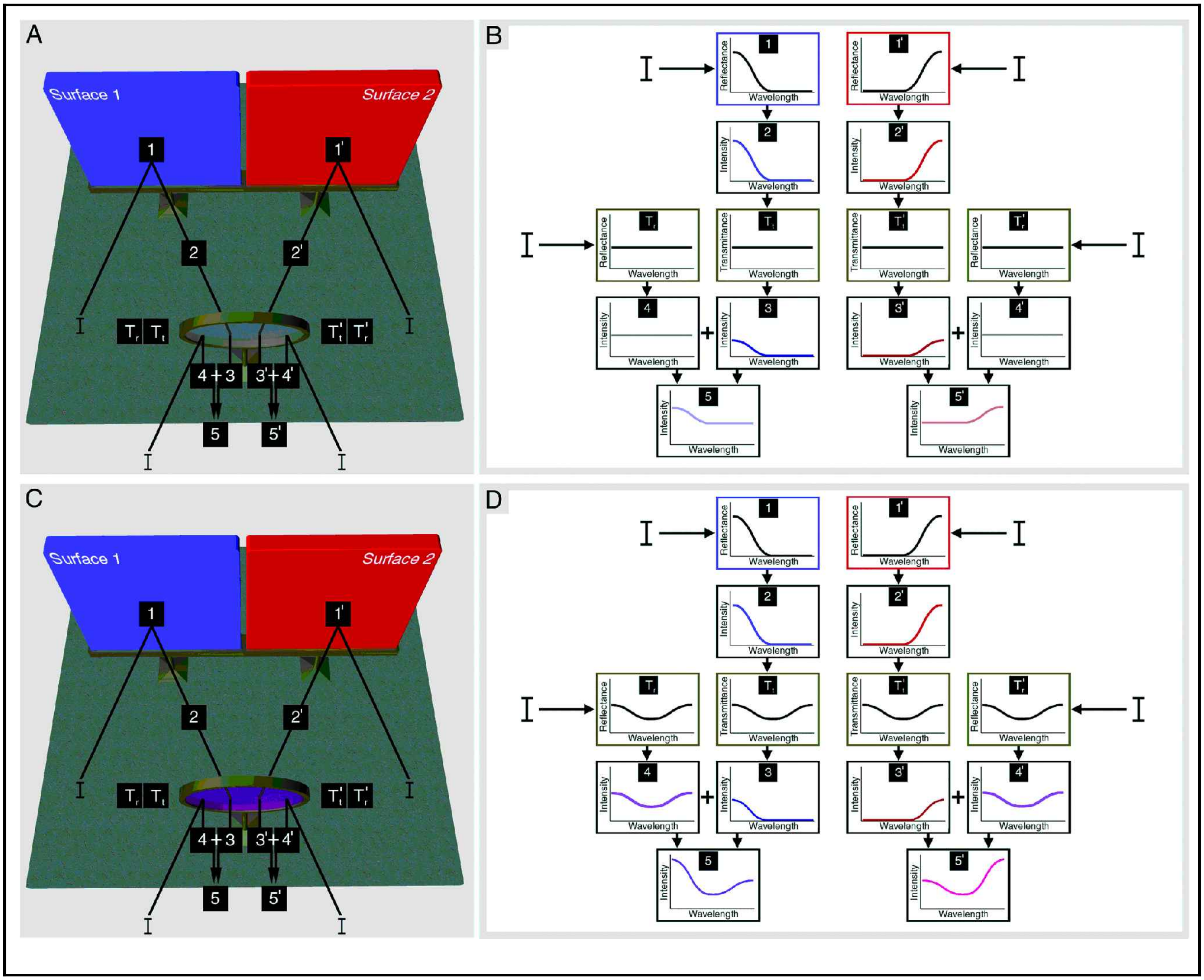

Figure 5. The physical effects of imperfectly transmitting media on the spectra returned to the eye from chromatic target surfaces. (A) Diagram of effect on the 'purity' of the spectral returns from the target surfaces due to the interposition of a neutral filter (perceived as saturation). (B) Indication of how the spectra are changed by the interposition of the neutral filter. (C) Diagram of the effect on the distribution of the spectral returns from the target surfaces due to the imposition of a chromatic filter (perceived as hue). (D) Indication of how the spectra are changed by the interposition of the chromatic filter.

the medium in this instance not only filters out similar wavelengths from each return, but adds light characteristic of the reflectance efficiency function of the medium itself (see Figure 5D and D'Zmura et al., 1997). Thus, if the Chubb effect is indeed a manifestation of the empirical consequences of transmittance, the saturation or hue of a target should also be changed by making the stimulus consistent with either imperfect achromatic or chromatic transmittance, respectively.

To test this prediction, subjects were first presented with the stimuli in Figure 6A and B and asked to judge which of the target patterns appeared lower in saturation contrast (i.e., which of the targets appeared grayer). In this case, the surround has been made continuous with the target pattern and the chromatic relationships made consistent with viewing the equiluminant 'red' and 'blue' elements of the surround through a centrally located achromatic transmitting medium (Figure 6B; cf. Figure 5). Subjects would therefore be expected to perceive the target elements in Figure 6B to be lower in saturation contrast than when presented on a uniform surround of the same average color, as in Figure 6A. This expectation was met for all 20 subjects tested ($p < .01$).

Subjects were then presented with the stimuli shown in Figure 6C and D. Relative to Figure 6C, which is again ambiguous with respect to transmittance, the spectral returns from the continuous patterns are more consistent with viewing the surrounding texture through a centrally located, imperfectly transmitting 'purple' medium (a filter, for instance). As a result, the perceived difference in the hues of the patterned elements in Figure 6D should be less (they should both appear more 'purplish', thereby incorporating transmittance into the

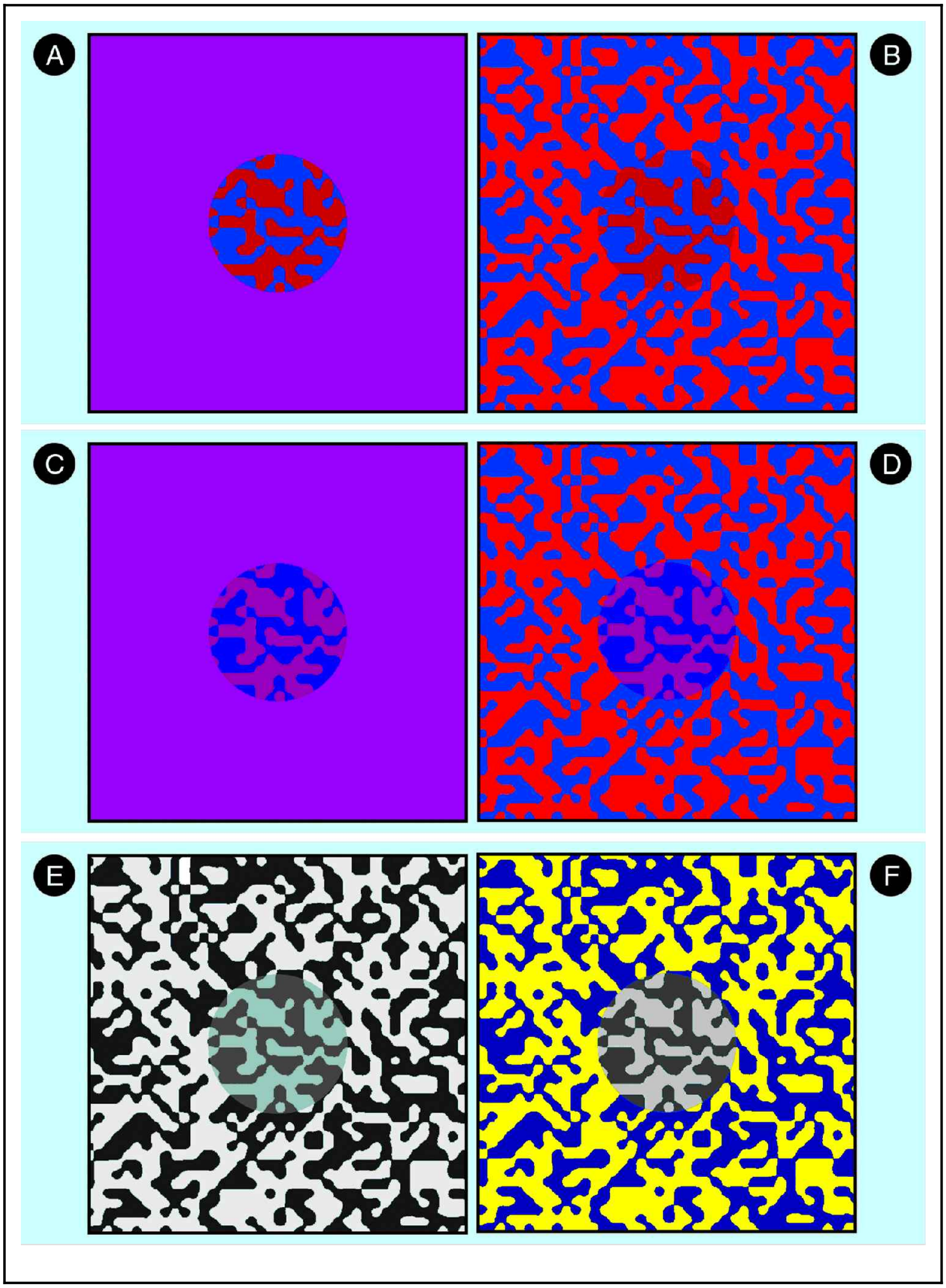

Figure 6. Altering the apparent saturation (A,B) and hue (C,D) of the central target pattern by manipulating apparent transmittance (see text for explanation). (E) and (F) show the further effect of using chromatic information to reduce the probability of imperfect transmittance as an important influence on the spectral returns (see text for explanation).

perception) than when the same target is viewed against a uniform chromatic surround, as in Figure 6C. In keeping with this predication, 19 of the 20 subjects reported the elements of the target in Figure 6D to be more purplish relative to their more reddish and bluish appearance in Figure 6C, even though the average spectral contrasts between the targets and their surrounds are identical in the two scenes (p = .01).

Whereas the stimuli in Figure 6B and D utilize the spectral information of continuous patterns to increase the probable contribution of transmittance to the target (and thereby decrease the apparent color contrast of its constituent returns), the spectral information in Figure 6F does exactly the opposite. In this example, the spectral information in Figure 6E is consistent with viewing the target through an imperfectly transmitting medium; conversely, the spectral information surrounding the same target in Figure 6F is inconsistent with this possibility, since it is not possible to simultaneously neutralize the returns from both the 'yellow' and the 'blue' surrounding elements by the interposition of an imperfectly transmitting medium (Figure 5). As a consequence, all 20 subjects perceived the target on the chromatic surround (Figure 6F) to be higher in contrast than the same target on the achromatic surround (Figure 6E), even though the light and dark gray elements of the surround in Figure 6E and the yellow and blue elements in Figure 6F are equiluminant (p = .01).

DISCUSSION

The illumination of the objects in a scene, the reflectances of those objects, and the transmittance of the media between the objects and observer necessarily determine the spectral content of any visual stimulus. The conflation of these factors in the spectral return means that the significance of the light that interacts with retinal receptors is inevitably ambiguous. Successful behavioral responses to spectral stimuli nonetheless depend on an evaluation of the relative contributions to the stimulus of illumination, reflectance, and transmittance: The response will be inappropriate if the contribution from one of these factors is mistaken for that of another. Since an observer cannot determine these relative values from the stimulus as such, we have argued that the visual system can only resolve this dilemma by generating perceptions empirically, that is, according to past experience with the same or a similar stimulus (reviewed in Purves et al., 2001). In previous studies of this hypothesis we focused on the relative contributions of illumination and reflectance to the empirical significance of spectral profiles, rationalizing in these terms phenomena such as simultaneous brightness contrast (Williams et al., 1998a, 1998b; Lotto & Purves, 1999), color contrast (Lotto & Purves, 2000), Craik–O'Brien–Cornsweet effects (Purves et al., 1999), and Mach bands (Lotto et al., 1999a, 1999b).

Similarly, the common denominator of the observations reported here is also the empirical consequences of an aspect of the physics of light not previously considered in these terms, namely, the effects of imperfect transmittance on the light that reaches the eye (see also Singh & Anderson, 2001). In the presence of imperfect transmittance, observers will always have experienced a reduced difference in luminance or spectral contrast from object surfaces (see also Metelli, 1970, 1974; Metelli et al., 1985). As a result, when the pattern of light that falls on the retina is consistent with a contribution of imperfect transmittance to the stimulus, perceptions of contrast accord not with the luminances of the stimulus per se, but with the typical effects of transmittance on the spectral return from object surfaces. The reason in this conception is that, because visual percepts are elicited empirically on the basis of what particular spectral returns have turned out to be in the past, the characteristic effects of imperfect transmittance are included in the percept elicited by the target in proportion to the experienced frequency of the possible sources underlying the same or similar stimuli.

For instance, by placing the central target in Figure 7A within a scene that makes the continuity of the pattern and the relative luminances consistent with the past experience of observers viewing the surrounding pattern through an imperfectly transmitting medium (as in Figure 7B), the typical consequences of transmittance are 'incorporated' into the percept, causing the contrast between the elements of the target texture to be reduced. Conversely, when the same target is placed in the same scene, but in a way such that the stimulus is inconsistent with transmittance (as in Figure 7C), the perceived contrast of the target is less affected because the typical physical behavior of imperfect transmittance is not included in the pattern of central neuronal activity elicited by the stimulus (i.e., in the percept). In short, any pattern of contrasts consistent with a contribution of imperfect transmittance to the stimulus will alter perception in the direction and to the degree of the source typically experienced in the presence of that constellation of luminances.

These observations contradict explanations of the Chubb effect based on the anomalous activation of inhibitory connections between neurons similarly tuned to spatial contrast frequencies in the stimulus (see Chubb et al., 1989). If this interpretation were correct, then changing the motion (Figure 3), luminance (Figure 4), or spectral distribution of the target surround (Figure 6) should have had little or no effect on the percepts elicited, since these manipulations alter neither the relevant spatial frequencies nor the luminance contrast

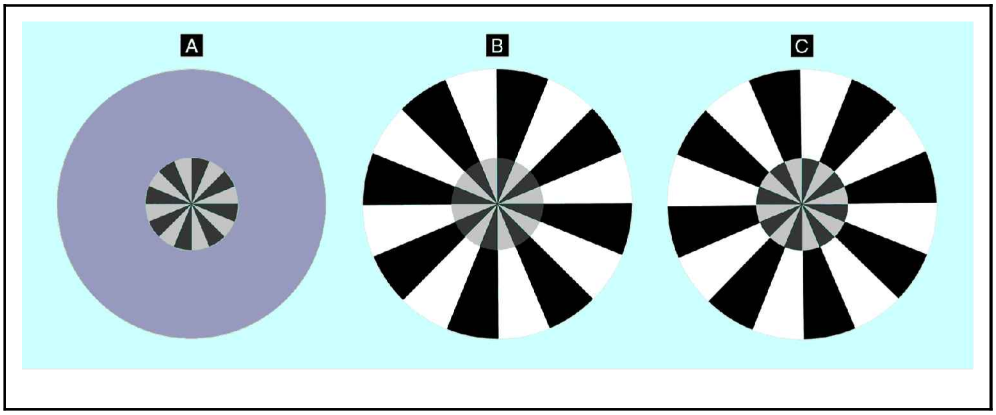

Figure 7. Summary of an empirical explanation of the Chubb effect. Although the central target is identical in (A), (B), and (C), the different scenes are either consistent (B) or inconsistent (A and C) with viewing the surrounding pattern through an imperfect transmitting medium (see text for explanation). The incorporation of these empirical influences into the pattern of central neuronal activity triggered by the stimuli is what we take to underlie the Chubb effect.

ratios of the stimulus. The observations are also inconsistent with interpretations of 'illusions' of brightness on the basis of the 'contour junctions' in the stimulus (see, for instance, Anderson, 1997; Adelson, 2000), since such junctions are not explicit in the Chubb stimulus (as originally pointed out by Anderson, 1997).

In summary, these results add further support to the general conclusion that visual percepts are entirely determined by the experience of the human visual system with the frequency of occurrence of the possible sources of inherently ambiguous stimuli.

METHODS

Construction and Presentation of Computer Graphics

All test graphics were created with a Macintosh G4 computer, using Adobe Photoshop 5.0 software and displayed on a calibrated 19.8″ (diagonal) color monitor (Sony Trinitron Color Graphic Display GDM-F500R; resolution = 1152 × 870; scan rate 75 Hz, noninterlaced). The computer interface for these experiments was created with Director 7.0 (Macromedia, San Francisco, CA). All stimulus pairs were viewed from a distance of 60 cm and subtended 13.5° × 27.5°; the subjects were allowed to scan them freely. The test stimuli were counterbalanced in that the target that appeared lower in contrast was both presented on the left (as in Figures 3A/B, 4C/D, and 6E/F), and on the right (as in Figures 4A/B, 6A/B, and C/D) in order to control for possible systematic left–right asymmetries in brightness judgements (Nicholls, Bradshaw, & Mattingley, 1999).

The luminances of the elements in the various scenes were measured with an optical power meter (Model 371R, Graseby Optronics, Orlando, FL) under the relevant test conditions. For the motion stimuli in Figure 3, the luminance of the lighter and darker surrounding elements was 106 and 0.5 cd/m^2, respectively, and the light and dark target elements were 70 and 14 cd/m^2, respectively. For the scenes in Figure 4A and B the luminance of the lighter and darker surrounding elements was 100 and 10 cd/m^2, respectively, and in Figure 4C and D the luminance of the lighter and darker surrounding elements was 26 and 2.6 cd/m^2, respectively. The uniform surrounds in Figure 4A and C were equiluminant with the spatial average of the surrounds in Figure 4B and D, respectively; and in all cases the light and dark target elements were 77 and 25 cd/m^2, respectively. Finally, for scenes in Figure 5, the red and blue surrounding elements were both 21 cd/m^2, whereas the luminance of the target elements were both 19 cd/m^2 in Figure 5B and 14 cd/m^2 in Figure 5D. For the scenes in Figure 5E and F the luminance of the lighter and darker surrounding elements was 9 and 5 cd/m^2, respectively, for both scenes, and the light and dark target elements, which was the same in both scenes, were 63 and 19 cd/m^2, respectively.

Subjects and Testing

Twenty subjects (14 men and 6 women) with visual acuity of 20/20 or better (9 of the subjects had corrected vision), and whose color vision was normal (determined with standard Ishihara plates) were tested. Each subject was first familiarized with meanings of 'higher-' and 'lower-contrast', the terms used to describe the targets in the subsequent presentations. They were then shown each of the demonstrations illustrated here once, and asked to select which of the two targets at the centers of the two random-dot textures appeared to have the higher contrast. Subjects were allowed to take as long as needed in choosing the higher contrast target (although selections were typically made within 10 sec). In preliminary observations we found that subjects were not actually able match the contrast of the two identical targets with any certainty, even though the difference in the apparent contrast of the targets was clear. Although an explanation for this inability to match the targets is beyond the scope of this study, it presumably indicates the impossibility of equalizing by adjustments of luminance the brightness of two identical targets whose empirical significance differs (see also Williams et al., 1998a).

The statistical significance of the selections made in the responses to subjects to each of the test stimuli was calculated using a chi-square test.

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