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Brief Communication

Voluntary attention modulates the brightness of overlapping transparent surfaces

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Abstract

A new class of brightness illusions is introduced that cannot be entirely accounted for by bottom-up models of neuronal processing. In these new illusions, brightness can be modulated by the location of voluntary attention in the absence of eye movements. These effects may arise from top-down or mid-level mechanisms that determine how 3D surfaces and transparent layers are constructed, which in turn influence perceived brightness. Attention is not the only factor that influences perceived brightness in overlapping transparent surfaces. For example, grouping procedures may favor the minimal number of transparent layers necessary to account for the geometry of the stimulus, causing surfaces on a common layer to change brightness together. Attentional modulation of brightness places constraints on possible future models of filling-in, transparent surface formation, brightness perception, and attentional processing.

Keywords: Attention; Brightness; Grouping

A given patch of gray will appear brighter against a dark background and darker against a bright background. The earliest models of brightness perception attempted to explain such illusions in terms of lateral inhibition occurring in the retina (Cornsweet, 1970) or cortex, where the activation of one cell inhibits the activation of its neighbors. Such models failed to explain how higher level perceptual factors, such as inferred three-dimensional shape (Adelson, 1993), layout (Gilchrist, 1977), or curvature (Knill & Kersten, 1991), could influence brightness perception. In particular, the visual system must determine what portion of a single luminance value detected at a location on the retina arises from each of several possible causes of that value in the world, such as surface coloring, shadow, illumination, or an intervening transparent layer. Models attempting to explain these effects have gone well beyond earlier models based solely on lateral inhibition among adjacent neurons. More recent models incorporate both low-level factors, such as lateral-inhibition, and mid-level factors, such as the global geometric analyses that may underlie the decomposition (Watanabe & Cavanagh, 1993) of the image into contributions from reflectance, illumination, shadow, and transparency. These models (Gove, Grossberg, & Mingolla, 1995; Singh & Anderson, 2002) are nonetheless all bottom-up in the sense that perceived brightness is ultimately driven by the stimulus rather than some internal factor. The new class of illusions described here demonstrates that voluntary attention plays an important role in the perceived brightness of overlapping transparent surfaces. This requires a new class of models that account for top-down contributions to brightness perception. Moreover, this new class of illusions makes clear the importance of surface grouping in determining

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perceived brightness. In particular, the visual system appears to settle on an interpretation where there is the minimum number of transparent layers necessary to account for the geometry of the stimulus.

The effect can be seen when visually fixating any of the fixation spots in Fig. 1A while attending to any one of the gray disks. The attended disk appears to darken in the absence of eye movements. The author tested himself with an eyetracker (eyelink2, SRresearch) using a state system that turned the screen red any time the left eye strayed outside a half-degree radius window centered on the fixation point. Shifting attention to another disk without breaking fixation decreases the brightness of this disk in turn. Of sixteen observers tested on a version of this figure presented on a CRT screen (60 Hz refresh, 57 cm viewing distance, circle diameter 5.5°, White background $\sim$89 cd/m^2, light gray $\sim$46 cd/m^2, middle gray $\sim$ 32cd/m^2, dark gray $\sim$12 cd/m^2 as measured using Minolta CA-100), all said that they experienced the effect and said that they could "will" a chosen disk to darken by shifting attention to that disk ($p < .0001$, two-tailed under binomial test).

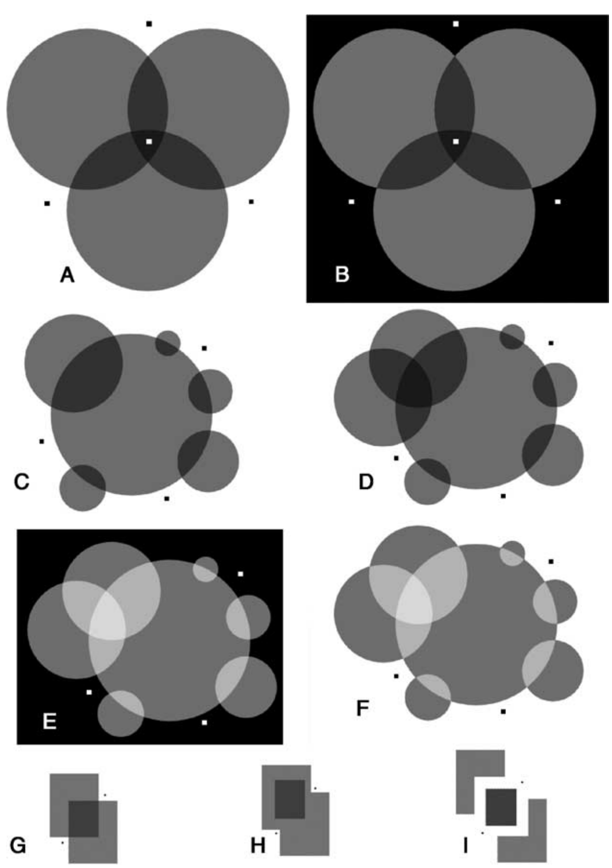

Fig. 1. Attending to one disk or another in 1A leads to a perceived darkening of that disk in the absence of eye movements. In the absence of cues to transparency, as in 1B, the effect disappears. Remaining figures are described in the text.

This illusion appears to require that disks be interpreted as transparent surfaces occluding a background. The effect is very robust, and any combination of gray values seems to create the illusion, as long as the appearance of transparent layers is preserved. When such an interpretation is not possible, because key image cues for transparency (Metelli, 1974; Singh & Anderson, 2002) are absent, as in Fig. 1B, where the background alone has changed to black (<1 cd/m^2), perceived brightness is not modulated by attentional allocation (0 of 16 observers noted darkening with attentional shifts across disks; $p < .0001$). Fig. 1A and D are also consistent with a shadow interpretation. However, the luminance inverse of Fig. 1D, shown in Fig. 1E, is not consistent with a shadow interpretation, and nonetheless expresses the effect. Thus a model that is built on the shadow interpretation alone cannot be generally valid. Attending to any disk in Fig. 1E brightens rather than darkens the disk (14 of 16 observers could see brightening; $p = .004$). However, when the same disks are placed on a white background, as in Fig. 1F, making the disks inconsistent with a transparency interpretation (as in Fig. 1B), the effect disappears (0 of 16 observers noted brightening with attentional shifts across disks; $p < .0001$). Although Fig. 1E is consistent with an overlapping spotlights interpretation, the transparency model appears to be the only one that can account for the general case.

In Fig. 1C, either the large disk alone or the entire group of smaller disks tend to change brightness together. The entire group of smaller disks appears to group together as a darkened group even when effort is made to attend to a single small disk. In Fig. 1D, attending to one of the two overlapping medium-sized disks does permit darkening of the attended disk, as in Fig. 1A, but the remaining four small disks tend to remain dark if either medium-sized disk is attended. This suggests that more is involved in generating this effect than voluntary attention. It appears that the visual system operates under a tacit assumption that as few transparent layers as possible should be inferred in order to account for the geometry of a stimulus. For example, the minimum number of layers consistent with both the global arrangement of shapes and local junction cues is two for Fig. 1C, but three for Fig. 1A, D, and E. Accordingly, there are two ways in which brightness changes occur in Fig. 1C, but three in Fig. 1A, D, and E. Several objects or surfaces may belong to a common layer. Attending to any object or surface on a layer appears to decrease/increase the brightness of all objects belonging to that layer. Largely automatic grouping procedures may place similar elements or configurations of elements on a common layer, which accounts for their joint brightness changes when any member of that layer is attended. These apparently automatic grouping procedures may operate under the minimal layer assumption and modulate the ability of voluntary attention to drive the effect.

The simplest arrangement where the effect occurs is shown in Fig. 1G, involving just two layers. A minimum amount of apparent surface overlap appears to be necessary to permit the effect. However, a dark overlap-like region alone is also not sufficient to drive the effect; Note that the effect does not occur in Fig. 1H or Fig. 1I, presumably because this arrangement is not consistent with a transparency interpretation. In order for the overlap region to count as the occluding portion of a transparent layer, contours must be co-aligned as in Fig. 1G.

Attending to one of the transparent disks or rectangles may lead to the interpretation that it is in front of or in back of the other(s) because attention may create a transparent figure that occludes a background or an opaque figure that is occluded by transparent occluders. This figural account predicts that a disk will appear to become opaque when placed behind all other layers and transparent when placed in front of other layers by voluntary attention. Placing the disks on different layers using binocular disparity (cross fuse), as in Fig. 2, does not destroy the effect, and may indeed enhance it. The backmost disk now remains permanently opaque, while the other two remain permanently transparent. Indeed, consistent with the presumed need for a transparency interpretation, the backmost, opaque disk is not modulated by the darkening effect, whether it is the attended layer or not, whereas the transparent disks still undergo brightness modulation.

Much empirical work remains to be done to determine the causes of brightness changes of overlapping transparent surfaces. One factor appears to be voluntary attention, but even this must be empirically established. For example, it is possible that the darkening happens for non-attentional reasons, such as the representational flipping that occurs in binocular rivalry and multistable figures generally (Leopold & Logothetis, 1999), and that attention is then drawn exogenously to this perceived change. Some bistable phenomena, such as the perceptual flipping in binocular rivalry appear not to be modulated by selective attentional control, whereas others, such as the Necker cube, can be modulated by voluntary selective attention (Meng & Tong, 2004). Future experiments will have to determine whether perceptual flipping is largely automatic, as in binocular rivalry, or modulated by voluntary attentional shifts, like the Necker cube. The initial data reported here imply that the present multistable phenomenon is modulated by voluntary attentional shifts (16 out of 16 observers claimed that they could choose which disk to make darker in Fig. 1A, $p < .0001$), but this result requires further corroboration. In addition, future experiments should precisely specify the parameters under which this effect occurs so that future modeling can specify likely neuronal mechanisms that might cause it. There have been surprisingly few studies to date showing that attention modulates stimulus appearance (The most direct test of this being Carrasco, Ling, & Read, 2004; see also Cameron, Tai, & Carrasco, 2002; Carrasco, Penpeci-Talgar, & Eckstein, 2000). Indeed, there are studies that conclude that attention cannot modulate perceived brightness (Prinzmetal, Nwachuku, Bodanski, Blumenfeld, & Shimizu, 1997) or that attention reduces the perceived contrast between a stimulus and its background (Tsal, Shalev, Zakay, & Lubow, 1994), contrary to the present findings. In Carrasco et al. (2004), changes in perceived brightness were subtle and not consciously noticed by observers, though statistically significant as measured using points of subjective contrast equality specified by psychometric functions. The presumed mechanism for the type of contrast enhancement described by Carrasco et al. is attentional modulation of neuronal response gain in early visual areas (Reynolds, Pasternak, & Desimone, 2000; Reynolds & Desimone, 2003; Martinez-Trujillo & Treue, 2002; McAdams & Maunsell, 1999; Treue, 2000). The new effect described here shows for the first time in a consciously noticeable and apparently voluntarily manipulable manner that attention can modulate perceived brightness. This may require new models that invoke higher-level mechanisms than gain control, such as surface, layer, and boundary formation, filling-in, or inhibition among higher-level surface, object, or layer representations. Whatever model eventually best describes this new effect, future models will have to take into account the role of top-down factors such as voluntary attention on perceived brightness. Entirely bottom-up or stimulus-driven models of perceived brightness appear to no longer be adequate in light of these findings.

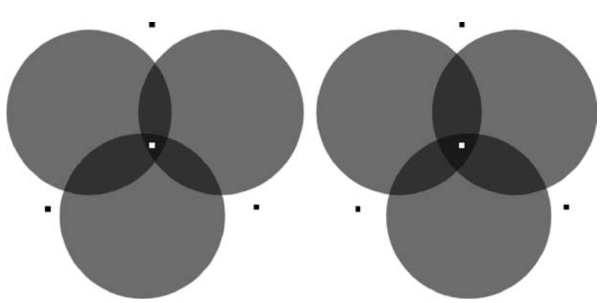

Fig. 2. Cross-fusion permits the disks to appear to be staggered in 3D depth. The backmost disk becomes opaque. The effect is weakened for this disk, but remains strong for the transparent disks.

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