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SHORT AND SWEET

Perceptual organization in colour perception: Inverting the gamut expansion effect

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Abstract. In the well-known gamut expansion effect, uniformly coloured target patches are perceived as more colourful when they are embedded in a uniform grey surround than when they are embedded in a variegated one. Here, we provide a demonstration showing that this effect can be inverted when the uniformly coloured target patches are replaced by variegated ones. This observation suggests that the gamut expansion effect is due to mechanisms of transparency perception rather than due to contrast adaptation.

Keywords: simultaneous colour contrast, gamut expansion effect, perceptual transparency, colour scission, perceptual organization.

The two top panels of Figure 1 show a variant of Brown and MacLeod's (1997) gamut expansion effect. The six squares embedded in the patterned surround on the right are physically identical to those embedded in the uniform surround on the left, yet the latter appear more colourful. The four chromatic targets look more saturated, and the two achromatic ones on the top appear as more pronounced shades of white and black. Regarded as points in three-dimensional colour space, the perceived colours of the targets in the uniform surround are all shifted in the direction away from the intermediate grey of the surrounds.

The gamut expansion effect has stirred much interest because it clearly violates traditional laws of simultaneous contrast. According to the "complementarity law" of simultaneous colour contrast, the surround induces a shift in the perceived colour of the target, which is complementary to the colour of the surround. That is, the vector in colour space representing the colour shift should have a direction opposite to the vector from the grey point to the surround colour (Figure 2a). Furthermore, the direction of the colour shift should be the same for targets of any colour, as long as the colour of the surround is fixed. Figure 2(b) schematically illustrates the kind of colour changes typically observed in investigations of the gamut expansion effect (Brown & MacLeod, 1997; Ekroll & Faul, 2013; Faul, Ekroll, & Wendt, 2008). The observation that the perceived colours of the targets in the uniform grey surround appear more saturated than those in the variegated one, but of the same hue, means that they are shifted in the directions corresponding to the vectors pointing from the colour of the surround (which is grey in this case) to the colours of the target. Based on many lines of converging evidence, we have argued that the latter is a general rule ("direction law"), which holds for surrounds of arbitrary colour (not just grey ones; see Figures 2b and c), and is characteristic not only of the gamut expansion effect but also of the classical simultaneous contrast effect (Ekroll & Faul, 2012a, 2012b).

Traditional explanations of simultaneous colour contrast appeal to mechanisms providing colour constancy across illumination changes (Helmholtz, 1866/1962; Lotto & Purves, 2000; Walraven, Benzschawel, & Rogowitz, 1987). When the colour of the illumination changes in a given direction in colour space, the colour of the light reflected from objects in the scene typically change in roughly the same direction and any visual mechanism that shifts the object colours in the opposite ("complementary") direction would counteract the influence of the illumination and thus provide approximate colour constancy. Thus, presuming that the visual system uses the colour of the surround as a cue to the

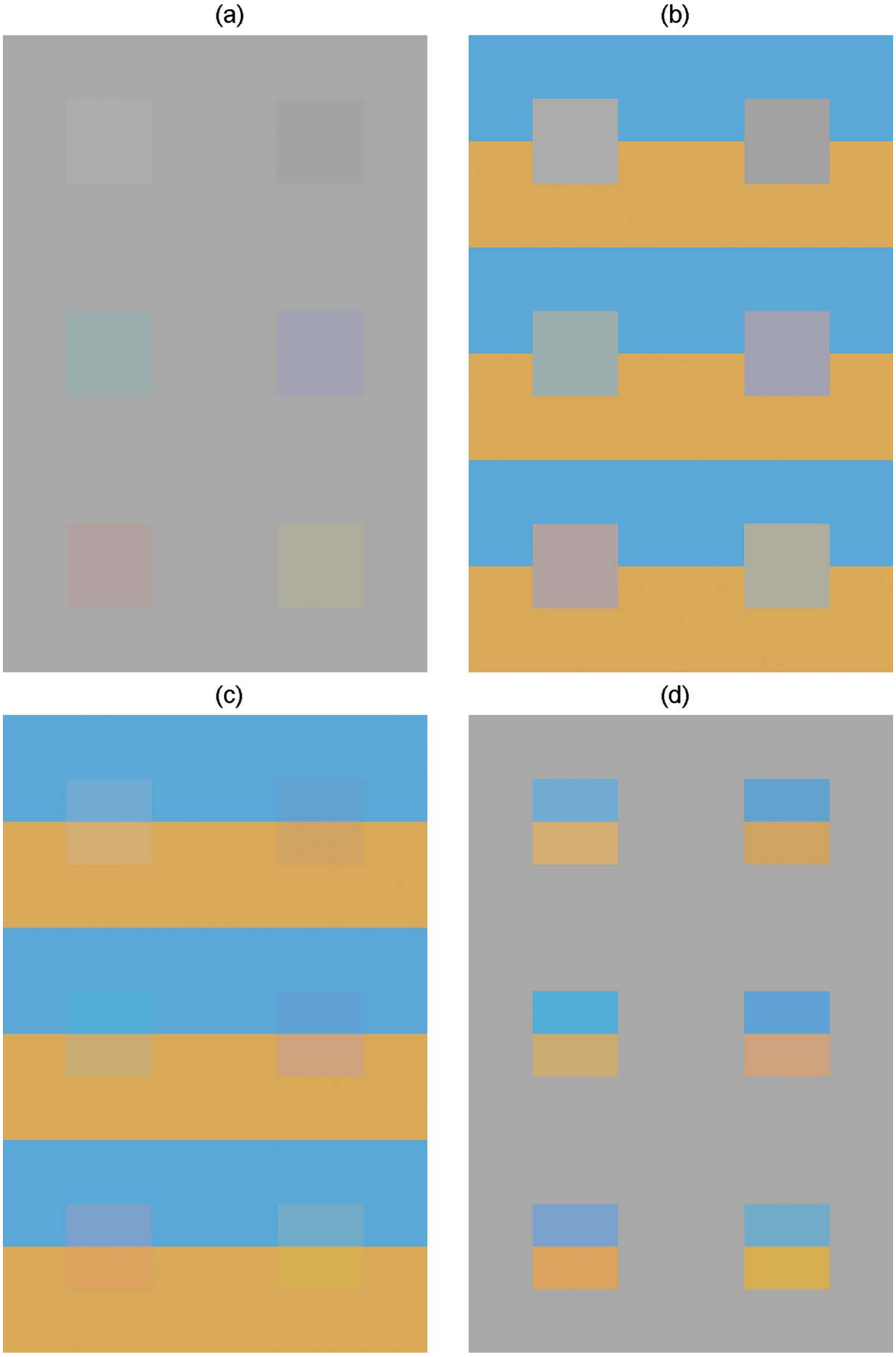

Figure 1. In the top panels, the perceived difference between the target patches is more pronounced in the uniform surround (a) than in the variegated surround (b). In the lower panels, the converse is true. Here, the target patches in the variegated surround (c) appear (in a qualitatively similar way) more different than the physically identical ones shown in the uniform surround (d). Together, the classical gamut expansion effect (top) and the inverted one (bottom) suggest that the compatibility with a perceptual interpretation in terms of transparency, which is given in the left panels, but not in the right ones, is the crucial determinant of the effect. The demonstration should preferably be viewed on-screen for optimal colour reproduction.

colour of the illumination, this kind of mechanism can be expected to produce a simultaneous contrast effect that is complementary to the colour of the surround. However, if the simultaneous contrast effect actually obeys the direction law rather than the complementarity law, this traditional explanation would seem less plausible, suggesting that an alternative theoretical account is needed.

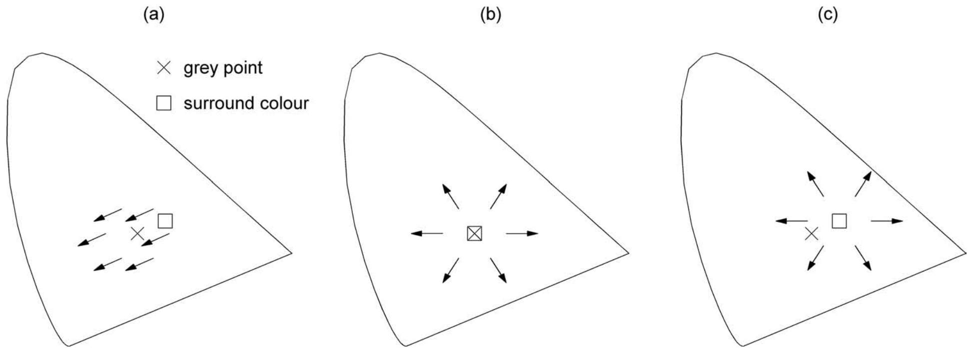

Figure 2. (a) According to the traditional complementarity law, the direction of the perceived colour shifts (arrows) induced by a coloured surround is opposite to the direction given by the vector point from the grey point to the colour of the surround. (b) The colour shifts observed in the gamut expansion effect exhibit a different pattern. Here, the targets in the uniform grey surround appear more saturated than those in the non-uniform surround. This corresponds to colour shifts having the same direction as the vectors from the grey surround to the targets. (c) According to our theory, the same principle ("direction law") also applies for coloured surrounds.

Addressing this point, we have proposed that the gamut expansion effect (as well as the classical simultaneous contrast effect) is instead due to mechanisms subserving the perception of transparent media (Ekroll & Faul, 2012a, 2012b, 2013; Faul et al., 2008). As illustrated in Figure 3, a uniformly coloured disc embedded in a uniformly coloured surround (Figure 3a) is compatible with the perceptual interpretation of a transparent disc in front of a uniformly coloured background (Figure 3b). If the perceptual system makes this interpretation, and infers the colour of the transparent disc based on the colour-mixture equations underlying Metelli's model of perceptual transparency (Gerbino, in press; Metelli, 1985), then the inferred colour of a disc embedded in a grey surround should be more saturated than its proximal colour. According to Metelli's equations, the perceived colour E of the transparent disc is related to the proximal colour P of the disc and the proximal colour B of the surround by the equation $P = \alpha B + (1 - \alpha)E$, where $0 < \alpha < 1$ is the perceived transmittance of the transparent disc. Intuitively, this equation means that the proximal colour P is located on the line segment connecting the colours B and E in colour space. Hence, if B is an achromatic colour, the proximal colour P of the disc is always less saturated than its inferred layer colour E. Importantly, though, this enhancement of perceived saturation should only occur when the stimulus is compatible with perceptual transparency. Since the structure of the background will generally be visible through a transparent object (see Figures 3c–d), a centre-surround stimulus should only be compatible with transparency of the central patch if the central patch and the surround exhibit compatible patterning (or a compatible lack of patterning). That is, a uniform target is compatible with transparency only when the surround is also uniform. If the surround is non-uniform, transparency would only be a viable solution if the target is also non-uniform (as in Figure 1c or Figures 3c–d). Thus, according to our theory, the gamut expansion effect (top panels of Figure 1) results because the uniform targets can be interpreted as transparent when they are embedded in the uniform surround (Figure 1a) but not when they are embedded in the non-uniform surround (Figure 1b).

The results reported in Ekroll and Faul (2013) lend strong support to this explanation of the gamut expansion effect. A further interesting prediction of this theory, though, is that it should be possible to invert the gamut expansion effect by using non-uniform target squares rather than uniform ones. The demonstration shown at the bottom of Figure 1 suggests that this is indeed the case. Here, the six squares embedded in the uniform surround (Figure 1d), each composed of two differently coloured rectangles, are physically identical to those embedded in the variegated surround (Figure 1c). In this case, the target squares embedded in the non-uniform surround appear more different from each other than the ones embedded in the uniform surround, rather than the other way around, as was the case with the uniform target squares (Figures 3a–b). Thus, as predicted by our theory, the crucial variable determining which targets look more saturated is not the contrast of the surround, but the compatibility with a perceptual interpretation in terms of perceptual transparency.

Judging colours of the square targets in the bottom panels of Figure 1 is somewhat complicated by the fact that each square consists of two differently coloured rectangles rather than a single colour. It is particularly difficult to judge the colour of the squares on the right, since no common transparent

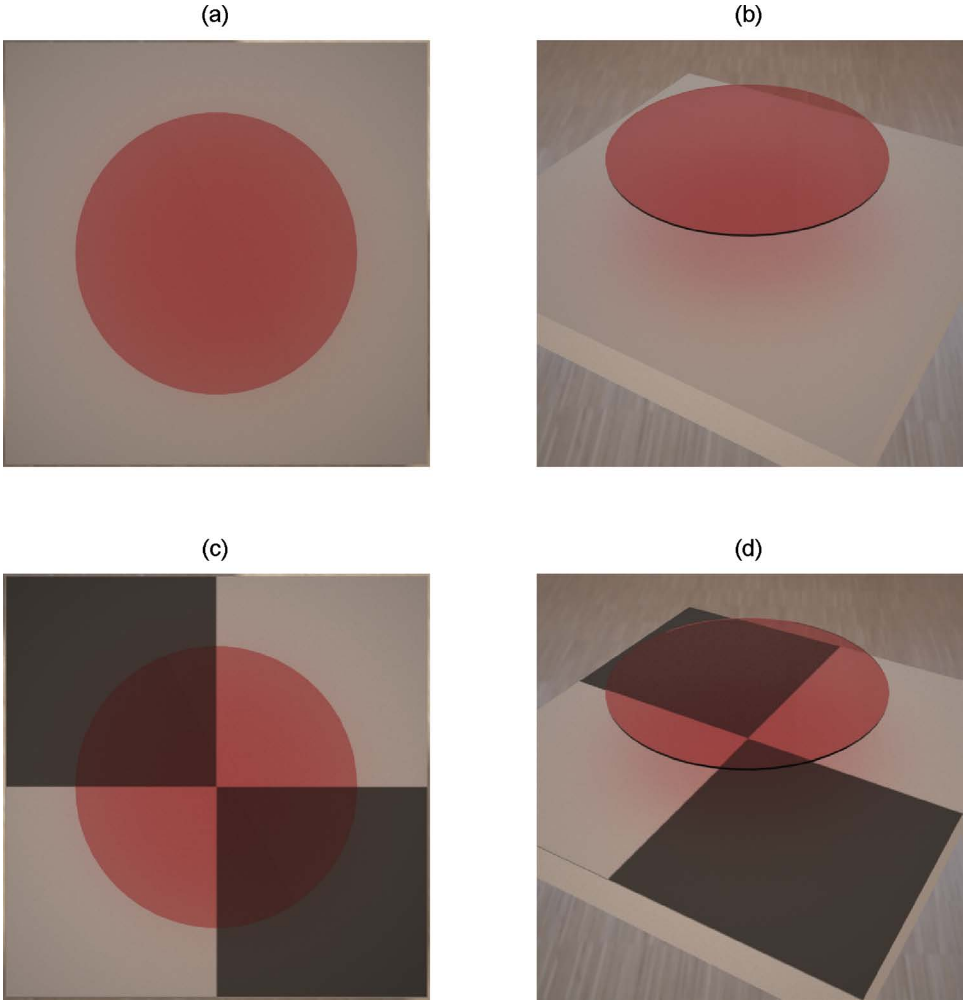

Figure 3. (a) A uniformly coloured target disc embedded in a uniformly coloured surround (a) can be interpreted as a transparent disc in front of a uniformly coloured background (b). Traditional research on perceptual transparency, however, has focused on the slightly more complex stimuli shown in (c), which can be interpreted as a transparent disc in front of a non-uniform background. Reproduced from Ekroll & Faul, (2013) by kind permission of the *Journal of the Optical Society of America* A.

layer is perceived in the square region corresponding to the two rectangles. Thus, whether the squares in Figure 1(c) actually look more saturated than those in Figure 1(d) will, to some extent, depend on what one regards as "the" colour of the two rectangles—which clearly also requires some mental construal. It is comparatively straightforward, however, to compare the colours of the transparent squares in Figure 1(c) with the uniform squares in Figure 1(b). Although the average colour within each square in Figure 1(c) is identical to the colour of the corresponding square in Figure 1(b), the squares in Figure 1(c) appear more saturated, which cannot be attributed to contrast adaptation, since the two surrounds are identical.

Historically, the simple centre-surround stimuli shown in Figure 3(a) and the slightly more complex stimuli shown in Figure 3(c) are strongly associated with two separate research traditions pursuing different goals with different strategies. The former kind of stimulus has been extensively used within the tradition of sensory psychophysics, which aims to study simple low-level mechanisms by eliminating or at least minimizing the influence of perceptual organization. The latter kind of stimulus, on the other hand, was preferred within the tradition of Gestalt psychology (Fuchs, 1923; Metelli, 1985), which aims to reveal the role of perceptual organization by using stimuli containing sufficient structure for doing so (Gerbino, in press, Wagemans et al., 2012a, 2012b). Modern approaches typically appeal to both lines of reasoning within a theoretical framework postulating multiple levels of visual processing (Adelson, 2000; Kingdom, 2003). While the idea of multiple levels of processing seems quite plausible, there is no *a priori* justification for the widespread assumption that simpler stimuli engage less complex visual mechanisms than more complex stimuli do. As our analysis suggests, the very simple stimulus in Figure 1(a) may engage the same kind of comparatively complex visual processing as the more complex stimulus in Figure 1(c). Thus, the well-documented influence of perceptual organization and layered scene representation on colour appearance (Anderson, in press; Wollschläger & Anderson, 2009) may even play a crucial role in simple centre-surround stimuli. From this perspective, it appears less surprising that the phenomenon of simultaneous contrast evoked by these deceivingly simple stimuli has defied any simple and consistent explanation for more than a century (Shevell, 1978; Whittle, 2002).

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