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Simultaneous Brightness and Apparent Depth from True Colors on Grey: Chevreul Revisited

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Abstract
We show that true colors as defined by Chevreul (1839) produce unsuspected simultaneous brightness induction effects on their immediate grey backgrounds when these are placed on a darker (black) general background surrounding two spatially separated configurations. Assimilation and apparent contrast may occur in one and the same stimulus display. We examined the possible link between these effects and the perceived depth of the color patterns which induce them as a function of their luminance contrast. Patterns of square-shaped inducers of a single color (red, green, blue, yellow, or grey) were placed on background fields of a lighter and a darker grey, presented on a darker screen. Inducers were always darker on one side of the display and brighter on the other in a given trial. The intensity of the grey backgrounds varied between trials only. This permitted generating four inducer luminance contrasts, presented in random order, for each color. Background fields were either spatially separated or consisted of a single grey field on the black screen. Experiments were run under three environmental conditions: dark-adaptation, daylight, and rod-saturation after exposure to bright light. In a first task, we measured probabilities of contrast, assimilation, and no effect in a three-alternative forced-choice procedure (background appears brighter on the 'left', on the 'right' or the 'same'). Visual adaptation and inducer contrast had no significant influence on the induction effects produced by colored inducers. Achromatic inducers produced significantly stronger contrast effects after dark-adaptation, and significantly stronger assimilation in daylight conditions. Grouping two backgrounds into a single one was found to significantly decrease probabilities of apparent contrast. Under the same conditions, we measured probabilities of the inducers to be perceived as nearer to the observer (inducers appear nearer on 'left', on 'right' or the 'same'). These, as predicted by Chevreul's law of contrast, were determined by the luminance contrast of the inducers only, with significantly higher probabilities of brighter inducers to be seen as nearer, and a marked asymmetry between effects produced by inducers of opposite sign. Implications of these findings for theories which attempt to link simultaneous induction effects to the relative depth of object surfaces in the visual field are discussed.

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1. Introduction

Almost two centuries ago, the French chemist Michel Eugène Chevreul published his observations on the perceptual modifications produced by the mutual proximity of colors (*De la loi du contraste simultané des couleurs et de l'assortiment des objets colorés*, Chevreul, 1839). He therein defined what later has become known as simultaneous color contrast (e.g. Beck, 1966; De Weert, 1984; De Weert and Spillmann, 1995; Dresp and Fischer, 2001; Gerrits and Vendrik, 1970; Heinemann, 1955; Helson, 1963; Pinna, 2008; Shapley and Reid, 1985) or color context effects (e.g. Long and Purves, 2003; Reeves *et al.*, 2008; Shevell and Kingdom, 2008). Observing how colors placed side by side or surrounding each other change in appearance according to which color is put next to which other, Chevreul suggested how they needed to be displayed in space to produce specific effects on the perception of the human observer. His laws of color and contrast provide valuable intuitions about the effects of color on processes of perceptual organization that have inspired artists, architects, designers and visual scientists ever since. Two such laws describe what Chevreul (1839) invoked in terms of a law of true color and a law of contrast, both relevant to our study here.

The law of true color states that for any color to truly appear to the observer as that particular color, the background must be grey, implying that a color on a grey background should be the least likely to produce mutual interactions that alter the appearance of either. From his observations "on the juxtaposition of colored bodies with grey", reported in Chapter VI of his essay, Chevreul concludes:

> "... it may be conceived that grey bodies, judiciously selected with regard to their depth in tone, would, by contiguity to colored bodies, exhibit the color in a more striking manner than either black or white bodies would; ...colors in juxtaposition with grey being more perceptible than when juxtaposed with white or black" (Chevreul, 1839, translated by Spanton in 1854, Chapter VI).

This conclusion summarizes Chevreul's idea that all primary colors would gain 'purity' and 'brilliancy' by the proximity of grey, rather than white or black, which tend to affect a color's brightness and thereby alter the perception of its tone. When placed nearby other so-called inducing colors, the appearance in either brightness or tint of the so-called test color often changes dramatically (e.g. Livitz *et al.*, 2011). Such changes may be reflected by a contrast effect, where the perceived brightness or tone of the test color changes away from that of the inducing color, or by an assimilation effect, where the perceived brightness or tone of the test color changes toward that of the inducing color (Wyszecki, 1986). Interaction of a similar kind occurs between achromatic stimuli of positive and negative contrast polarities, producing either contrast, where a bright surface makes an adjacent one look darker and a dark one makes an adjacent one look brighter, or assimilation, where a bright surface makes an adjacent one look brighter and a dark surface makes an adjacent one look darker (e.g. Beck, 1966; Festinger *et al.*, 1970; Hamada, 1985; Heinemann, 1955; Helson, 1963). Chevreul's law of true color has never been challenged by induction studies, and mutual interactions where colors change the appearance of nearby or surrounding grey fields, or where grey fields change the appearance of nearby or surrounding colors, have up to date not been investigated.

For a color to be seen as standing out in depth against the background, or to be seen as figure rather than as ground, the difference in luminance or brightness between the color and its background must be strong, as stated in Chevreul's law of contrast. This intuition that differences in luminance would act as a cue to relative depth in the visual field has been confirmed since by psychophysical studies showing that surfaces with the stronger luminance contrast in the two-dimensional plane tend to be perceived as figure rather than as ground, or as nearer to the human observer than surfaces with the weaker luminance contrast (Bugelski, 1967; Dresp *et al.*, 2002; Guibal and Dresp, 2004; O'Shea *et al.*, 1994; Oyama and Yamamura, 1960; Rohaly and Wilson, 1999; Schwartz and Sperling, 1983). Mutual interactions between colors in terms of assimilation and contrast may be linked to their capacity for generating effects of relative depth or, in other words, to the likelihoods that they will be perceived as belonging to the same or as belonging to different surfaces in the visual field (Long and Purves, 2003), a possibility that was not made explicit by Chevreul at the time.

The effect of frames on the appearance of tones and their brightness, or "the difference between the effect of a framed picture and the effect of that same picture when seen through an opening" was considered critical by Chevreul, who observed that the "contiguity of the frame" could alter any of the perceptual effects produced by any of his laws under conditions where no frame is present. His intuition that distinct object borders influence our perception of color and contrast is consistent with studies showing interactions between color appearance and the spatial profile of surface contours, or the geometric configuration of the visual display (Devinck *et al.*, 2006; De Weert and Spillmann, 1995; Dresp and Fischer, 2001; Fach and Sharpe, 1986; Pinna, 2008, 2011; Pinna and Reeves, 2006).

Here, we present a new kind of induction phenomenon where true colors in the sense of Chevreul, placed on grey background fields presented on a black screen, produce changes in the appearance of their immediate grey backgrounds (Fig. 1). When spatially distributed sets of small squares, all of the same color and darker on one side of the display and brighter on the other, are placed on spatially separated grey fields of homogenous intensity presented on a dark (black) screen, the grey background to the colors may be seen as brighter on one side. The induction can switch from contrast, where the grey field containing the darker inducers appears brighter, to assimilation, where the grey field containing the brighter inducers appears brighter. Such effects are absent when the grey background fields do

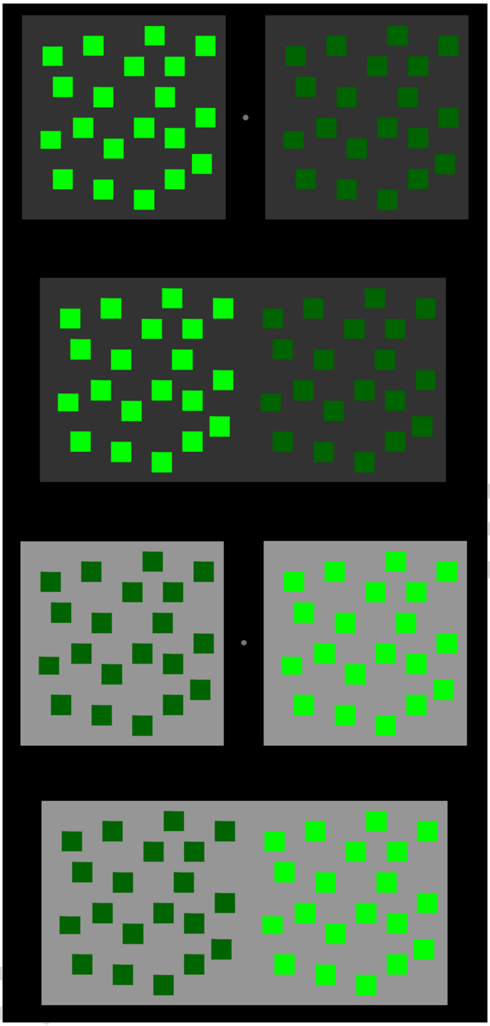

Figure 1. The stimulus configurations here consisted of patterns of colored inducers of a single color, with a brighter luminance on one side and a darker luminance on the other, placed on grey backgrounds. Background intensity varied between trials, between a lighter and a darker luminance, and backgrounds were presented as either spatially separate fields (top and lower middle) or as single fields (upper middle and bottom) placed on a uniformly darker screen. (This figure is published in colour in the online version of this paper.)

not contain any inducers at all (Fig. 2), or when the background fields consist of a single uniformly grey surface (Fig. 3). Conversely, when the green inducers of a stronger and a weaker luminance are placed on grey background fields of identical luminance which themselves have an even darker background, the colored squares produce simultaneous induction effects in terms of apparent contrast and assimilation, where the grey background on either side of the display may appear brighter

Figure 2. Two grey fields of identical luminance presented on a uniformly dark screen generally appear equal in brightness to the human observer, i.e. the probability of one being seen as brighter than the other is considered zero.

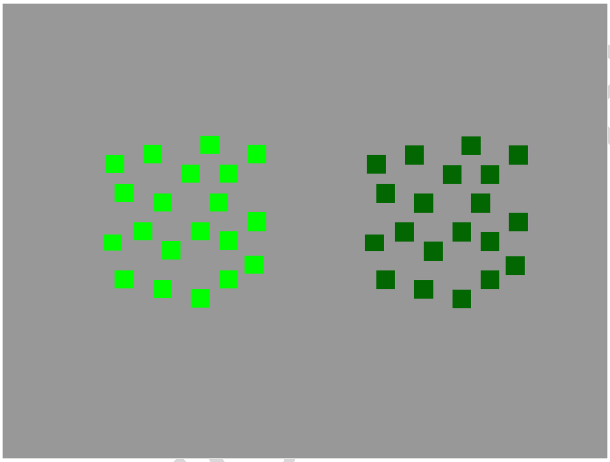

Figure 3. When the colored inducers are placed on a single uniformly grey background, the induction effects shown in Fig. 1, top and lower middle, are weakened or abolished, as in Fig. 1, upper middle and bottom. (This figure is published in colour in the online version.)

than on the other side (Fig. 1, top). When two grey backgrounds are grouped into a single one on a dark screen, they are then seen as if surrounded by a single dark frame. The simultaneous induction effects are considerably weakened or abolished in such a configuration (Fig. 1, upper middle), which closely approaches the example shown in Fig. 3. Changes in inducer contrast do not seem to affect the induction effects (Fig. 1, lower middle and bottom), but alter the perception of relative depth in a way that is consistent with Chevreul's law of contrast. Brighter squares tend to be seen as standing out in front of the grey backgrounds, while darker ones tend to be seen in the same plane with the background. Grouping the backgrounds into a single one (Fig. 1, upper middle and bottom) does not appear to change this apparent depth effect.

To quantify this new phenomenon, we presented several such configurations with colored inducers on grey generating varying inducer luminance contrasts, investigating their probability of producing brightness induction effects in terms of contrast and assimilation. Given that such induction effects often occur together with changes in the perceived depth of either the inducing field or the test field, as in the watercolor illusion (e.g. Pinna and Reeves, 2006; von der Heydt and Pierson, 2006), we compared probabilities of simultaneous induction with the probabilities that the patterns which generate them are seen as nearer to the observer. In fact, inducers with a stronger tendency to be perceived as separated in depth from their immediate backgrounds may also have a stronger tendency to produce induction effects in terms of apparent contrast. This assumption relates to a theoretical framework that searches for a universal explanation of color context effects in terms of statistical properties of natural scenes. Similarly toned, with regard to either luminance or color or both, objects would have a tendency to generate assimilation because they would have a higher probability of belonging to the same surface and, therefore, to lie in the same depth plane. Strongly contrasting ones would have a tendency to generate contrast because they would be more likely to belong to different surfaces and, therefore, to lie in different depth planes (e.g. Katz, 1911; Long and Purves, 2003). If such a prediction holds, then a strong positive correlation between the luminance contrast of colored objects, the apparent contrast effects induced by these objects, and their perceived depth is to be expected.

The induction effects produced by the complex spatial configurations displayed here are likely to originate from mechanisms of neural processing well beyond the receptor level (e.g. De Weert and Spillmann, 1995; Dresp and Fischer, 2001; Long and Purves, 2003). The relative contributions of rods and cones determines both the appropriate luminance input (photopic or mesopic) and the input stream to the visual cortex. Also, color and luminance may be affected by rod-cone interactions at the low brightness levels typical of computer monitors (e.g. Cao *et al.*, 2008; Stabell and Stabell, 1975). To assess the contribution of rods relative to that of cones, we tested observers under three different conditions of light-dark adaptation, in both experimental tasks.

2. Materials and Methods

Experiments were run on a PC computer equipped with a mouse device and a high resolution color monitor. Selective combinations of RGB increments generating the colors of the stimuli were calibrated with a spectrophotometer (Cambridge Research Instruments). Subjects were seated at a distance of 75 cm from the screen, their heads comfortably resting on a head-and-chin support.

2.1. Subjects

Eight observers, most of them students at NU, with normal or corrected-to-normal vision and fully functional color vision were run in the simultaneous contrast task. Eight observers, most of them also students at NU, with normal or corrected-to-normal vision and fully functional color vision, were run in the relative distance task. Three of the sixteen subjects were run in both tasks.

2.2. Stimuli

The stimuli (see Fig. 1A, B, C and D for illustration) consisted of pairs (as in Fig. 1, top and lower middle), the spatially separated configurations, or singles, the regrouped configurations (as in Fig. 1, upper middle and bottom). Colored inducers were placed on light grey and dark grey background fields, displayed on the considerably darker (5.45 cd/m^2, with the color guns of the screen at $R = 0$, $G = 0$ and $B = 0$) background of the computer screen. Twenty small squares, the so-called inducers, of a given color were placed on the darker (Fig. 1, lower middle and bottom) and lighter grey immediate backgrounds (Fig. 1, top and upper middle) backgrounds. Five different inducer colors were generated (red, green, blue, yellow, and white) in different configurations, with always the same color in a given configuration. The luminance of red inducers was 56.7 cd/m^2 for the brighter ones (color guns of the screen at $R = 255$, $G = 0$, $B = 0$) and 27.2 cd/m^2 for the darker ones ($R = 100$, $G = 0$, $B = 0$). Green inducers were displayed at 69.8 cd/m^2 ($R = 0$, $G = 255$, $B = 0$) and 27.7 cd/m^2 ($R = 0$, $G = 100$, $B = 0$), blue inducers at 70.9 cd/m^2 ($R = 0$, $G = 0$, $B = 255$) and 44.3 cd/m^2 ($R = 0$, $G = 0$, $B = 125$) yellow inducers at 81.6 cd/m^2 ($R = 255$, $G = 255$, $B = 0$) and 43.7 cd/m^2 ($R = 100$, $G = 100$, $B = 0$), and grey inducers at 148.6 cd/m^2 ($R = 190$, $G = 190$, $B = 190$) and 54.3 cd/m^2 ($R = 100$, $B = 100$, $G = 100$). The luminance of the light grey background was 72.7 cd/m^2 ($R = 150$, $G = 150$, $B = 150$), the luminance of the dark grey background was 23.2 cd/m^2 ($R = 50$, $G = 50$, $B = 50$). Inducers were always darker on one side of the display, and brighter on the other in a given trial. The intensity of their grey backgrounds varied between trials only. Combining inducing patterns with two luminance intensities with the light and dark grey backgrounds produced four different inducer contrasts for each color. Table 1 gives these inducer contrasts, expressed in terms of $(\mathrm{L}_{\text{inducer}} - \mathrm{L}_{\text{background}})/(\mathrm{L}_{\text{inducer}} + \mathrm{L}_{\text{background}})$, for a given color with a given luminance on a background of a given intensity. Brighter inducers appeared on the left and on the right of a given configuration in random order, with always a set of darker inducers on the other side. The horizontal distance between two spatially separated squares on the screen was 3.5 cm. The height of each such square was 9.7 cm, the width 10 cm. The height of regrouped grey backgrounds was 9.7 cm, their width 13.2 cm. Each type of configuration was displayed centrally on the screen. The smallest horizontal distance between colored inducers was 0.4 cm, the smallest vertical distance 0.5 cm. All colored inducers had identical height (0.9 cm) and width (1 cm).

2.3. Task Instructions

Three response alternatives ('left', 'right' or 'same') were given to subjects in each of the two tasks. In the simultaneous contrast task, they were asked to indicate on which side of a given configuration ('left' or 'right') the grey background appeared brighter to them, or whether both sides appeared equal in brightness ('same'). It was made clear to the subjects that they should judge the relative brightness of the background, not that of the inducers. In the relative distance task, subjects had to

Table 1.
The configurations of colored inducers on light and dark grey backgrounds, used as stimuli in the experiments here, generated four inducer contrasts of varying intensity and polarity for each color, expressed here in terms of $(L_{\text{inducer}} - L_{\text{background}})/(L_{\text{inducer}} + L_{\text{background}})$. These contrasts and their sign (negative or positive) are given here, for each inducer color, inducer luminance (a higher one and a lower one), and background intensity (light grey and dark grey)

	Red	Green	Blue	Yellow	Achromatic
The brighter inducer					
on dark grey background	+0.42	+0.50	+0.51	+0.56	+0.72
on light grey background	−0.12	−0.02	−0.01	−0.06	+0.34
The darker inducer					
on dark grey background	+0.08	+0.09	+0.31	+0.31	+0.40
on light grey background	−0.45	−0.44	−0.24	−0.25	−0.14

decide on which side of a given configuration (‘left’ or ‘right’) the colored inducers appeared nearer to them, or whether all seemed equally near or distant (‘same’).

2.4. Procedure

The experiments were run in a room with no windows, under three separate conditions of visual adaptation. In the first (‘daylight’), subjects were run under conditions similar to daylight, generated by diffuse, soft-white, 60 W tungsten light (General Electric). In the second condition (‘dark-adapted’ observers), subjects were dark-adapted for 25 min and then tested with all room lights off. The only illumination was provided by the screen. In the third condition (‘rod-saturated’ observers), subjects were pre-exposed to an intense, full-field, white adaptation light from a model PS22 Grass Photonic Stimulator run at 45 Hz, which was progressively intensified to 1 500 000 candelas, where it was held before the subject’s open eyes for one minute. Subjects were then dark-adapted for two minutes to permit cones to recover, but leave rods relatively inactive for the next ten to fifteen minutes, knowing that a given set of experimental trials for a given adaptation level lasted for about three to five minutes. In each of these conditions, the grouped and ungrouped configurations with a given background intensity and inducer color were presented in random order for about one second each. Inter-stimulus intervals typically varied from one to three seconds and were placed under the control of the subject to allow for individually experienced after-images to vanish before the next trial was initiated. Subjects were instructed to fixate the center of the screen and to blink between trials to check for residual after-images, which were especially noticeable in the dark adapted condition, in which a few subjects took as long as six seconds between trials to recover (after-images were rarely experienced in the daylight and rod-saturated conditions). In stimulus displays with spatially separated backgrounds, a small, dim fixation mark was displayed in the center of the screen (as shown in Fig. 1, top and upper middle) to remind subjects where to look, and between stimulus presentations, subjects were exposed to a uniformly dark ($5.45\ \mathrm{cd/m^2}$) screen, with the fixation mark still displayed in the center. They were allowed to break fixation and look left or right when comparing two backgrounds. Each individual session consisted of 40 trials per adaptation level, giving a total of 120 trials per subject within a 3 × 4 × 2 × 5 experimental design, with three adaptation levels, four inducer contrasts, two types of spatial configuration, and five colors.

3. Results

The data from the two tasks were analyzed as a function of adaptation level, inducer contrast, spatial configuration ('grouped fields' *versus* 'separate fields'), and inducer color. Probabilities of inducers of a given color to produce effects of apparent contrast, assimilation, and relative depth were computed for each experimental condition and subjected to repeated measures analyses of variance (ANOVA). Given that the levels of the factor inducer contrast were not identical for different colors (see Table 1), separate ANOVA were performed for each level of the color factor and a 3 × 4 × 2 factorial design, with three levels of the adaptation factor, four levels of inducer contrast, and two levels of spatial configuration. Average results, summed over the adaptation level factor, will be shown here for each inducer color given that no significant effect of visual adaptation, or interaction of this factor with inducer contrast or type of spatial configuration, was found with inducers of any of the four colors studied here. Only the achromatic configurations varied significantly with conditions of visual adaptation, as will be shown here.

The probabilities of GREEN inducers to produce effects of apparent contrast, assimilation, or relative depth ('nearness') are shown as a function of the luminance contrast of the inducers (Fig. 4, top left). Green inducers systematically generated higher probabilities of assimilation compared with probabilities of contrast, at all levels of inducer contrast. Effects of the luminance contrast of green inducers on either the probability of assimilation or the probability of apparent contrast are not statistically significant. Conversely, the effect of inducer contrast on the probability of green inducers to be seen as nearer to the observer is highly significant ($F(3, 23) = 45.12$, $p < 0.001$). Inducers with the strongest positive luminance contrast produced the highest probability to be seen as nearer. The probabilities of 'near' generated by green inducers reveal an asymmetry between negative and positive contrast signs, where green inducers of negative contrast (here $\mathrm{C} = -0.02$ and $\mathrm{C} = -0.44$) failed to produce an effect of relative depth, while roughly equivalent positive contrasts (here $\mathrm{C} = +0.09$ and $\mathrm{C} = +0.50$) produced probabilities of 'near' between 0.75 and 0.90. Grouping the backgrounds into a single field had no significant effect on probabilities of relative depth (Fig. 4, top right), but significantly influenced induction effects, in terms of contrast ($F(1, 23) = 82.33$, $p < 0.001$). Induction effects are significantly stronger, producing higher probabilities of apparent contrast, in configurations where the background fields are spatially separated

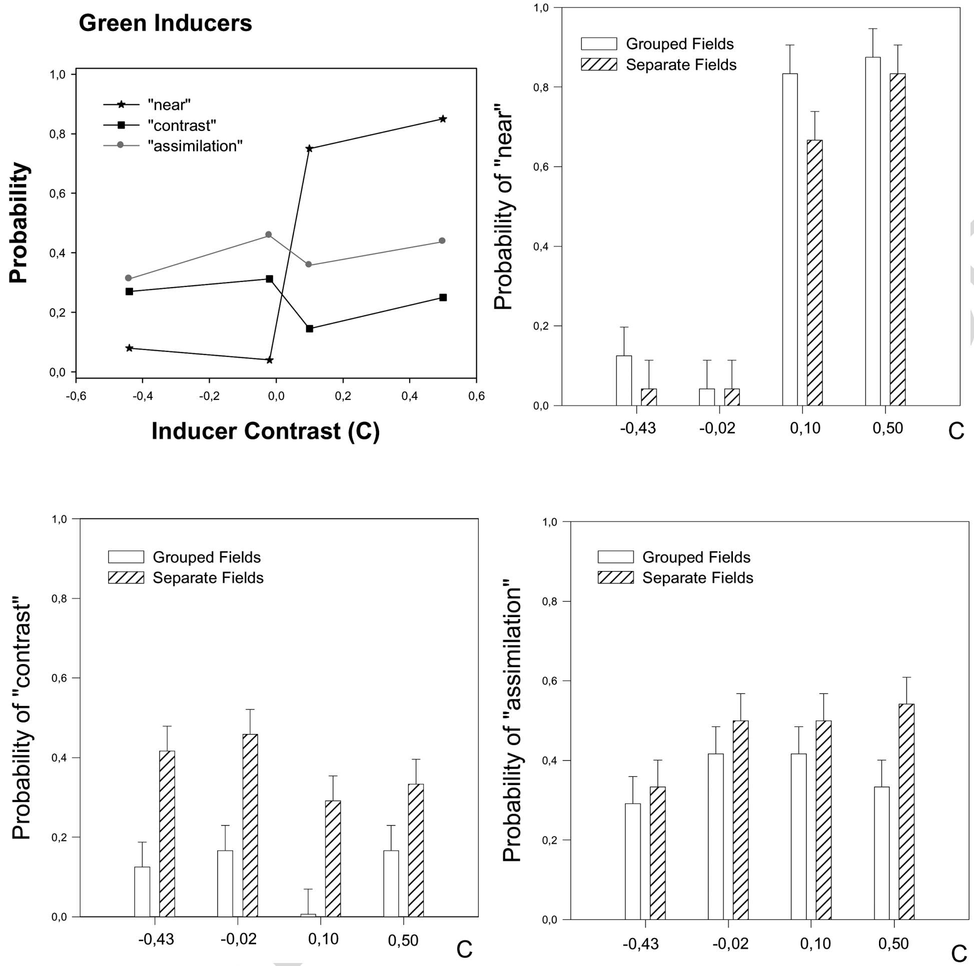

Figure 4. Probabilities of contrast, assimilation, and relative depth (‘near’), averaged over the adaptation level factor, are shown as a function of the luminance contrast of the GREEN inducers and the type of background configuration.

(Fig. 4, bottom left). The effect of grouping on assimilation tends in the same direction, but was not statistically significant for the green inducers (Fig. 4, bottom right). There is no significant interaction between grouping and the luminance contrast of the green inducers.

The probabilities of BLUE inducers to produce effects of apparent contrast, assimilation, or relative depth (‘nearness’), as a function of the luminance contrast of the inducers, are shown next (Fig. 5, top left). As observed with the green inducers, blue inducers also systematically generated higher probabilities of assimilation compared with probabilities of contrast, at all levels of inducer contrast. Effects of the luminance contrast of blue inducers on either the probability of assimilation or the probability of apparent contrast are not statistically significant. Interestingly, the

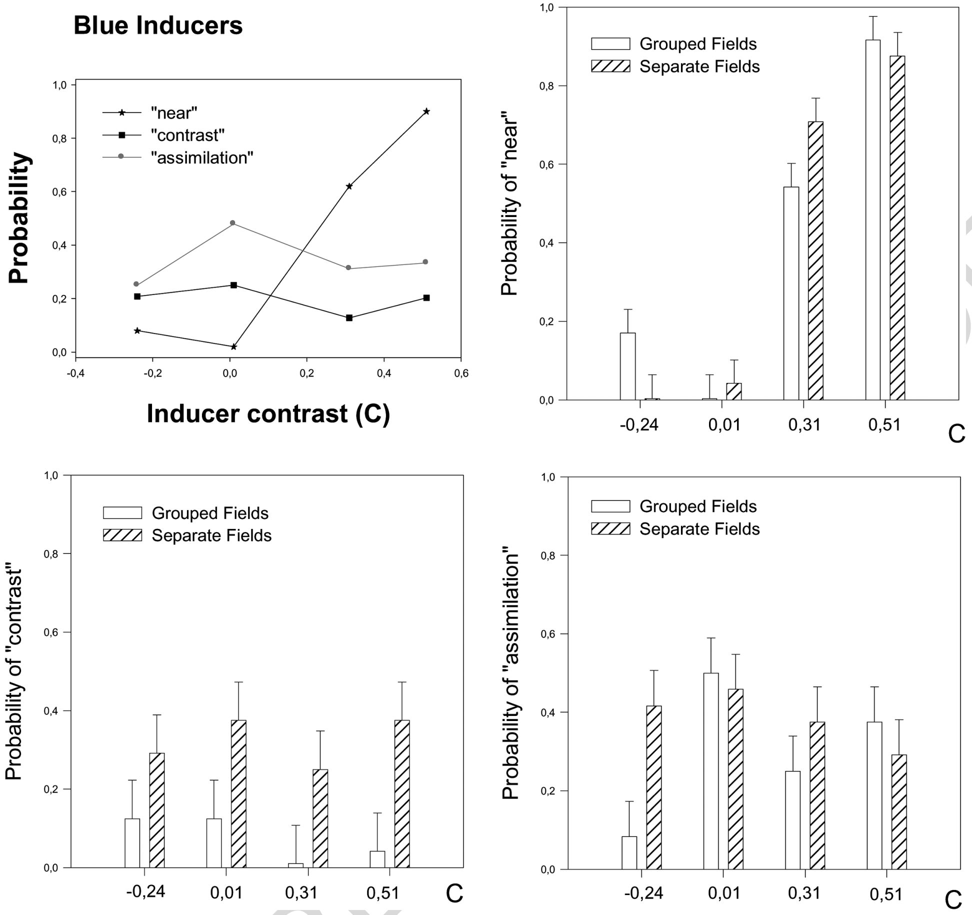

Figure 5. Probabilities of contrast, assimilation, and relative depth (‘near’), averaged over the adaptation level factor, are shown as a function of the luminance contrast of the BLUE inducers and the type of background configuration.

blue inducers with zero luminance contrast (equiluminant color contrast) produced the strongest induction effects, in terms of summed probabilities of assimilation and apparent contrast (P ‘assimilation’ + P ‘contrast’ = 0.78), but the lowest probability of standing out in depth from the background (P ‘near’ = 0.09). The effect of inducer contrast on the probability of inducers to be seen as nearer to the observer is, again, highly significant ($F(3, 23) = 77.86$, $p < 0.001$). Inducers with the strongest positive luminance contrast produced the highest probability to be seen as nearer. The probabilities of ‘near’ generated by blue inducers reveal the same kind of asymmetry between negative and positive contrast signs observed with the green inducers, where blue inducers of negative contrast (here C = −0.24) failed to produce an effect of relative depth, while similar positive contrasts (here C = +31 or C = +0.51) produced probabilities of ‘near’ between 0.60 and 0.90. Group-

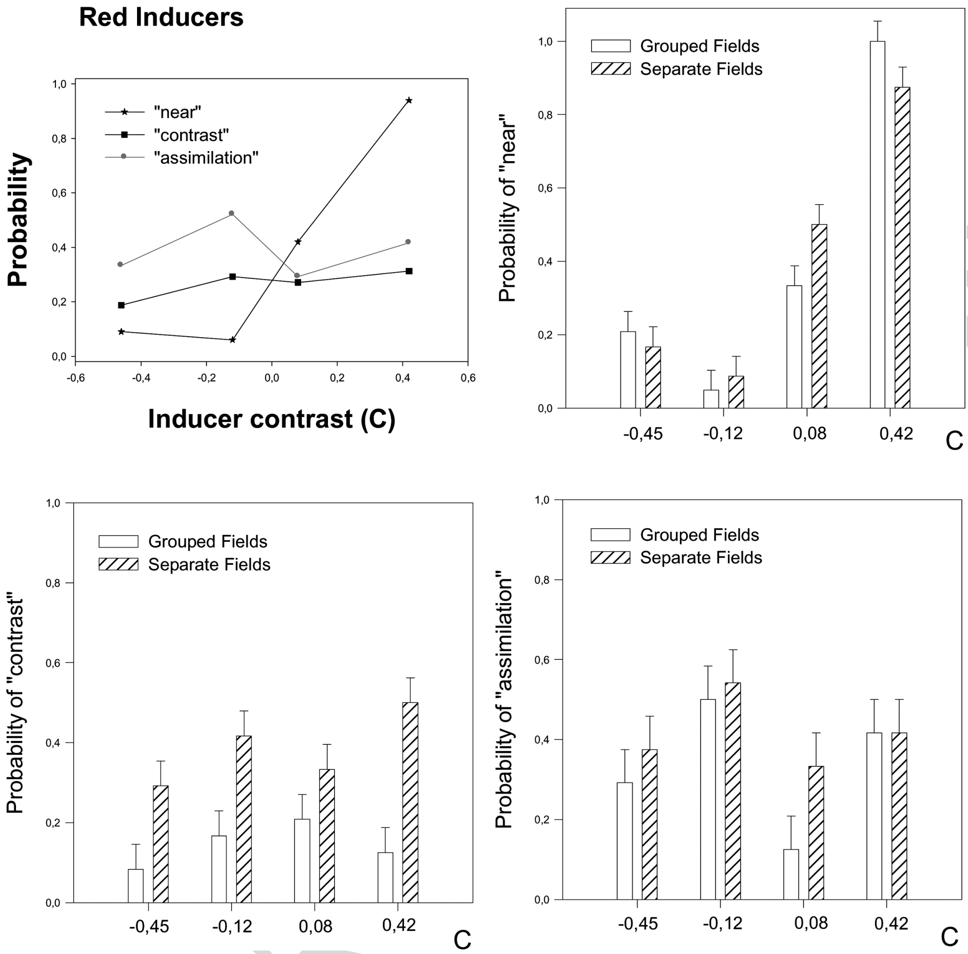

Figure 6. Probabilities of contrast, assimilation, and relative depth ('near'), averaged over the adaptation level factor, are shown as a function of the luminance contrast of the RED inducers and the type of background configuration.

ing the backgrounds into a single field had no significant effect on probabilities of relative depth (Fig. 5, top right), but significantly influenced induction effects in terms of apparent contrast ($F(1, 23) = 24.33$, $p < 0.01$). In configurations where the background fields are spatially separated, the probabilities of apparent contrast are significantly higher (Fig. 5, bottom left). As with the green inducers, the effect of grouping on assimilation was not statistically significant for the blue inducers (Fig. 5, bottom right). Again, there was no significant interaction between grouping and the luminance contrast of the inducers.

The probabilities of RED inducers to produce effects of apparent contrast, assimilation, or relative depth ('nearness'), as a function of the luminance contrast of the inducers, are shown next (Fig. 6, top left). As observed with green and blue, red inducers also systematically generated higher probabilities of assimilation compared with probabilities of contrast, at all levels of inducer contrast. Effects of the luminance contrast of red inducers on either the probability of assimilation or the probability of apparent contrast are not statistically significant. The effect of inducer contrast on the probability of inducers to be seen as nearer to the observer is, again, highly significant ($F(3, 23) = 58.18$, $p < 0.001$). Inducers with the strongest positive luminance contrast produced the highest probability to be seen as nearer. The probabilities of 'near' generated by red inducers reveal the same kind of asymmetry between negative and positive contrast signs observed with the green and blue inducers, with red inducers of negative contrast (here $\mathrm{C} = -0.45$) producing only a weak effect of relative depth, while similar positive contrasts (here $\mathrm{C} = +0.42$) produced probabilities of 'near' higher than 0.90. Grouping the backgrounds into a single field had no significant effect on probabilities of relative depth (Fig. 6, top right), but significantly influenced induction effects in terms of apparent contrast ($F(1, 23) = 24.33$, $p < 0.01$). In configurations where the background fields are spatially separated, the probabilities of apparent contrast are significantly higher (Fig. 6, bottom left). Again, the effect of grouping on assimilation was not statistically significant (Fig. 6, bottom right), and there was no significant interaction between grouping and the luminance contrast of the inducers.

The response probabilities generated by the YELLOW inducers are shown next (Fig. 7, top left). As observed with the green, blue, and red inducers, yellow inducers also systematically generated higher probabilities of assimilation compared with probabilities of contrast, at all levels of inducer contrast. Effects of the luminance contrast of yellow inducers on either the probability of assimilation or the probability of apparent contrast are not statistically significant. Again, it is shown that inducers with a luminance contrast near physical equiluminance (here $\mathrm{C} = 0.06$) produced the strongest induction effects, in terms of summed probabilities of assimilation and apparent contrast (P 'assimilation' + P 'contrast' = 0.79), but the weakest probability of standing out in depth from the background (P 'near' = 0 here). The effect of inducer contrast on the probability of inducers to be seen as nearer to the observer is, again, highly significant ($F(3, 23) = 36.29$, $p < 0.001$). Inducers with the strongest positive luminance contrast produced the highest probability to be seen as nearer. The probabilities of 'near' generated by yellow inducers reveal the same kind of asymmetry between negative and positive contrast signs observed with green blue and red inducers. Yellow inducers of negative contrast (here $\mathrm{C} = -0.25$) produced no effect of relative depth here, while a similar positive contrast (here $\mathrm{C} = +0.31$) produced a probability of 'near' higher than 0.80. Grouping the backgrounds into a single field had no significant effect on probabilities of relative depth (Fig. 7, top right), but significantly influenced induction effects in terms of apparent contrast ($F(1, 23) = 17.02$, $p < 0.01$). In configurations where the background fields are spatially separated, the probabilities of apparent contrast are significantly higher (Fig. 7, bottom left). Again, the effect of grouping on assimilation tends in the same direction, but was not statistically significant (Fig. 7,

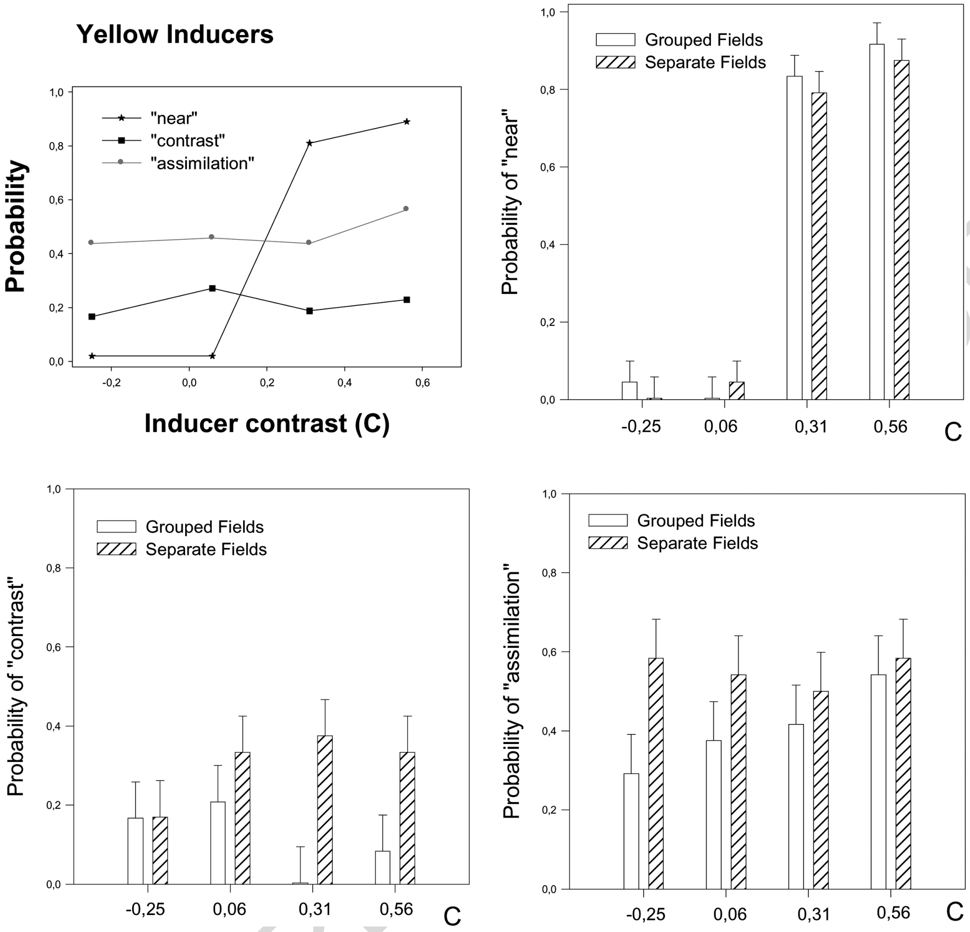

Figure 7. Probabilities of contrast, assimilation, and relative depth (‘near’), averaged over the adaptation level factor, are shown as a function of the luminance contrast of the YELLOW inducers and the type of background configuration.

bottom right). Again, there was no significant interaction between grouping and the luminance contrast of the inducers.

The probabilities of ACHROMATIC inducers to produce induction effects were markedly influenced by the visual adaptation conditions, with significant effects of adaptation level on probabilities of apparent contrast ($F(2, 23) = 5.46$, $p < 0.05$) and on probabilities of assimilation ($F(2, 23) = 10.50$, $p < 0.01$). Probabilities of achromatic inducers to produce effects of apparent contrast, assimilation, or relative depth (‘nearness’) are shown as a function of the luminance contrast of the inducers and the adaptation level (Fig. 8). Achromatic inducers produce the highest probabilities of apparent contrast in dark-adapted observers, and the lowest probabilities of apparent contrast in daylight, while the reverse is observed for assimilation, with the highest probabilities of assimilation in daylight and the lowest after dark-adaptation

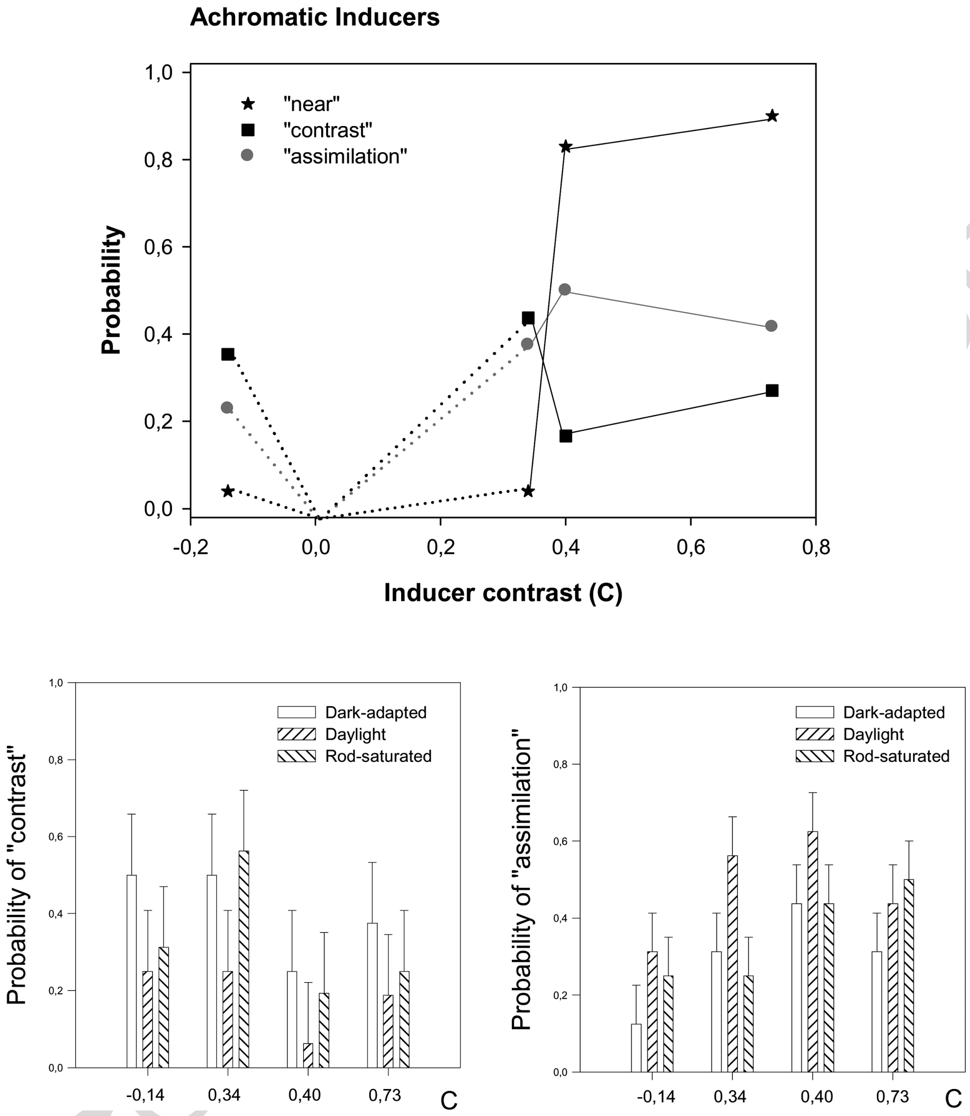

Figure 8. Probabilities of contrast, assimilation, and relative depth (‘near’) are shown as a function of the luminance contrast of the ACHROMATIC inducers (top) and the adaptation level (bottom). The dotted lines in the graph on top suggest the theoretical drop to zero of all effects at physical equiluminance of achromatic inducers and backgrounds (see Fig. 1).

(Fig. 8, bottom). The luminance contrast of the achromatic inducers had a significant effect on induction, in terms of apparent contrast ($F(3, 23) = 4.47$, $p < 0.05$) and in terms of assimilation ($F(3, 23) = 11.09$, $p < 0.01$). For a luminance contrast of negative sign (here $\mathrm{C} = -0.14$), the probability of apparent contrast is higher than the probability of assimilation, while the reverse is found to hold for strong inducer contrasts of positive sign. The effect of inducer contrast on the probability of inducers to be seen as nearer to the observer is, again, highly significant ($F(3, 23) = 32.95$, $p < 0.001$). Inducers with the strongest positive luminance contrasts produced the highest probability to be seen as nearer. Adaptation level had no significant effect on perceived relative depth. No significant interaction between adaptation level and inducer contrast was found for any of the three dependent variables. Grouping the backgrounds into a single field had no significant effect on probabilities of relative depth (Fig. 8, top), but significantly influenced induction effects in terms of apparent contrast ($F(1, 23) = 17.02$, $p < 0.01$). In configurations where the background fields are spatially separated, the probabilities of apparent contrast are significantly higher (Fig. 8, middle). As with the colored inducers, the effect of grouping on assimilation is not statistically significant in configurations with achromatic inducers (Fig. 8, bottom). Again, there was no significant interaction between grouping and the luminance contrast of the inducers.

Interestingly, green and yellow inducers with a low luminance contrast of positive sign (Figs 4 and 7, upper left) produced noticeably stronger depth effects than red inducers with a low luminance contrast of positive sign (Fig. 6, upper left). Otherwise, there are no noticeable differences between the different colors in terms of their probability to produce apparent contrast, assimilation, or relative depth effects, as shown here when the probabilities, averaged over the adaptation level and inducer contrast factors, are plotted as a function of the inducer color and type of background configuration (Fig. 10).

4. Discussion

Repetitive patterns of a single color placed on achromatic backgrounds of a lighter and a darker tone induce simultaneous contrast effects where the background's brightness may be altered either towards apparent contrast or towards assimilation. The observation that perception can switch from one to the other in one and the same configuration is consistent with psychophysical data on achromatic configurations of positive and negative contrast polarities (Beck, 1966; Hamada, 1985; Heinemann, 1955; Helson, 1963), sometimes described in terms of a 'brightness paradox' (De Weert and Spillmann, 1995). These effects have been interpreted in terms of non-linear spatial interactions, and their potential neural origins, ensuring the discounting of changes in global illumination to facilitate the perception of complex objects under variable lighting conditions (Gerrits and Vendrik, 1970; Grossberg, 1997; Reid and Shapley, 1988; Shapley and Reid, 1985). Such an interpretation is fully consistent with our observations here, and accounts well for the insensitivity of the simultaneous induction effects to either visual adaptation or luminance contrast of the colored inducing patterns. Roughly equiluminant chromatic inducers often produced the strongest brightness induction on their grey backgrounds, with systematically more assimilation than contrast, as previously found in other geometrically complex displays (Wyszecki, 1986). We conclude that chromatic patterns, regardless of their luminance contrast and under any condition of

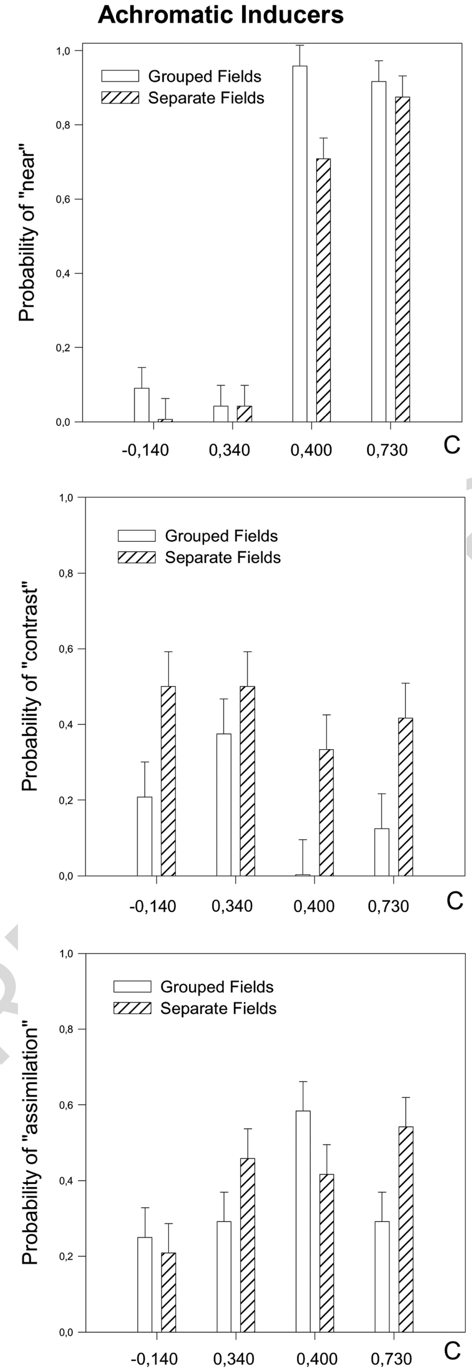

Figure 9. Probabilities of contrast, assimilation, and relative depth (‘near’) are shown as a function of the luminance contrast of the ACHROMATIC inducers (top) and the type of background configuration (bottom).

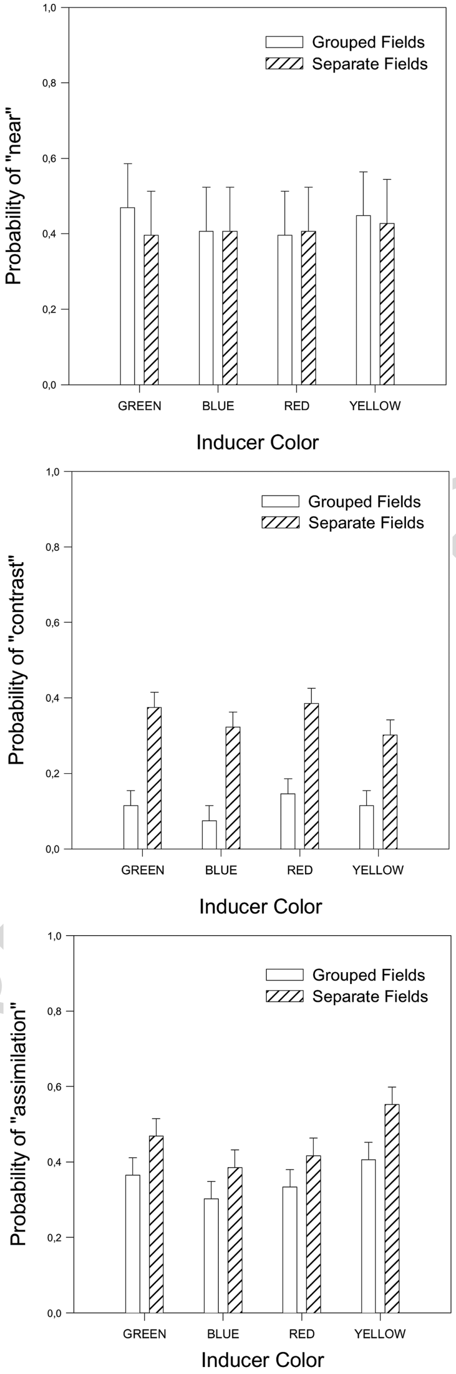

Figure 10. Probabilities of contrast, assimilation, and relative depth (‘near’), averaged over the adaptation level and the inducer contrast factors, are shown as a function of the color of the inducers and the type of background configuration.

light-dark adaptation of the eye, alter the appearance of achromatic backgrounds by producing unsuspected ‘paradoxical’ (e.g. De Weert and Spillmann, 1995) changes in their perceived intensity. These observations shed a new light on Chevreul’s law of ‘true’ color, bearing in mind that it is based on the idea of an absence of mutual interaction between color and grey. Here we show that colored patterns may have an either suppressive or enhancing effect on the perceived brightness of their immediate grey backgrounds when these latter are placed on an even darker general background. At or near physical equiluminance with the grey backgrounds, colors produced effects similar or identical to those of colors with strong luminance contrasts. Significant variations in either assimilation or contrast as a function of the luminance contrast of a given color were not found.

We are confident that individual differences in equiluminance, although we did not measure them, had little or no effect on our results as the average psychophysical equiluminance for ten or more subjects, selected from the same population as in this study, approaches physical equiluminance (Dresp and Fischer, 2001; Guibal and Dresp, 2004), and differences at the threshold level are unlikely to be relevant here. Configurations with spatially separated background fields, where the inducers are seen as belonging to two different visual objects separated by a gap in the middle, produced significantly higher probabilities of apparent contrast compared with the regrouped configurations, where inducers and background form a single object. Here, we observe that the grey object surfaces separated by the wide gap in the middle have a significantly higher probability to induce apparent contrast. Devinck *et al.* (2006) observed a significant increase in assimilation in the watercolor illusion with increasing width of the contour separating the assimilated field from its surround. Such effects are the direct perceptual consequence of what Chevreul called “the contiguity of the frame”, which he believed could destroy or alter the perception of any attribute of a scene when observed “without the frame”. Visual configurations may thus be seen as pictures, hung side by side when separated by distinct borders, or unified into a single one when the backgrounds are regrouped. Chevreul’s concept points towards a structural analysis of visual configurations at higher levels of perceptual and cognitive processing. Object borders and pattern contours have previously been found to influence induction effects, produced by colors or achromatic surfaces, in often unsuspected ways (Devinck *et al.*, 2006; De Weert and Spillmann, 1995; Dresp, 1992; Dresp and Fischer, 2001; Grossberg, 1997; Pinna, 2008; von der Heydt and Pierson, 2000) and no single explanation suffices to account for them all. Given the insensitivity of the brightness induction effects produced by the colors here to adaptation levels and luminance contrast, low-level explanations in terms of critical interactions at the receptor levels can be safely excluded.

In marked contrast with the induction effects produced by colors, the effects generated by achromatic inducers, in terms of either contrast or assimilation, were found to vary significantly with the luminance contrast of the inducers and the visual adaptation level, with apparent contrast being the strongest after dark-adaptation, assimilation the strongest under daylight conditions. This may suggest that the simultaneous induction effects produced by the achromatic inducing patterns arise at different levels of visual processing than the induction effects produced by the colored patterns. While these latter are likely to involve complex interactions between chromatic and achromatic visual pathways (e.g. Hong and Blake, 2009), the induction effects produced by grey inducers would involve only the achromatic pathways, or the contrast sensitive on-center-off-center pathways of the brain. Interestingly, with achromatic inducers on grey backgrounds, the probability of contrast was found to be higher than the probability of assimilation when inducer contrasts bear a negative sign, while the reverse holds for inducer contrasts of positive sign. This observation is reminiscent of conclusions from earlier experiments by Magnussen and Glad (1975) on brightness and darkness enhancement during flicker assessed by human observers and their potential neural correlates, assessed on the basis of firing activities in the contrast selective on-center-off-center pathways of cat cortex. Functional asymmetries for contrasts of negative and positive sign consistent with our observations were found, originating in the retina and communicated to visual cortex through ‘straight-through’ neural pathways. Contrast-sensitive asymmetries in the processing of visual objects of negative and positive sign (see also Dresp and Langley, 2005) have been reported in various earlier studies. Many of these results have remained unexplained (see McCormick *et al.*, 2012, for a deeper analysis).

Although the bright inducers with the highest luminance contrasts are the most likely to be seen as nearer, they turn out to be the most unlikely to induce apparent contrast effects. Yet, a strong positive correlation between apparent contrast and relative inducer depth is to be expected if a direct functional link between such induction effects and the relative depth of inducing and test surfaces in the visual field exists, as suggested by Long and Purves (2003) or, a century ago, by Katz (1911). We find, instead, that the perceived relative distance of inducers appears to be independent of the induction effects they produce in terms of either apparent contrast or assimilation. The perception of the relative distance of the colored inducing patterns is determined solely by their luminance contrast under conditions where no cues to depth are made available, as predicted by Chevreul’s law of contrast. However, in our experiments here the law only holds for contrasts of a strong positive sign. Colors with luminance contrasts of a strong negative sign did not generate strong probabilities to be perceived as nearer. This may be explained if the three surface planes in the visual field (as here in Fig. 1) compete for perceptual organization into foreground and background. Given that the general background of the screen is always darker than the immediate background fields of the inducers (as here in Fig. 1), inducers with a strong negative sign may generate some probability of belonging to that darker general background, of lying behind their immediate inducing fields, in other words. Post-experimental discussions with the subjects revealed that some of them had, indeed, the feeling that “sometimes the darker inducers seemed to lie behind their background fields”. With two surface planes only (as here in Fig. 3), this ambiguity disappears, and competition for perceptual organization predicts that inducers of strong and equivalent negative and positive contrast signs will generate equal likelihoods to be perceived as nearer to the observer than inducers with weaker contrasts. Simultaneous induction effects, however, are unlikely with the two-surface displays, as indicated by our results with the regrouped background fields. These considerations deserve attention in further research.

Also, the tendency of red inducers with a low luminance contrast of positive sign to produce weaker depth effects than green and yellow inducers with a low luminance contrast of a positive sign calls for further testing. Additional experiments with a tighter sampling of inducer contrasts in the lower positive range would be needed to help determine whether a particular effect of low contrast green and yellow exists in the perceptual genesis of relative depth of chromatic inducers with weak positive luminance contrast. The effects reported here are insensitive to visual adaptation levels. They definitely do not involve chromatostereopsis (e.g. Dengler and Nitschke, 1993; Simonet and Campbell, 1990), as we chose configurations where the chromatic or wavelength characteristics of the stimuli were always constant in a given display, only the luminance contrast of the inducers varied.

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References

Beck, J. (1966). Contrast and assimilation in lightness judgments, *Percept Psychophys.* **1**, 342–344.

Bugelski, B. R. (1967). Traffic signals and depth perception, *Science* **157**, 1464–1465.

Cao, D., Pokorny, J., Smith, V. C. and Zele, A. J. (2008). Rod contributions to color perception: linear with rod contrast, *Vision Research* **48**, 2586–2592.

Chevreul, Michel Eugène (1839). *De la loi du contraste simultané des couleurs et de l'assortiment des objets colorés*. Translated into English by J. Spanton as *The Laws of Contrast of Color* (1854). Lightning Source, Milton Keynes, UK.

Dengler, M. and Nitschke, W. (1993). Color stereopsis: a model for depth reversals based on border contrast, *Percept. Psychophys.* **53**, 150–156.

Desimone, R. and Schein, S. J. (1987). Visual properties of neurons in area V4 of the macaque: sensitivity to stimulus form, *J. Neurophysiol.* **57**, 835–868.

Devinck, F., Spillmann, L. and Werner, J. S. (2006). Spatial profile of contours inducing long-range color assimilation, *Vis. Neurosci.* **23**, 573–577.

De Weert, C. M. M. (1984). The role of colors in the formation of subjective contours, *Psycholog. Res.* **45**, 117–134.

De Weert, C. M. M. and Spillmann, L. (1995). Assimilation: asymmetry between brightness and darkness? *Vision Research* **35**, 1413–1419.

Dresp, B. (1992). Local brightness mechanisms sketch out surfaces but do not fill them in: psychophysical evidence in the Kanizsa square, *Percept. Psychophys.* **52**, 562–570.

Dresp, B. and Fischer, S. (2001). Asymmetrical contrast effects induced by luminance and color configurations, *Percept Psychophys.* **63**, 1262–1270.

Dresp, B. and Langley, O. K. (2005). Long-range spatial integration across contrast signs: a probabilistic mechanism? *Vision Research* **45**, 275–284.

Dresp, B., Durand, S. and Grossberg, S. (2002). Depth perception from pairs of overlapping cues in pictorial displays, *Spatial Vision* **15**, 255–276.

Fach, C. and Sharpe, L. T. (1986). Assimilative hue shifts in color gratings depend on bar width, *Percept. Psychophys.* **40**, 412–418.

Festinger, L., Coren, S. and Rivers, G. (1970). Effect of attention on brightness contrast and assimilation, *Amer. J. Psychol.* **83**, 189–207.

Gerrits, H. J. M. and Vendrik, A. J. (1970). Simultaneous contrast, filling-in process and information processing in man's visual system, *Exper. Brain Res.* **11**, 411–430.

Grossberg, S. (1997). Cortical dynamics of three-dimensional figure–ground perception of two-dimensional figures, *Psycholog. Rev.* **104**, 618–658.

Guibal, C. R. C. and Dresp, B. (2004). Interaction of color and geometric cues in depth perception: When does 'red' mean 'near'? *Psycholog. Res.* **10**, 167–178.

Hamada, J. (1985). Asymmetric lightness cancellation in Craik–O'Brien patterns of negative and positive contrast, *Biolog. Cybernet.* **52**, 117–122.

Heinemann, E. G. (1955). Simultaneous brightness induction as a function of inducing and test-field luminance, *J. Exper. Psychol.* **50**, 89–96.

Helson, H. (1963). Studies of anomalous contrast and assimilation, *J. Optic. Soc. Amer.* **53**, 179–184.

Hong, S. W. and Blake, R. (2009). Interocular suppression differentially affects achromatic and chromatic mechanisms, *Attent. Percept. Psychophys.* **71**, 403–411.

Katz, D. (1911). Die Erscheinungsweisen der Farben und ihre Beeinflussung durch die individuelle Erfahrung, *Zeitschrift für Psychologie* **7**, 6–31.

Long, F. and Purves, D. (2003). Natural scene statistics as the universal basis for color context effects, *Proc. Nat. Acad. Sci. USA* **100**, 1519–1593.

Livitz, G., Yazdanbakhsh, A., Eskew, R. T. Jr. and Mingolla, E. (2011). Perceiving opponent hues in color induction displays, *Seeing and Perceiving* **24**, 1–17.

McCormick, M. C., Hon, A. J., Huang, A. E. and Altschuler, E. (2012). Contrast polarity preservation's role in perception: explained and unexplained stimuli, *Perception* **41**, 12–25.

Magnussen, S. and Glad, A. (1975). Temporal frequency characteristics of spatial interactions in human vision, *Exper. Brain Res.* **23**, 519–528.

O'Shea, R. P., Blackburn, S. G. and Ono, H. (1994). Contrast as a depth cue, *Vision Research* **34**, 1595–1604.

Oyama, T. and Yamamura, T. (1960). The effects of hue and brightness on depth perception in normal and color-blind subjects, *Psychologia* **3**, 191–194.

Pinna, B. (2008). A new perceptual problem: the amodal completion of color, *Vis. Neurosci.* **25**, 415–422.

Pinna, B. (2011). The organization of shape and color in vision and art. *Frontiers in Human Neuroscience* **5**, Article 104.

Pinna, B. and Reeves, A. (2006). Lighting, backlighting and the laws of figurality in the watercolor illusion, *Spatial Vision* **19**, 341–373.

Reeves, A., Amano, K. and Foster, D. H. (2008). Color constancy: phenomenal or projective? *Percept. Psychophys.* **70**, 219–228.

Reid, R. C. Jr. and Shapley, R. (1988). Brightness induction by local contrast and the spatial dependence of assimilation, *Vision Research* **28**, 115–132.

Rohaly, A. M. and Wilson, H. R. (1999). The effects of contrast on perceived depth and depth discrimination, *Vision Research* **39**, 9–11.

Schwartz, B. J. and Sperling, G. (1983). Luminance controls the perceived 3D structure of dynamic 2D displays, *Bull. Psychonom. Soc.* **17**, 456–458.

Shapley, R. and Reid, R. C. Jr. (1985). Contrast and assimilation in the perception of brightness, *Proc. Nat. Acad. Sci.* **82**, 5983–5986.

Shevell, S. K. and Kingdom, F. A. (2008). Color in complex scenes, *Ann. Rev. Psychol.* **59**, 143–166.

Stabell, U. and Stabell, B. (1975). The effect of rod activity on color matching functions, *Vision Research* **15**, 1119–1123.

Simonet, P. and Campbell, M. C. W. (1990). Effect of luminance on the directions of chromatostereopsis and transverse chromatic aberration observed with natural pupils, *Ophthalm. Physiolog. Optics* **10**, 271–279.

Von der Heydt, R. and Pierson, R. (2006). Dissociation of color and figure–ground effects in the watercolor illusion, *Spatial Vision* **19**, 323–340.

Wyszecki, G. (1986). Color appearance, in: *Handbook of Perception and Human Performance*. L. K. K. R. Boff and J. P. Thomas. *Sensory Processes and Perception Series, Vol. I*. J. Wiley and Sons, Chichester, UK.