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## **Colors on Grey: Chevreul's laws of contrast and depth**

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## **Abstract**

Chevreul (1839) predicted that a color on a grey background would be the least likely to produce mutual interactions altering the appearance of either (law of true color), and that its luminance contrast directly determines its likelihood to be seen as figure against the grey background (law of contrast). We show that such “true” colors produce unsuspected simultaneous brightness induction effects on their grey backgrounds, where assimilation and apparent contrast may occur in one and the same configuration. We examined the possible link between these induction effects and the perceived relative depth of colored and achromatic inducers as a function of their luminance contrast. In a first task, we measured probabilities of contrast, assimilation, and no effect in a three-alternative forced-choice procedure (background appears brighter on “left”, on “right”, or the “same”). Sets of 20 red, green, blue, yellow, and light grey, square-shaped inducers were placed on light and dark grey background fields. Inducers of a sole color, darker on one side of the display and brighter on the other, were shown on spatially separated backgrounds and on single fields of a given intensity. Background intensity varied between displays, generating five different levels of inducer contrast for each color, presented in random order. Experiments were run under three environmental conditions: dark-adaptation, daylight, and rod-saturation after exposure to bright light. While these had no significant influence on induction effects produced by colored inducers, we found that achromatic inducers produced significantly stronger contrast effects after dark-adaptation, and significantly stronger assimilation in daylight conditions. The luminance contrast of colored inducers did not influence the induction effects. Grouping two backgrounds into a single one was found to significantly increase probabilities of apparent contrast. Under the same conditions, we measured apparent depth effects in terms of probabilities of the inducers to be perceived as nearer to the observer on the left or right, or at the same distance. These were determined by luminance contrast only, with a marked asymmetry between negative and positive contrast signs, and with significantly higher probabilities of the brighter inducers to be seen as nearer, regardless of adaptation level or background grouping. It is concluded that the induction effects and the depth effects originate from different mechanisms. Having excluded all other cues to depth, we found that Chevreul’s law of contrast holds for strong luminance contrasts of positive sign.

## 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. Heinemann, 1955; Helson, 1963; Beck, 1966; Gerrits & Vendrik, 1970; Shapley & Reid, 1980; De Weert, 1984; De Weert & Spillmann, 1995; Dresch & Fischer, 2001; Pinna, 2008) or color context effects (e.g. Long & Purves, 2003; Shevell & Kingdom, 2008; Reeves, Amano, & Foster, 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 (1939) invoked in terms of a general 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, 1939, 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, Yazdanbakhsh, Eskew and Mingolla, 2001). 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 and 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. Heinemann, 1955; Helson, 1963; Beck, 1966; Festinger, Coren & Rivers, 1970, Hamada, 1985). Surprisingly, 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; Oyama & Yamamura, 1960; Schwartz & Sperling, 1983; Rohaly & Wilson, 1993; O'Shea, Blackburn, & Ono, 1994; Dresp, Durand, & Grossberg, 2002; Guibal & Dresp, 2004). Mutual interactions between colors in terms of assimilation and contrast may be linked to their capacity of 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 & 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 (Fach & Sharpe, 1986; Dresp & Fischer, 1992; De Weert & Spillmann, 1995; Devinck, Spillmann, & Werner, 2006; Pinna & Reeves, 2006; Pinna, 2008; 2011).

Here, we present a new kind of induction phenomenon where true colors in the sense of Chevreul, placed on grey fields, produce changes in the appearance of their achromatic backgrounds. When spatially distributed sets of small colored squares with two luminance intensities, darker on one side of the display and brighter on the other, are placed on grey fields of homogenous intensity, the background is systematically seen as brighter on one side. The induction can switch from contrast, where the background field containing the darker inducers appears brighter, to assimilation, where the background field containing the brighter inducers appears brighter. One example of such a configuration is shown here (Figure 1), with green inducers of a stronger and a weaker luminance placed on grey background fields of identical luminance, either divided into two separate fields or grouped into a single 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 than on the other side (1A). When the backgrounds are grouped into a single grey background and brighter and darker inducers are seen as if surrounded by a single dark frame, the simultaneous induction effects are considerably weakened or abolished (1B). Changes in background luminance do not seem to affect the induction effects (1C and D), 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 (1B and D) does not appear to change this apparent depth effect.

To quantify this new phenomenon, we produced several such configurations with colored inducers of varying luminance contrast and investigated their probability of generating induction effects in terms of contrast and assimilation. The probabilities of generating induction are compared with probabilities that the inducers are seen as nearer to the observer, testing the assumption that inducers with a stronger tendency to be perceived as separated in depth from their backgrounds may also have a stronger tendency to produce induction effects in terms of apparent contrast. The induction effects produced by the complex spatial configurations displayed here are likely to be generated at levels of neural processing well beyond the receptor level (e.g. Weert & Spillmann, 1995; Long & Purves, 2003). To assess the nonetheless possible influence of low-level visual integration, involving rod-cone interactions at the fairly low brightness levels typical of computer monitors (e.g. Stabell and Stabell, 1975; Cao, Pokorny, Smith and Zele, 2008), we tested observers under three different conditions of light-dark adaptation, in both experimental tasks.

## 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.

### *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.

### *Stimuli*

The stimuli (see Figure 1A, B, C and D for illustration) consisted of pairs (as in 1A and C), the so-called spatially separated configurations, or singles, the so-called regrouped configurations (as in 1B and D) of colored inducers placed on light grey and dark grey background fields, displayed on a considerably darker ( $5.45\text{cd/m}^2$ ) general background. Twenty small squares, the so-called inducers, of a given color were placed on the dark (see Figure 1C and D) and the light grey (see Figure 1A and B) backgrounds. Five different inducer colors were presented (red, green, blue, yellow, and white) in different configurations, with always the same color in a given configuration. These combinations generated 20 configurations on spatially separated background fields (as in 1A and C) and configurations on background fields regrouped into a single one (as in 1B and D). The luminance of red inducers was  $56.7\text{cd/m}^2$  for the brighter ones (color guns of the screen at  $R=255, G=0, B=0$ ) and  $27.2\text{cd/m}^2$  for the darker ones ( $R=100, G=0, B=0$ ). Green inducers were displayed at  $69.8\text{cd/m}^2$  ( $R=0, G=255, B=0$ ) and  $27.7\text{cd/m}^2$  ( $R=0, G=100, B=0$ ), blue inducers at  $70.9\text{cd/m}^2$  ( $R=0, G=0, B=255$ ) and  $44.3\text{cd/m}^2$  ( $R=0, G=0, B=125$ ) yellow inducers at  $81.6\text{cd/m}^2$  ( $R=255, G=255, B=0$ ) and  $43.7\text{cd/m}^2$  ( $R=100, G=100, B=0$ ), and grey inducers at  $148.6\text{cd/m}^2$  ( $R=190, G=190, B=190$ ) and  $54.3\text{cd/m}^2$  ( $R=100, G=100, B=100$ ). The luminance of the light grey background was  $72.7\text{cd/m}^2$  ( $R=150, G=150, B=150$ ), the luminance of the dark grey background was  $23.2\text{cd/m}^2$  ( $R=50, G=50, B=50$ ). Configurations of colored inducers on the

light and dark grey backgrounds produced four inducer contrasts of varying intensity and polarity for each color, expressed in terms of  $(L_{\text{inducer}} - L_{\text{background}}) / (L_{\text{inducer}} + L_{\text{background}})$ . Table 1 gives these inducer contrasts and their sign 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).

### *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 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”).

### *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 minutes 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 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). Between stimuli, subjects were exposed to a uniformly dark ( $5.45 \text{ cd/m}^2$ ) screen, with a small, slightly brighter, fixation cross displayed in the center, which was to help them control the direction of gaze. Each individual session consisted of 40 trials per adaptation level, giving a total of 120 trials per subject within a  $3 \times 4 \times 2 \times 5$  experimental design, with three adaptation levels, four inducer contrasts, two types of spatial configuration, and five colors.

## 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 analysis 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  $3 \times 4 \times 2$  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 (Figure 2, 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 [ $F(3, 23) = 45.12, p < .001$ ]. 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  $C = -0.02$  and  $C = -0.44$ ) failed to produce an effect of relative depth, while roughly equivalent positive contrasts (here  $C = +0.09$  and  $C = +0.50$ ) 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 (Figure 2, top right), but significantly influenced induction effects, in terms of contrast [ $F(1, 23) = 82.33, p < .001$ ]. Induction effects are significantly stronger, producing higher probabilities of apparent contrast, in configurations where the background fields are spatially separated (Figure 2, bottom left). The effect of grouping on assimilation tends in the same direction, but was not statistically significant for the green inducers (Figure 3, 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 (Figure 3, 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 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 [ $F(3, 23) = 77.86, p < .001$ ]. 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  $C = +0.31$  or  $C = +0.51$ ) produced probabilities of “near” between 0.60

and 0.90. Grouping the backgrounds into a single field had no significant effect on probabilities of relative depth (Figure 3 top right), but significantly influenced induction effects in terms of apparent contrast [ $F(1, 23) = 24.33, p < .01$ ]. In configurations where the background fields are spatially separated, the probabilities of apparent contrast are significantly higher (Figure 3, bottom left). As with the green inducers, the effect of grouping on assimilation was not statistically significant for the blue inducers (Figure 3, 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 (Figure 4, 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 [ $F(3, 23) = 58.18, p < .001$ ]. 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  $C = -0.45$ ) producing only a weak effect of relative depth, while similar positive contrasts (here  $C = +0.42$ ) produced probabilities of “near” higher than 0.90. Grouping the backgrounds into a single field had no significant effect on probabilities of relative depth (Figure 4, top right), but significantly influenced induction effects in terms of apparent contrast [ $F(1, 23) = 24.33, p < .01$ ]. In configurations where the background fields are spatially separated, the probabilities of apparent contrast are significantly higher (Figure 4, lower graphs, on left). Again, the effect of grouping on assimilation was not statistically significant (Figure 4, 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 (Figure 5, 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  $C = 0.06$ ) 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 [ $F(3, 23) = 36.29, p < .001$ ]. 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  $C = -0.25$ ) produced no effect of relative depth here, while a similar positive contrast (here  $C = +0.31$ ) 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 (Figure 5, top right), but significantly influenced induction effects in terms of apparent contrast [ $F(1, 23) = 17.02, p < .01$ ]. In configurations where the background fields are spatially separated, the probabilities of apparent contrast are significantly higher (Figure 5, bottom left). Again, the effect of grouping on assimilation tends in the same direction, but was not statistically significant (Figure 5, 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 [ $F(2, 23) = 5.46, p < .05$ ] and on probabilities of assimilation [ $F(2, 23) = 10.50, p < .01$ ]. 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 (Figure 6). 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 6, bottom). The luminance contrast of the achromatic inducers had a significant effect on induction, in terms of apparent contrast [ $F(3, 23) = 4.47, p < .05$ ] and in terms of assimilation [ $F(3, 23) = 11.09, p < .01$ ]. For a luminance contrast of negative sign (here  $C = -0.14$ ), 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 [ $F(3, 23) = 32.95, p < .001$ ]. 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 (Figure 7, top), but significantly influenced induction effects in terms of apparent contrast [ $F(1, 23) = 17.02, p < .01$ ]. In configurations where the background fields are spatially separated, the probabilities of apparent contrast are significantly higher (Figure 7, middle). As with the colored inducers, the effect of grouping on assimilation is not statistically significant in configurations with achromatic inducers (Figure 7, 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 (Figures 2 and 5, upper left) produced noticeably stronger depth effects than red inducers with a low luminance contrast of positive sign (Figure 4, 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 (Figure 8).

## **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 (Heinemann, 1955; Helson, 1963; Beck, 1966; Hamada, 1985), sometimes described in terms of a "brightness paradox" (De Weert & 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 & Vendrik, 1970; Shapley &

Reid, 1985; Reid & Shapley, 1988; Grossberg, 1997). Such an interpretation accounts well for the brightness induction effects produced by colored inducers on their achromatic backgrounds, which as shown here do not vary with visual adaptation or inducer luminance. Roughly equiluminant chromatic inducers often produced the strongest brightness induction on the 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 light-dark adaptation of the eye, alter the appearance of achromatic backgrounds by producing unsuspected “paradoxical” (e.g. De Weert & Spillmann, 1995) changes in their perceived intensity. These observations challenge Chevreul’s law of color, however, only in part. The law predicts an absence of mutual interaction between color and grey, and we have investigated effects in only one direction here, testing the influence of color on grey. Whether an effect of grey backgrounds on the appearance of the colors displayed on them is likely to occur remains to be seen.

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, Spillmann and Werner (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 (Grossberg, 1997; Dresch, 1992; De Weert & Spillmann, 1995; Dresch & Fischer, 2001; von der Heydt & Pierson; Devinck, Spillmann and Werner, 2006; Pinna, 2008) and no single explanation suffices to account for them all. Given the insensitivity of the brightness induction effects of colors on grey to adaptation levels and

luminance contrast in our results here, low-level explanations in terms of critical interactions at the receptor levels can be safely excluded.

Conversely, the induction effects produced by achromatic inducers, in terms of apparent contrast and in terms of assimilation, are sensitive to adaptation levels and luminance contrast. Apparent contrast is the strongest after dark-adaptation, assimilation the strongest under daylight conditions, and the probability of contrast is higher than the probability of assimilation with inducer contrasts of negative sign, while the reverse holds for inducer contrasts of positive sign. These observations are reminiscent of earlier experiments by Magnussen & Glad (1975) on perceptual effects of 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 & Langley, 2005) have been reported in various earlier studies, and many of these results have remained unexplained (see McCormick, Hon, Huang, and Altschuler, 2012 for a deeper analysis).

Induction effects in terms of apparent contrast and assimilation often occur together with perceived changes in apparent depth of the inducing field or the test field, as in the watercolor illusion (e.g. Pinna & Reeves; von der Heydt & Pierson, 2006). The induction effects and the apparent depth effects reported in our study here are not sensitive to the same stimulus characteristics. The perception of the relative distance of the colored patterns, which change the appearance of their grey backgrounds, is determined solely by their luminance contrast. Chevreul’s law of contrast, predicting the effect of the luminance contrast of a color on its perceived relative depth in the plane, is thereby confirmed. It holds, as shown here, for contrasts of strong positive sign, under conditions where no cues to depth other than a difference in luminance between inducers were made available. 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 positive sign potentially deserves further attention. Additional experiments with a tighter sampling of inducer contrasts in the lower positive range would be needed to determine whether a particular effect of low contrast green and yellow in the perceptual genesis of relative depth of chromatic inducers with weak positive luminance contrast can be confirmed. The depth effects reported here are insensitive

to the level of visual adaptation and definitely do not involve chromatostereopsis (e.g. Dengler & Nitschke, 1993; Simonet & Campbell, 1990), as we chose configurations where the chromatic or wavelength characteristics of the stimuli were always constant in a given display, only luminance contrast varied.

Although brighter 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. A strong positive correlation between apparent contrast and relative inducer depth would be expected if a direct functional link between induction effects and the relative depth of inducing and test surfaces in the visual field existed, as suggested previously by Long & Purves (2003). We find, instead, that the perceived relative distance of inducers is independent from the induction effects they produce in terms of either apparent contrast or assimilation.

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## Table and Figure Captions

### 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).

### Figure 1

Examples of stimulus configurations from the experiments. Colored inducers of a brighter and a darker luminance were placed on grey backgrounds of a lighter and a darker luminance, presented as spatially separate (A and C) and regrouped (B and D) configurations on a uniformly dark screen.

### Figure 2

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.

### Figure 3

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.

### 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 RED inducers and the type of background configuration.

### 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 YELLOW inducers and the type of background configuration.

### Figure 6

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.

Figure 7

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 8

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.

	<u>RED</u>	<u>GREEN</u>	<u>BLUE</u>	<u>YELLOW</u>	<u>ACHROMATIC</u>
<u>the brighter inducer</u>					
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
<u>the darker inducer</u>					
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

TABLE 1

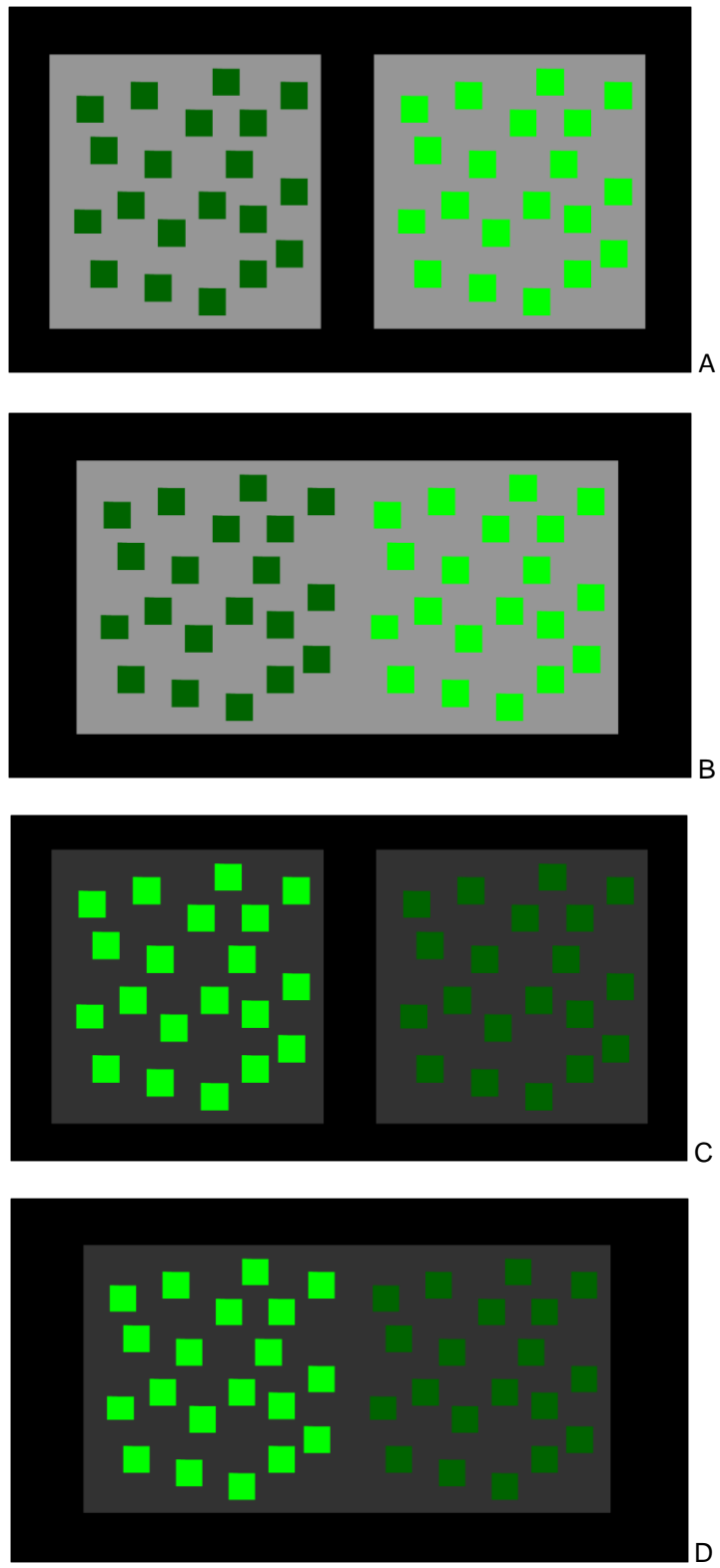


FIGURE 1

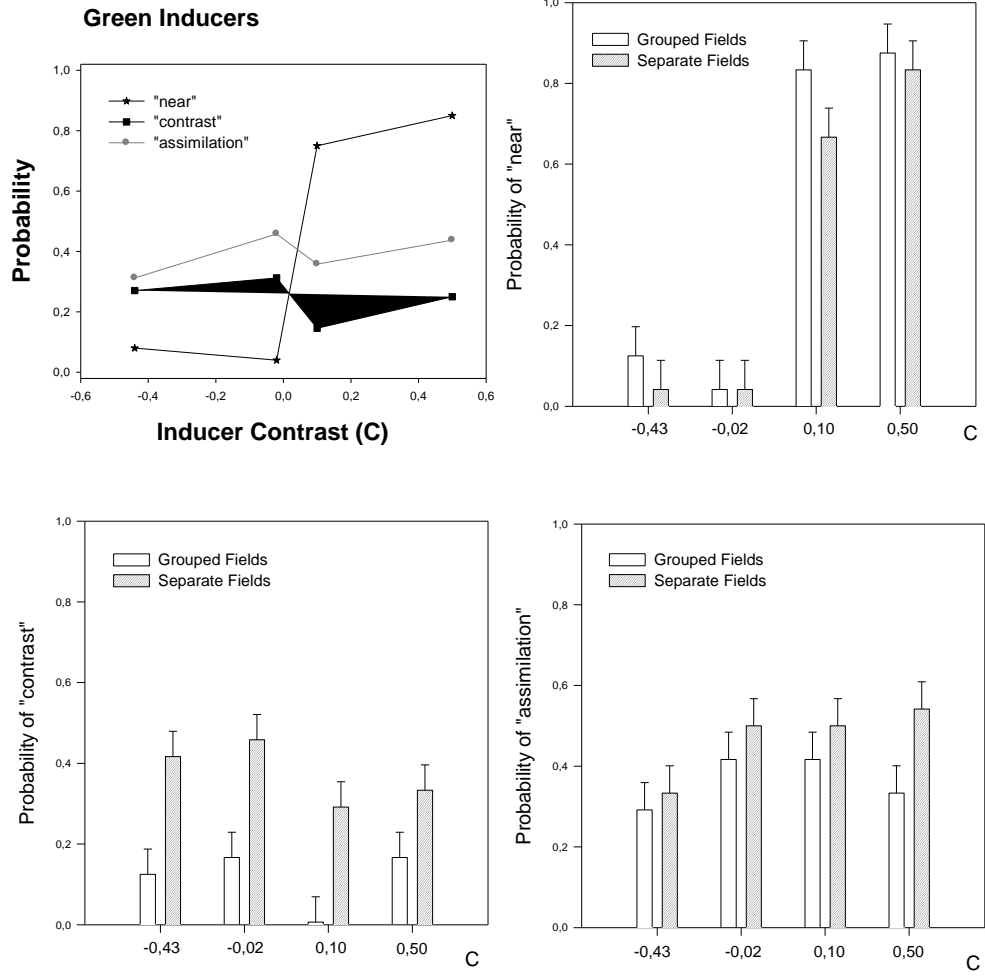


FIGURE 2



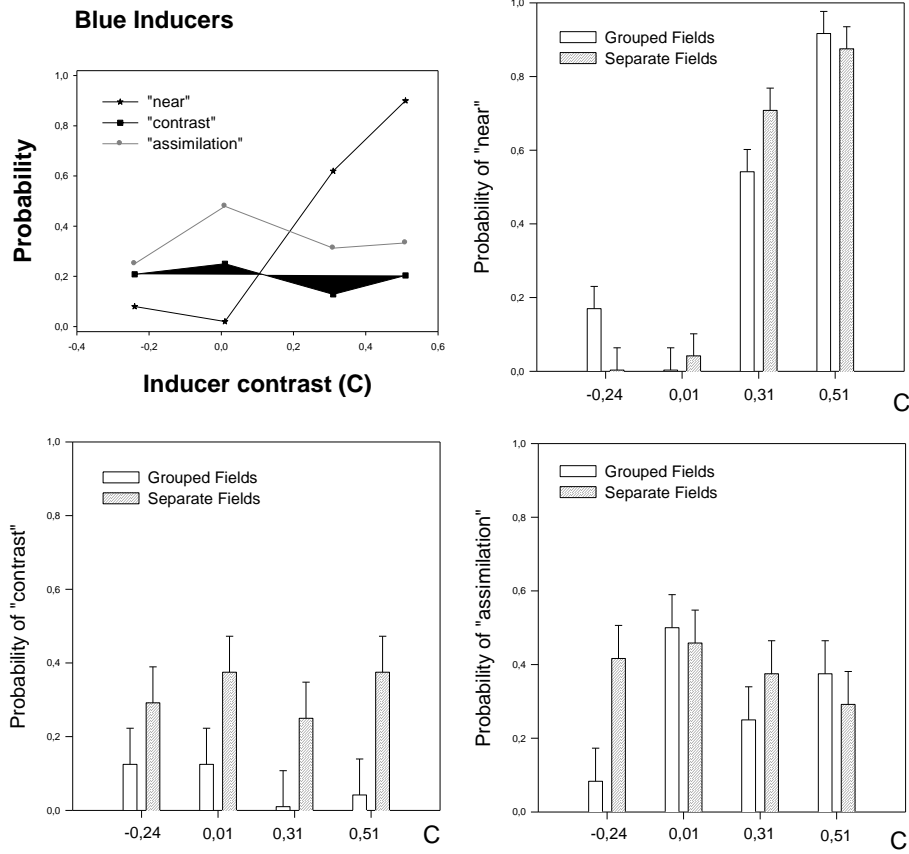


FIGURE 3

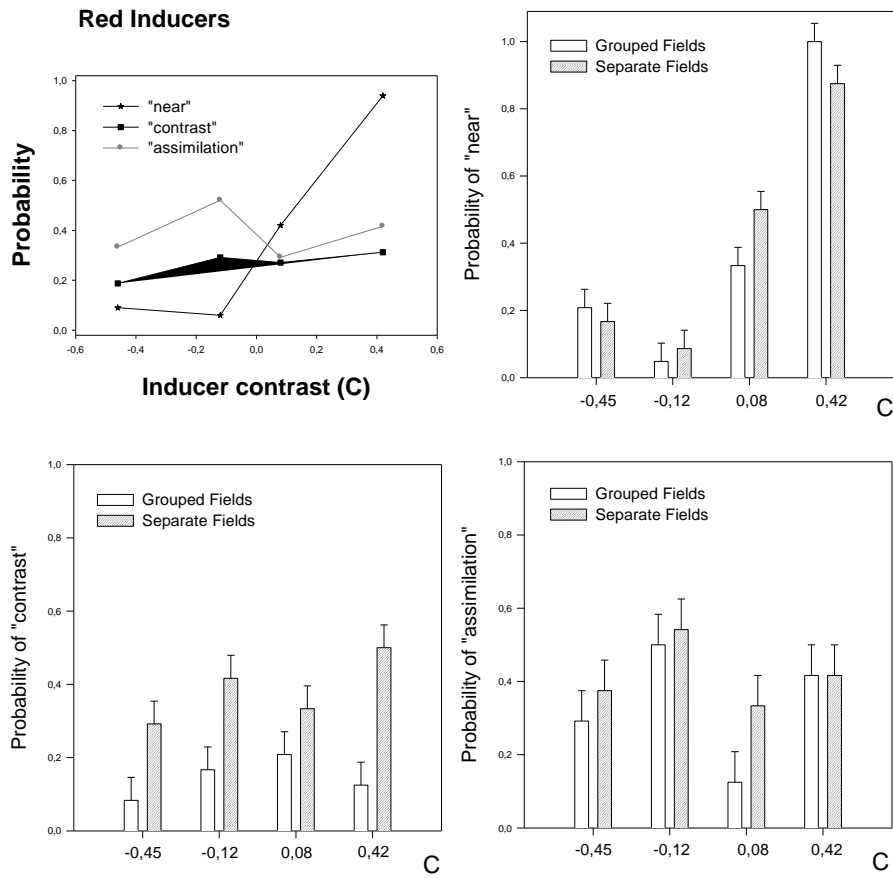


FIGURE 4

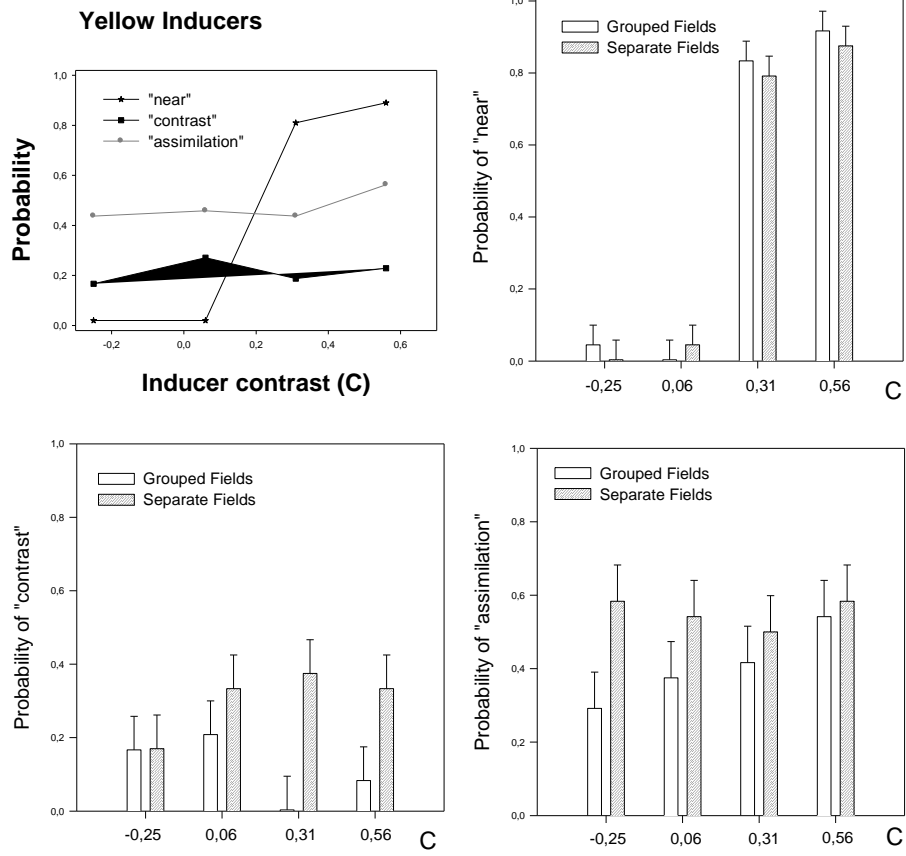
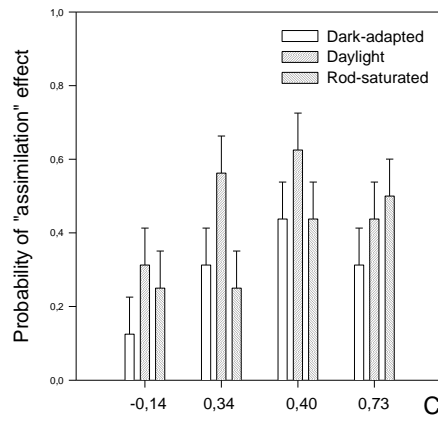
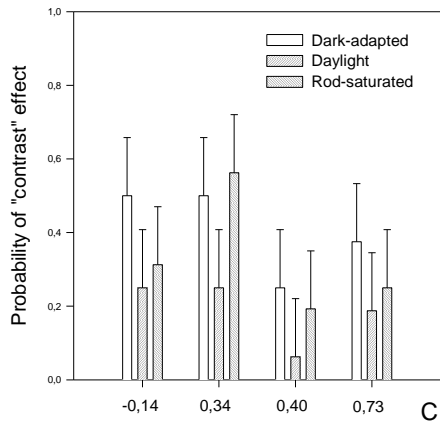
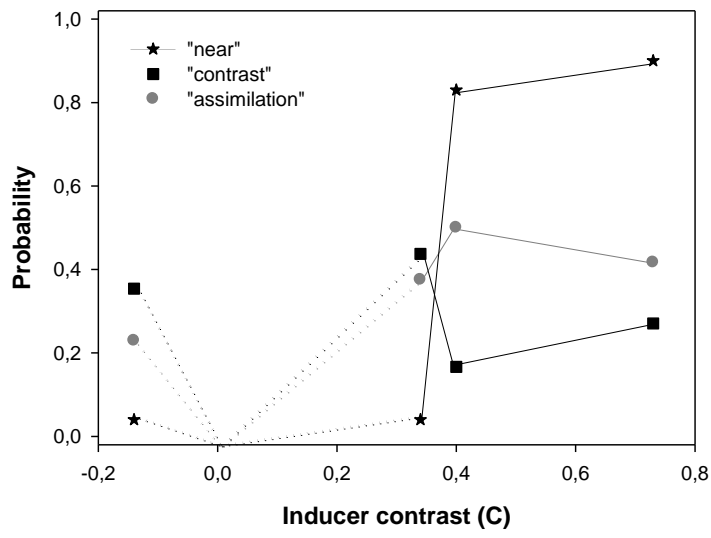


FIGURE 5

**Achromatic Inducers**



**FIGURE 6**

### Achromatic Inducers

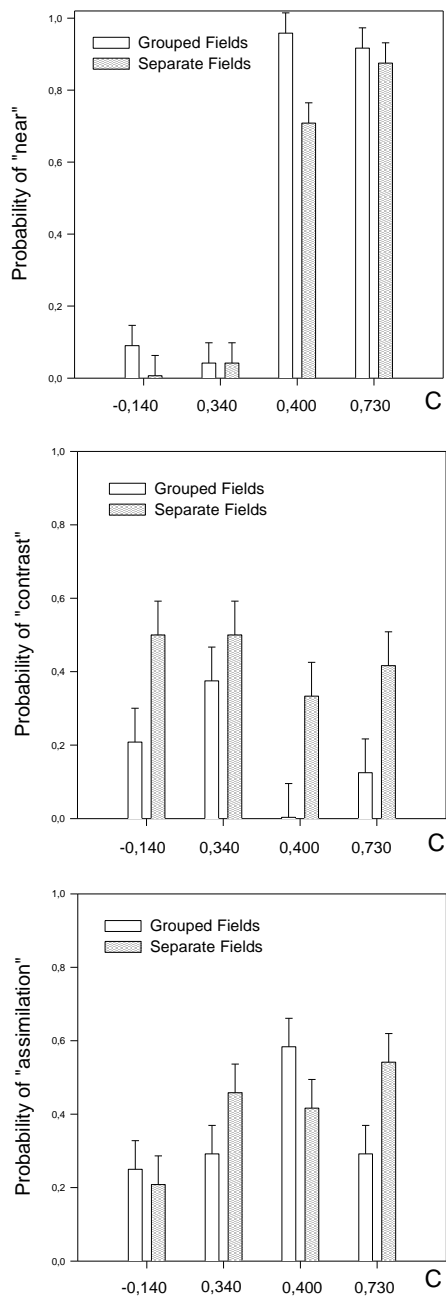


FIGURE 7

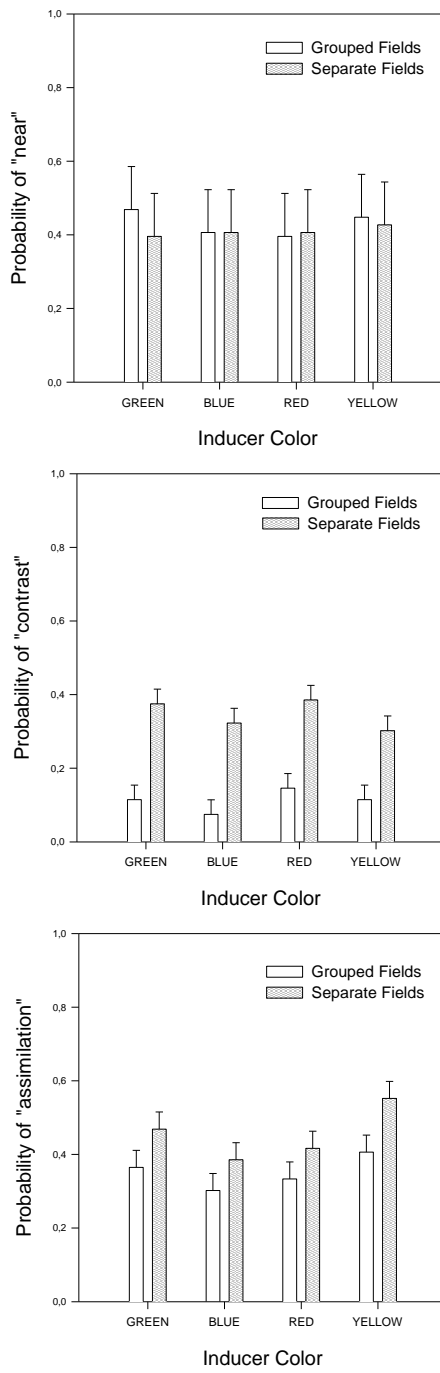


FIGURE 8