COMBINING ACHROMATIC AND CHROMATIC CUES TO TRANSPARENCY

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ABSTRACT

We investigated how achromatic and chromatic cues interact to produce transparency. Observers were shown six-region stimulus displays similar to those used by Kasrai & Kingdom (2001) and made adjustments of the color and luminance attributes of one of the filter regions to achieve the best percept of transparency. The dependent measure of primary interest was *setting reliability*, the reciprocal of setting variance. We wished to determine whether the combination of chromatic and achromatic information leads to enhanced reliability of perceived transparency. In Experiment 1, we measured reliability for achromatic, **L*,*** superimposed luminance with color, **L+C*,*** and superimposed luminance with polarity-reversing color, **L+iC*.*** We found that observers' reliability was highest for the **L+C** condition consistent with *effective cue combination*. In a second experiment, we compared setting reliability for **L**, **L+C**, and a new chromatic-only condition **C**. In the **L+C** condition, observers were asked to make separate and iterative settings of luminance and color to achieve the best percept of transparency. We compared their settings in **L** with the luminance settings in **L+C** and their settings in **C** to their color settings in **L+C**. Color adjustments were more reliable when accompanied by luminance information, but not vice versa. In Experiment 3, we manipulated the transmittance of the achromatic and chromatic filters separately, and investigated how this influences the settings made for each attribute. No systematic influence of filter transmittance on the settings made for perceived transparency was found.

INTRODUCTION

Consider the stimulus in Figure 1A. Most readers will perceive this display as consisting of a homogeneous, partially-transmissive disk overlying a three-part background, "…a transparent coloured veil … spread over the field …." (von Helmholtz, 1910/1962, pp. 285-286). A small rotation of the disk, however, disrupts the percept of transparency and reveals the three discrete colors that this region comprises (Figure 1B). The striking difference between the perceived homogenous color of the filter in the transparency display (Figure 1A) and the three sector colors comprising the central disk (Figure 1B) illustrates the phenomenon of transparency. Under appropriate image conditions, the visual system effectively assigns two sets of colors to an image region, one belonging to an underlying background surface and the other to the transparent layer through which the background is seen. This phenomenon is also referred to as 'color scission' (Koffka, 1935; Metelli, 1974a).

In addition to geometric constraints (such as the continuity of contours, disrupted in Figure 1B), the percept of transparency also depends on photometric constraints. Metelli (1970, 1974ab) developed a model of achromatic transparency based upon a physical setup—an episcotister—from which he derived two qualitative constraints for the perception of transparency. This model also makes quantitative predictions for the transmittance and reflectance of a filter (such as the overlying disk in Figure 1A). The model was based on a physical setup involving a bipartite background underlying a transparent disk—thereby generating a four-region display (Figure 2A). Throughout the article, we will adopt a notation in which corresponding background and filtered regions are denoted as b_i and f_i, respectively, where $i = 1, 2, .., n$ and n is the number of background regions. So, by this convention, $n = 3$ in Figure 1A, and $n = 2$ for Metelli's diagram in Figure 2A.

Given this four-region diagram, Metelli modeled the luminance[1] of the filtered regions f_i as a convex mixture of the corresponding background color b_i and a filter luminance t,

$$f_i = \alpha b_i + (1-\alpha)t, \quad i = 1,\cdots,n, \tag{1}$$

where α is the transmittance of the filter (the proportion of incident light it transmits).

When the number of background regions is $n \geq 2$, and perceptual decomposition of an image region yields a background surface composed of the regions $b_i, i = 1,\cdots,n$ with an overlying transparent layer composed of the filtered regions $f_i, i = 1,\cdots,n$, we can solve simultaneous equations based on Eq. 1 to obtain the transmittance α and the luminance t of the filter.

Metelli's qualitative constraints follow immediately from the equation above, along with the assumption that the transmittance, α, is non-negative with magnitude no greater than 1. The first constraint states that the region of possible transparency must preserve contrast polarity relative to the background: if a contrast border in the background is dark-light in a given direction (say, $b_1 > b_2$), then its extension into the filter region must also be dark-light ($f_1 > f_2$). This is a powerful ordinal constraint that has been used by many researchers (Adelson & Anandan, 1990; Anderson, 1997; Beck & Ivry, 1988), sometimes with striking consequences (e.g., Anderson & Winawer, 2005). If violated, the 'filter' regions are *polarity-reversing* and transparency is not perceived. The second constraint states that the magnitude of the luminance difference within the filter region should be no greater than in the region in plain view

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[1] In Metelli's original formulation, the model was expressed in terms of reflectance values, i.e., with the filter properties being its reflectance and transmittance. However, Gerbino et al. (1990) have shown that the same equations are obtained in the luminance domain, under the assumption that all surfaces are uniformly illuminated.

$|b_1 - b_2| \geq |f_1 - f_2|$. In Figures 1A and 2A, then, the conjunction of preserved contrast polarity across the boundary of the central disk, and reduced contrast magnitude within it, constitutes a powerful cue to transparency so that the presence of an overlying layer is perceived to be responsible for the reduced contrast.

Transparency as convergence in color space

Metelli's model was intended to describe transparency in achromatic displays. D'Zmura et al. (1997) extended Metelli's model to three-dimensional color space. Rather than treating b_i, f_i and t in Eq. 1 as scalars denoting luminance values, they treated them as three-dimensional vectors in color space. It follows from Eq. 1 with this reinterpretation that the presence of an overlying color filter leads to a global convergence in color space. If $b_i,\ i = 1, \cdots, n$ are the color vectors of the background regions and $f_i, i = 1, \cdots, n$ are the corresponding filtered regions, the vector differences $\Delta_i = b_i - f_i, i = 1, \cdots, n$ point to the common convergence point t. The degree of convergence is the scalar $1 - \alpha$ where α is the transmittance of the filter.

Metelli's achromatic model can be expressed, then, as a special case of the convergence model where the vectors b_i, f_i and t all lie along the luminance axis of color space and their magnitudes correspond precisely to the scalar values in his model. We will generalize Metelli's model to the case of any three collinear vectors and their mixtures below. This will allow us to parsimoniously express conditions analogous to Metelli's for transparency in equiluminant displays that are also consistent with the convergence model.

***Six regions for a unique solution*.**

Although four-color displays, such as the one in Figure 2A, have been widely used in tests of the convergence model (e.g., Chen & D'Zmura, 1998; Beck, Prazdny & Ivry, 1984; Gerbino et al., 1990), they have a major shortcoming. Fixing the two background luminances of the two background regions b_1 and b_2, and the luminance of one of the filtered regions, say f_2, yields infinitely many values of f_1 that are consistent with Metelli's model (and the convergence model) for different values of α and t. Figure 2B depicts two such solutions for f_1. Since the experimental task we use involves the adjustment by observers of one of the colors in a transparency display, we naturally prefer a display configuration in which the prediction of the convergence model is uniquely defined.

As noted by Kasrai & Kingdom (2001), this uniqueness of solution is readily achieved with six-region configurations ($n = 3$ in our notation), such as the one in Figure 1A. Given fixed values for the background region luminances b_1, b_2, b_3 as well as two of the filter region luminances f_2, f_3 there is a unique value f_1, which satisfies Metelli's equations, consistent with the convergence model. This is demonstrated schematically in Figure 3. The four values b_2, b_3 and f_2, f_3 together determine α and t. The solution for f_1 is now uniquely determined by these quantities.

Combination of achromatic and chromatic cues

In what follows, we investigate how chromatic and achromatic cues combine to determine the reliability or precision of perceived transparency. Although there has been a great deal of research on both chromatic and achromatic transparency (Beck et al., 1984; D'Zmura et al., 1997; Da Pos, 1989; Faul & Ekroll, 2002; Gerbino et al., 1990; Hagedorn & D'Zmura, 2000; Khang & Zaidi, 2002; Nakuchi, Silfsten, Parkkinen &

Ussui, 1999; Singh & Anderson, 2002; Singh, 2004), the question of how these two sources of information combine to determine percepts of transparency has not been addressed. Physical processes such as colored filters typically confound changes in luminance with changes in chroma. We will manipulate the chromatic and achromatic properties of our displays independently to avoid such confounds.

The primary measure that we will use is the *reliability* ρ of observers' settings for the adjustable sector, defined as the reciprocal of setting variance (Backus & Banks, 1999). We specifically investigate whether the *combination* of chromatic and achromatic cues leads to a more reliable percept of transparency. For Figure 3A, we noted that in a six-region achromatic display, the convergence model predicts a unique luminance f_1 for the variable sector as demonstrated in the diagram in Figure 3B. In an experiment using this configuration, Kasrai & Kingdom (2001) found that although this luminance prediction for the variable sector is supported, there is in fact a relatively wide range of luminance values around f_1 that generate a percept of transparency. We ask whether the addition of equiluminant color to such a display will "sharpen" the percept of transparency, thereby decreasing the variability in observers' settings.

In addition to the achromatic case—which we will refer to as the **L** condition—we will have a purely-chromatic (equiluminant color) condition, **C**. An example of such a condition is shown in Figure 4A, in which all chromatic variations are defined along the single dimension of saturation—going from neutral to highly-saturated yellow. We emphasize that, in the chromatic displays, the six regions are equiluminant. It is clear that, as in the achromatic case, there is a unique solution (here, for the saturation of the adjustable sector) that satisfies the convergence model (depicted in Figure 4B). A "cue-combined" version will be created by superimposing the **L** and **C** displays, so that the transparent filter in the resulting **L+C** display contains both achromatic and chromatic convergence. The details of how the superposition was achieved will be explained in the Methods section. The critical question will be whether setting reliability in the **L+C** case is systematically higher than in the **L** case. Moreover, to address the question of whether the introduction of *any* colors (rather than just polarity-preserving, transparency-consistent colors) improves the percept of transparency, a fourth condition **L+iC** will be included in which the chromatic component of the superposition is polarity-reversed—hence inconsistent with transparency (recall Metelli's qualitative constraints).

The first two experiments test whether adding color to luminance information makes transparency more precise relative to either cue in isolation. The third experiment applies further configuration manipulations in order to determine whether the relative strength and contrast between the two cues influence perceived transparency.

GENERAL METHODS

***Stimuli*.**

We used the convergence model described above in specifying our stimuli, which were computer-generated, six-region transparency displays (after Kasrai & Kingdom, 2001) presented stereoscopically following Singh & Anderson (2002)[2]. The filter had a disparity of 19.0 minutes of arc. A sample stereo pair is shown in Figure 5. The three wedges (i.e. filter-background pairs) of each six-region display were randomly permuted and counterbalanced from trial to trial so that observers made an equal number of adjustments for each of the three filter regions. The adjustable filter region was always in the upper left wedge. The displays differed in their chromaticity and luminance, depending upon experimental condition.

We first describe the construction of the stimuli intuitively and then in detail. Imagine a globe whose north-south axis is luminance and whose equator includes the equiluminant plane of our chromatic stimuli. The point *t* in the convergence model is the center of the globe, not the South Pole (which corresponds to the RGB value (0,0,0), i.e., "black"). We contracted achromatic stimuli along the North-South axis toward the center *t*(not toward the South Pole). We contracted chromatic stimuli within the equiluminant plane toward the center of the globe *t*, which shared the same luminance. Thus all chromatic stimuli were equiluminant with *t*.

We superimposed chromatic and achromatic stimuli by vector addition of the vector differences from *t*, ***not*** the vectors differences from the South Pole and, as a result, the chromatic and achromatic components of the stimuli continued to be defined

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[2] We noted in pilot studies that subjects did not always group the stimuli as a central disk with surrounding background when the stimulus was confined to a single depth plane. By presenting the stimuli in stereo, we force the visual system to segment the scene in accordance with the correct grouping we intended—the central region is perceived as separated from the background. Subjects are then left with the task of making the central region as uniformly transparent as possible through adjustments of one of the filter regions.

by a contraction to a common point *t*. This method of superposition is not the same as physical superposition. Physical superposition would increase the overall luminance of each region by the luminance shared by the equiluminant colors, changing *t*.

In order to produce the six-region stimuli, we first assigned each of the three background regions a weight along a 0-1 scale where 0 along the scale corresponds to black, 1 to white, and values in-between to intermediate grays. For color displays, this scaling corresponded to the saturation of the equiluminant yellow hue, with 1 being most saturated and 0 being the neutral gray. The assigned weights of the three background regions in our stimuli were always 1.0, 0.6, and 0.2, but were randomly permuted throughout the experiments so that, for example, the darkest background region was not always in the upper left wedge. The weights of the three filter regions were then determined by the Metelli equation (Eq. 1). For Experiments 1 and 2, the chromatic and achromatic components were derived with the same α and ***t*,** where α = 0.4 and *t* = 0. For Experiment 3, the chromatic component contained the same α and *t* values as the first two experiments, but the achromatic component took on one of three values for α ***:*** 0.55, 0.4, and 0.25. Because *t* was equal to 0 in all of the weight-defined stimuli, the use of the Metelli equations for the three filter regions meant that they were defined by an α compression with no additive term. Finally, the adjustable filter region was randomly jittered by +/- 0.2 on the scale so that the observer never saw the configuration containing all three Metelli-predicted filters.

In the conditions in which the luminance and chromaticity information were presented in isolation, **L** and **C** respectively***,*** the stimuli were generated as follows. In the **L** case, a weight w (between 0 and 1) specified an RGB vector that was a weighted mixture $wM + (1-w)B$ of linearized RGB[3] vectors M = (300 300 300) and B = (136 136 136), both neutral in appearance. The weight 1 corresponds to M, the weight 0 to B. Note that M lies outside the monitor gamut (0-255). We restricted ourselves to weights within the monitor gamut. The construction was similar in the C case except that M is replaced by a chromatic RGB vector Y that is equiluminous to B. We measured equiluminance and chose Y separately for each subject as discussed in the section titled "Procedure". The weight 0 now corresponds to B, the weight 1 to Y and all chromatic stimuli were weighted mixtures of these two vectors. Note that, in terms of the convergence model, the linearized RGB vector B is the convergence point *t.*

Superposition. Our method of superposition of the stimuli does not correspond to physical superposition, in which the **L** and **C** configurations would be added in their final form (i.e. once having been translated within color space) as described in the previous paragraph. With physical superposition, the resulting linearized RGB vector is $w_L(M-B)+w_C(Y-B)+2B$ which is higher in luminance than either of the components that we superimposed (B has been added twice). We interpreted superposition as $w_L(M-B)+w_C(Y-B)+B$ where the neutral gray B vector is added only once.[4] The resulting superposition has the same luminance as its achromatic component.

Contrast polarity reversal. Recall the constraints on perceived transparency articulated by Metelli: the filter must preserve contrast polarity relative to the background and the magnitude of contrast within the filter region should be no greater

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[3] The response of each of our monitor guns was nonlinear and we measured and corrected this non-linearity. The RGB values we refer to are these linearized luminance values on a scale of 0 to 255. A setting of 136, for example, is 136/255 of maximum gun intensity.

[4] In a pilot study, we obtained data for physically superimposed stimuli and found that observers' performance was qualitatively similar to the results found in Experiment 1 in this paper using the second method of superposition. We opted for this method to avoid confounding the overall stimulus luminance with superposition.

than in the region in plain view. A violation of these constraints, namely a contrast polarity reversal caused by transposing the two filter regions, as in Figure 6A, disrupts the percept of transparency. In the six-region display of Figure 6B the two filter regions, f_2 and f_3 are mismatched with their backgrounds and the resulting display no longer preserves polarity (see Figure 6B).

In one of our conditions, the stimuli contained a polarity-reversing filter. In the superimposed luminance with *polarity-reversing color* condition, **L+iC*,*** the weights of the two non-adjustable filter regions of the equiluminant yellow stimulus, f_2 and f_3 were switched after being assigned in accordance with Metelli's equations. Then the polarity-*preserving* achromatic stimulus and the polarity-*reversing* equiluminant stimulus were superimposed using the same method as that used for the **L+C** condition.

Software and apparatus.

The stimuli and experiments were programmed in MATLAB using the Psychophysical Toolbox extensions (Brainard, 1997; Pelli 1997). The computer used in the experimental apparatus was a Sony GDM-FW 900 workstation with a 24-inch monitor displaying 1280 by 1024 pixels at a vertical refresh rate of 100 Hz. The color quality was 32 bit and the graphics processor was a Quadro4 380x61. The system processor of the computer was an Intel Pentium 4 with SSE2. The stimuli were presented to the observers binocularly using a mirror stereoscope. Observers' viewing position was fixed by means of a chin rest that was placed approximately 82.5 cm from the computer screen.

***Task*.**

The task of the observer was to make color and luminance adjustments of the upper left third portion of the "floating" filter until the best percept of a coherent and uniform transparent filter was evoked.

Observers.

The same seven observers completed Experiments 1, 2, and 3. All were affiliated with New York University and not aware of the purpose of the experiment. All observers gave informed consent before participating in the experiment.

Procedure.

Observers were first required to complete a random-dot stereogram test, in which they were to indicate whether a rectangle appeared to float in front of or behind a "background" and whether the rectangle was horizontally- or vertically-oriented. This test was done to ensure that all observers were able to perceive stereoscopic depth. Upon successful completion of the stereo test, observers performed a minimization-of-borders and a minimization-of-flicker task in which they localized the yellow hue that appeared equal in intensity to the neutral gray value, *t*. This yellow hue was then incorporated into the experimental code as the equiluminant yellow point for that particular observer.

Observers were instructed to adjust the "upper left third" portion of the filter so that it produced the best percept of a coherent and uniform transparent filter. To be certain that observers understood the notion of transparency as defined by Metelli, a physical demonstration was provided using colored gels placed over three-region paper backgrounds. "Good" (polarity-preserving) cases of transparency were contrasted with "bad" (polarity-reversing) cases, to make this demonstration[5]. The

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[5] Since a gel itself cannot be polarity-reversing, the "bad" cases of transparency were made by altering the color of the paper background that rested under the gel, which produced the effect of a polarity-reversal and therefore a loss of perceived transparency.

description of how the adjustments were made and the experimental design will be described in each of the individual experiments.

EXPERIMENT 1

Experiment 1 investigates whether the combination of achromatic and chromatic cues increases the reliability of perceived transparency relative to that of the achromatic cue in isolation. In particular, we are interested in determining whether the visual system derives a more precise percept when provided with multiple transparency-consistent signals. For this purpose, two stimulus conditions were used and the reliability of the settings for each was compared. In the achromatic **L** condition, the stimulus contains only gray levels (Figure 7A). In the **L+C** condition*,* the stimulus comprises a superposition of achromatic and chromatic components (Figure 7B).

As suggested by the cue combination literature, an improvement in reliability in the two-cue, **L+C** condition indicates that perceived transparency benefits from an overall stronger sensory signal. In anticipation of finding an improvement in reliability with a combination of cues, we included a third stimulus condition, **L+iC**, in which an equiluminant chromatic configuration is altered to be polarity-reversing prior to superposition with a polarity-preserving achromatic configuration (Figure 7C). Thus, if the reliability of perceived transparency is a function of the strength of the transparency signal elicited by the input, and moreover, a polarity-preserving chromatic configuration provides a viable signal to the transparency mechanism, then we expect the most reliable settings to be made in the **L+C** condition relative to the other two conditions, **L** and **L+iC**. Furthermore, the addition of a transparency-inconsistent signal as occurs in the **L+iC** stimulus should not provide any reliability enhancement and therefore, we would expect that the reliability of the settings for this condition would be roughly equal to that of the **L** condition. If, on the other hand, the added color information improves reliability of perceived transparency but does not provide an explicit transparency signal to the visual system, then we expect that the reliability of the settings in the **L+C** and **L+iC** conditions will be equal, which in turn will be larger than that of the settings for the **L** condition.

Methods.

Task.

Observers made adjustments with a single set of keys that simultaneously controlled the weights assigned to luminance and color in the adjustable filter region. The luminance and color weights were always equal and the settings were thus constrained to lie along a single line in color space.

Design.

Observers were required to complete 4 sessions of 45 trials each, with the first session being practice. Each session contained 5 repetitions of 9-trial blocks, one trial for each of the three filter sectors per condition, yielding a total of 135 experimental trials per observer.

Results and analysis.

Reliability.

For each condition, the variance of the settings was determined, and the reciprocal of that value was used as a measure of reliability for that condition—greater setting reliability indicates that observers have a more stable or “sharper” percept of transparency. Having obtained these estimates, we can plot the reliabilities for each observer’s settings for one condition versus the reliabilities in another condition. If one condition consistently evokes more reliable percepts of transparency, then the data will fall on one side of the 45 degree line. Data falling on or near the 45 degree line indicates no strong difference between the reliabilities in the two conditions.

Figure 8A depicts the reliabilities of each of the seven observers' settings, with 95% confidence intervals, for the **L+C** condition (denoted ρ_{L+C}) versus the reliabilities for the **L** condition (denoted ρ_L). The confidence intervals were obtained by first finding the critical values for the variance within the χ^2 distribution: $\chi^2_{0.025,n}, \chi^2_{0.975,n}$ where n = (3*15)-3, or 42—the total number of degrees of freedom when collapsing over the three background permutations for any given condition. Using the critical values, the bounds of the confidence intervals on reliability were computed as the reciprocals of the ordinary confidence bounds on variance.

In this plot, four data points fall in the upper portion above the 45 degree line towards the **L+C** condition, while three lie essentially on the line. The combination of chromatic and achromatic cues improves the reliability of perceived transparency for several observers: performance with the combined cues is more precise than with the achromatic cue in isolation, referred to as *effective cue combination* (see Boyaci, Doerschner, & Maloney, under review). Although observers demonstrate this effect to different degrees, the results are consistent with other studies involving cue combination, which have also demonstrated individual differences in observers' abilities to make use of multiple cues (e.g. Oruc, Maloney, & Landy, 2003). We conclude, therefore, from the general trend in the results that having both luminance and chromaticity information leads to more reliable perceived transparency.

The first plot provides evidence that perceived transparency benefits from the combination of chromatic and achromatic cues, relative to the achromatic cue in isolation. Earlier, we demonstrated the need to distinguish between true cue combination and some other beneficial use of color information. The use of the **L+iC** stimulus configuration provides us with insight regarding this distinction. Figures 8B and 8C contain the comparisons for this condition.

In Figure 8B, the reliability ρ_{L+C} of the settings for the **L+C** condition is plotted versus the reliability ρ_{L+iC} of the settings for the **L+iC** condition. The data again fall largely in the upper portion of the plot, indicating that reliability is greater when added color is consistent with transparency (i.e. polarity-preserving).

Figure 8C provides additional insights. Here, the reliability ρ_{L+iC} of the settings for the **L+iC** condition is plotted versus the reliability ρ_{L} of the settings for the **L** condition. The majority of observers actually experience a *decline* in the reliability of perceived transparency when added color is inconsistent with transparency, relative to the achromatic condition. This demonstrates the sensitive nature of the transparency mechanism to the strength of transparency-consistent sensory signals.

This is also an indication of non-independent processing of luminance and chromaticity information in the derivation of perceived transparency. If the mechanisms responsible for deriving transparency maintained independent processing of the two sources of information and only incorporated the outcomes of these processes at the final stage, then we would expect that the reliability of the settings for **L+iC** condition would be as reliable as the settings for the **L** condition because the transparency-inconsistent color information would not provide anything useful for the resulting transparency percept and the luminance processing would become the source of information upon which the resulting percept is based. However, for the majority of observers, there is a decline in the overall reliability of the settings for the **L+iC** condition relative to that of the **L** condition, indicating that both sources of information interact to produce the resulting percept.

In sum, we conclude from the results of the reliability analyses of Experiment 1 that the precision of perceived transparency benefits from a combination of *transparency-consistent* chromatic and achromatic cues relative to the achromatic cue in isolation.

Mean settings.

Although setting reliability is our primary measure of performance, we may also investigate whether the benefit of the combined cue condition, **L+C**, is also reflected in the mean settings. Recall that our stimuli were constructed using a convergence model yielding a unique solution for each configuration that is polarity-preserving. Kasrai and Kingdom (2001) found in their study that observers' mean settings are highly accurate with respect to the predictions of this model under the conditions of the *achromatic* six-region configuration. Analyzing the mean settings obtained from the seven naïve observers in our study for both the **L** and **L+C** configurations, we find that all but one observer also conform well to the predictions of the convergence model under both stimulus conditions—there is no effect of combined cues on the mean settings. The two plots in Figure 9 depict the mean settings for each of the seven observers in the **L** (denoted w_L in Figure 9A) and **L+C** conditions (denoted w_{L+C} in Figure 9B), respectively. The anomalous seventh observer's data (represented by black triangles surrounded by dashed circles in both plots) reflect a different strategy in making the settings. Whereas the other six are clearly deriving accurate estimates of α and t and making their adjustments in accordance with those estimates (as evidenced by an increase in the adjusted weight with increasing weight of the background region, in agreement with the predictions), the anomalous observer's strategy appears to be one of uniformity within the entire three-sector filter region (indicated by that observer's settings being nearly equal for each of the three filter sectors).

In Figure 10A, we have isolated the anomalous observer's data set from the other six "converging" observers and collapsed across them for the **L** and **L+C** conditions, which have the same predicted settings. Results for the anomalous observer are reported separately in an online supplement (Figure S1). The mean settings are highly accurate with respect to the predicted ones (RMS[6] = 0.0241 (**L**); RMS = 0.04 (**L+C**)), thereby replicating Kasrai & Kingdom's (2001) accuracy results for achromatic (black markers) configurations and extending them to chromatic (green markers) configurations. In Figure 10B, we have re-plotted the collapsed mean adjustments in green for the six "converging" observers in terms of the convergence diagram for the six-region display introduced in Figure 3. As expected, they match well with the diagram with only slightly worse performance in the **L+C** condition.

For the anomalous observer's mean settings, see Figure S1 of the online supplement. It is interesting to note that the reliability of the settings is also greater in the combined-cue condition than in the isolated cue condition for this observer's strategy.

Discussion.

While most observers adhere to the convergence model for both the **L** and **L+C** conditions, they do differ in terms of the precision with which they do so. In particular, the reliability of perceived transparency increases with the combination of multiple transparency-consistent (i.e. polarity-preserving) cues—in other words, we have demonstrated *effective cue combination* for transparency. Whereas Kasrai & Kingdom (2001) found that observers made a fairly wide range of settings around the optimal one, our findings imply that the number of "acceptable" settings decreases when a greater amount of transparency-consistent information is available.

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[6] Here, RMS is the square root of the average of the squared deviations from those predicted by the convergence model: $\sqrt{\sum_{i=1}^{n}\left(X_i - X_{predicted}\right)^2 \Big/ n}$

We have not, however, tested for optimal cue combination. Since we do not have estimates of observers' reliability for an equiluminant color-only configuration, we are unable to determine whether the reliability of the **L+C** condition is an optimal combination of the two sources of information. We will address this in Experiment 2.

EXPERIMENT 2

The results of Experiment 1 demonstrated that the combination of two sensory signals consistent with transparency, chromatic and achromatic, increases the reliability of perceived transparency. When observers made their settings in Experiment 1, their adjustments were constrained to fall along a single line in color space, such that the luminance and chromatic weights of the adjustable filter portion were constrained to be equal. Although the stimuli were rendered such that the convergence model predicted the same adjusted weights for both cues, imposing this constraint does not allow one to test whether observers would indeed set the two to be equal if permitted to set them separately, or to make more precise statements regarding how the two cues actually combine to yield perceived transparency.

In Experiment 2, we no longer imposed the single-axis constraint on the settings and allowed observers to freely make separate and iterative adjustments of luminance and color. The stimuli were again rendered to have the same predicted solution for both cues, but by allowing the observers to adjust the chromatic and achromatic attributes of the filter portion separately, we can determine whether they are accurate along both dimensions, or perhaps tend to favor one cue over the other. Additionally, we can investigate the nature of the increase in reliability of perceived transparency by comparing the reliabilities among the separate settings. We may look for trends such as the reliability for both cues increasing equally, both increasing but to different extents, one showing a substantial increase while the other remains constant, etc. Lastly, we incorporated an equiluminant yellow stimulus, **C** stimulus (Figure 7D), thereby yielding three stimulus types for this experiment: **L**, **C,** and **L+C**. We now have the opportunity of testing for optimal cue combination of the **L** and **C** information within the **L+C** context, which we could not do previously in Experiment 1.

Methods.

Task.

The observers were provided with two sets of keys—one controlling the luminance of the filter and one controlling the saturation of the filter. In the superimposed condition, observers used both sets in any order or combination they preferred until the filter again evoked the best percept of transparency. In the single condition cases, observers only made adjustments with the appropriate set of keys, as the second set did not alter the display in any way. In the **L+C** conditions, we will have separate estimates of reliability for the two settings, denoted ρ_L^{L+C} (luminance) and ρ_C^{L+C} (chromatic) and two separate mean settings, w_L^{L+C} and w_C^{L+C}.

Design.

Observers were required to complete 4 sessions of 45 trials each, with the first session being practice. Each session contained 5 repetitions of 9-trial blocks, one trial for each of the three filter sectors per each of three conditions, yielding a total of 135 experimental trials per observer.

Results and analysis.

Reliability.

As in the previous experiment, the reliability of the settings in each condition was computed as the reciprocal of the variance, with 95% confidence intervals. The first comparison is depicted in Figure 11A*.* Here, the reliability ρ_C^{L+C} of each observer's color adjustments in the **L+C** condition is plotted against the reliability ρ_C of the color adjustments in the **C** condition. As before, the data fall towards the upper portion of the plot, indicating that the reliability of the color adjustments increases in the presence of luminance information.

Figure 11B shows the reliability ρ_L^{L+C} of the luminance adjustments in the **L+C** condition versus the reliability ρ_L of the luminance adjustments in the **L** condition. Here, the results show that there is no systematic increase in reliability for the luminance adjustments with the addition of color. Instead, for the majority of observers, the luminance adjustments are more reliable when there is no chromatic information available. This finding appears to contradict the conclusion that the reliability of perceived transparency benefits from the combination of achromatic and chromatic cues, since only the perceived transparency in the color component of the stimulus improves in the combined-cue condition. Moreover, the asymmetry in the results precludes any test for optimal cue combination since this requires that both settings are more reliable in the presence of the other cue, and that the reliability in the combined conditions reflect a weighted combination of the reliabilities of the two cues in isolation.

Next, we analyze the mean settings in each of these conditions for any trends not apparent from the reliability analysis, in order to gain insight into the cause of the asymmetry we find.

Mean settings.

The mean settings obtained in Experiment 1 indicated that observers who adopt the strategy of the convergence model are highly accurate for both the **L** and the **L+C** conditions with respect to the model's predictions—the benefit of the combined cue condition was seen in the reliability of the settings, but not in their accuracy. This implies that the mean settings for the separate color and luminance adjustments of Experiment 2 should also be accurate both in isolation and in the presence of the other cue. But recall that, in the first experiment, observers' adjustments were constrained so that both the color and luminance attributes within the adjustable sector were always equal. So, given that there is an asymmetry in the effects of the combined cue condition on the reliability of the independent settings, we will investigate how the mean settings compare among the isolated and combined-cue conditions, as well as how they compare among luminance and color settings.

The two plots in Figure 12 contain the collapsed mean luminance (Figure 12A) and color (Figure 12B) settings for the six converging observers. Within each graph, the settings made in the combined condition (w_L^{L+C}, w_C^{L+C}) are plotted in green, while the settings made in the isolated conditions (w_L, w_C), are plotted in black. The luminance settings w_L (in isolation) and w_L^{L+C} (combined) appear much like the mean settings from Experiment 1: highly accurate and consistent among the isolated and combined cue conditions (RMS = 0.0195 (**L**); RMS = 0.0297 (**L** of **L+C**). The color settings, however, are far less accurate (RMS = 0.0639 (**C**); RMS = 0.0740 (**C** of **L+C**), and do not conform well to the convergence model. In particular, the mean settings w_C and w_C^{L+C} made over the more saturated backgrounds (0.6 and 1.0 in weight) are nearly equal.

Let us now consider the collapsed mean adjustments re-plotted in green in the convergence model diagrams in Figure 13. In both conditions, the luminance adjustments maintain the high degree of accuracy noted in the first experiment. The color adjustments, however, exhibited a systematic pattern of deviation: they converged too much (i.e. towards uniformity), and did so towards a filter color more saturated than the one predicted by the convergence model. Thus, observers' settings of color are further from veridical with respect to the convergence model than their settings of luminance.

The mean settings for the anomalous observer are plotted separately in Figure S2 of the online supplement. Again, there is a clear strategy towards uniformity in all four conditions. Additionally, this observer showed an increase in reliability for the settings of *both* cues in the presence of the other one (this observer's data are marked by the presence of a red asterisk in Figure 11).

Discussion.

In apparent contradiction to the results of Experiment 1, the reliability analysis of Experiment 2 found that although color settings are more reliable in the combined cue condition, luminance settings are more reliable in the achromatic display than in the superimposed display. This asymmetry can be understood in terms of the mean settings, however, which remained accurate for the luminance settings in both conditions, but deviated in a patterned way for the color settings. We suggest that, because the color settings deviate from the model predictions, they make the luminance adjustment more difficult and therefore less reliable in the combined-cue case, than in the luminance-only condition. By contrast, in Experiment 1, since both attributes were constrained to vary together, the accuracy of both cues could be achieved and hence, a greater reliability was obtained in the combined-cue condition than in the isolated-cue condition.

At this stage, we may also address the anomalous observer's unique performance for Experiment 2 in which the reliability of both the color and luminance settings were larger in the presence of the other cue than in isolation (recall this observer's data marked with an asterisk in Figure 11). The mean settings for this observer have consistently been in accordance with a strategy of uniformity among the three filter sectors, thereby clearly deviating from the convergence model. Until this point, it has been argued that an increase in the reliability of perceived transparency for the combined-cue condition will occur only if the settings of both attributes are in accordance with the convergence model (i.e. that reliability is related to accuracy). Thus, for the “converging” observers, deviating from the convergence model in the color settings appears to hinder the ability to precisely set the luminance attributes in the combined-cue condition. However, the anomalous observer is never accurate with respect to the convergence model and yet still demonstrates an improvement in reliability for both attributes in the combined-cue condition. We summarize the results as follows: setting both attributes in accordance with one’s own strategy or internal model (and not necessarily the convergence model) will lead to increased reliability of perceived transparency. So, for the anomalous observer, setting both luminance and color filter attributes towards uniformity in the combined cue condition leads to increased reliability for both cues in that condition, and for the “converging” observers, incorrectly setting the color attributes while correctly setting the luminance attributes leads to an asymmetry in the reliability results.

EXPERIMENT 3

An asymmetry in the reliability results of Experiment 2 prompted us to scrutinize the mean settings for an explanation. This investigation led us to identify a patterned deviation from the convergence model in the color settings. Specifically, these settings tended towards being too saturated and too similar among the three filter sectors than would be predicted by the convergence model. This raises the question of whether contrast within the equiluminant yellow configuration is playing an unforeseen role. Although the filter transmittance, α, was equated for the achromatic and chromatic configurations, the apparent contrast may not have been large enough in the equiluminant yellow configuration, relative to that of the achromatic configuration, and therefore the overly-saturated settings could have resulted from attempts to "boost" the boundary contrast of the color component of the stimulus. Then, as described above, this overcompensation in the color settings creates a patterned deviation from the convergence model that in turn disrupts the reliability of the luminance adjustments. Experiment 3 tests this hypothesis by asking whether contrast is in fact responsible for the results obtained in Experiment 2, and moreover, whether those results can be altered through a manipulation of the relative filter-background contrast among the color and luminance attributes of the superimposed stimuli.

To do so, we replicated Experiment 2, but this time generating the stimuli so that the chromatic and achromatic configurations had different degrees of transmittance within the same display. Specifically, the filter transmittance α was held constant in the chromatic component, but varied in the achromatic component—with one value greater than, one equal to, and one less than the chromatic transmittance in the equivalent condition in Experiment 2.

Methods.

Stimuli.

The stimuli were the same as those used in Experiment 2, except the filter transmittance, α, was manipulated. The α used in the chromatic configurations was held constant at a value of 0.4, while the achromatic configurations could take on one of three α values: 0.55, 0.4, 0.25.

Task.

The task of the observers was the same as that of Experiment 2.

Design.

Observers were required to complete 6 sessions of 42 trials, again with the first being practice. Each session contained 2 repetitions of 21-trial blocks, one trial for each of the three filter sectors per each of seven conditions, for a total of 210 trials per observer.

Results and analysis.

Reliability.

In Figure 14, the reliability comparisons are once again plotted for the color adjustments of the **L*α*+C** condition $\rho_C^{L\alpha+C}$ versus ρ_C of the **C** condition (Figure 14A) and for the luminance adjustments $\rho_L^{L\alpha+C}$ of the **L*α*+C** condition versus $\rho_L^{L\alpha}$ of the **L** condition (Figure 14B). Within each plot, the reliabilities for the three luminance α values are plotted such that data obtained for the α = 0.25 condition are red, for the α = 0.4 condition are blue, and for the α = 0.55 condition are black.

We have clearly replicated the asymmetry found in Experiment 2, whereby the reliability of the color settings is greater when luminance information is available, while the reliability of the luminance settings is greater when luminance information is presented in isolation than in combination with color. In this experiment, the conditions where $\alpha = 0.4$ are identical to corresponding conditions in Experiment 2. However, the asymmetries in reliability are much more pronounced. We have no explanation for this discrepancy. Nevertheless, we now add to our findings the result that that transmittance of the filter in each configuration, α, does not influence the surprising pattern of results. This is indicated by the fact that the graphs do not contain three distinct clusters, one corresponding to each α condition. This finding makes it unlikely that a difference in apparent contrast is responsible for the asymmetry found in the results of Experiments 2 and 3.

Mean settings.

In Experiment 2, we found an analysis of the mean settings to be instructive in reconciling the asymmetry in the reliability results. Although there is no evidence that α systematically influences the reliability of the settings, we would like to determine whether α governs the choice of setting. Moreover, we would like to further investigate the suggestion that the asymmetry in reliability is a consequence of relative contrast within the stimulus configurations.

Figure 15 contains plots of the mean luminance settings relative to the predicted settings (solid line) for the six “converging” observers. Each column corresponds to one of the three α conditions. Note that a larger value of α corresponds to a more transmissive filter and therefore one with less contrast relative to the background regions. Within each graph, the black symbols correspond to the data for the settings made in the **L** condition, and the green symbols corresponds to the data for the luminance settings made in the **L*α*+C** conditions, where the filter transmittance for the chromatic configuration is held constant. While performance remains highly accurate for the six observers for all three α conditions (see Table 1), a trend is evident. The mean settings tend to become more accurate with decreasing α**,** or increasing contrast between the filter and the background. This is particularly the case for the luminance adjustments made in the **L*α*+C** conditions (note the accuracy difference between the α = 0.55 and α = 0.25 conditions, for example).

Figure S3 of the online supplement contains the mean settings for the anomalous observer. They demonstrate the same pattern of settings for each of the three α conditions (essentially identical settings that are independent of background color).

Figure 16 contains plots of the mean color settings relative to the predicted settings. The left-hand graph shows the color settings for the **C** condition. The collapsed settings for the six observers are shown in black symbols, while the settings for the anomalous observer are shown in green symbols. The six observers are less accurate (RMS = 0.0457) in this condition than they are when making the luminance settings, however they still show a systematic increase in mean setting in as predicted by the convergence model. The right-hand graph contains the color settings made for each of the three **L*α*+C** conditions, where α_c is always equal to 0.4, but α_L varies. The data for all seven observers have been collapsed for this graph, given that here even the “converging” observers no longer make their settings in accordance with the convergence model, but instead in accordance with a strategy of uniformity among the filter regions. We saw evidence of a compromise between the convergence model and the uniformity strategies in the performance of Experiment 2’s mean color settings, but in Experiment 3, uniformity has become the prevailing strategy. There is no effect of α , however, as all color settings are set to be highly saturated and similar.

Discussion.

We motivated Experiment 3 by posing the question of whether relative contrast of the achromatic and chromatic filter regions with respect to their backgrounds contributed to the asymmetry in the reliability results of Experiment 2. We considered in particular, whether the overly-saturated settings of color were due to an attempt to overcompensate for lesser contrast between the filter and background, relative to the contrast between the achromatic filter and its background in the **L*α*+C** stimulus. Experiment 3 investigated this through the use of superimposed stimuli containing varying degrees of filter transmittance, α, among the chromatic and achromatic configurations.

The asymmetry in the reliability of the settings was replicated in all conditions including when the transmittance of the luminance filter was greater than that of the color filter, thereby causing it to have less contrast relative to its background. A consideration of the mean settings again revealed accurate performance for the luminance settings both in isolation and in the presence of color, with a slight decline in performance with increasing filter transmittance (i.e., decreasing contrast between the filter and background sectors)[7].

The color settings, on the other hand, were less accurate, but nevertheless still in accordance with the convergence model for the **C** stimulus, but for all seven observers, were set to be nearly equal for each of the three **L*α*+C** conditions—specifically, they were all highly-saturated and uniform. This makes it unlikely that setting reliability and accuracy and the asymmetry in the reliability results are a function of relative stimulus contrast, as determined by the filter transmittances of the two configurations.

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[7] Either of the following explanations could account for this: (1). With increasing filter transmittance, the ‘true’ settings for the filter regions are more displaced from each other (i.e. less uniform), which requires that observers make a wider range of settings, so that by virtue of this, there is more room for error; (2). Given that the color settings are always improperly set (see next paragraph in the text), having a smaller degree of filter-background contrast in the luminance configuration will only compound the difficulty in making the adjustment and contribute to a greater magnitude of error.

GENERAL DISCUSSION

Perhaps the most relevant previous study on the combination of chromatic and achromatic information is that of Kingdom, Beauce, & Hunter (2004). In a forced choice between two displays depicting possible shadows, Kingdom et al. asked observers to identify the display with the “correct shadow.” They found superior performance in displays with chromatically variegated backgrounds as compared with achromatic backgrounds. They proposed that color can help to disambiguate shadows from reflectance changes via a simple rule: a luminance change that is accompanied by a color change is a reflectance boundary, whereas a luminance change unaccompanied by a color change is a shadow boundary.

Kingdom et al.’s rule relies on the assumption that shadows generally produce only an achromatic shift in color space—in particular, a uniform darkening, or convergence toward black. In this respect, the context of transparency is substantially more general than shadows, because the photometric transformation introduced by the presence of a transparent filter generally has both a chromatic and an achromatic component. As we have seen in the convergence model above, the photometric convergence introduced by transparency can be directed toward *any* point in color space, depending on the color t of the filter.

Given that reflectance boundaries and transparency boundaries can both generate chromatic as well as achromatic shifts in color space, it is evident that the rule for shadows articulated above cannot distinguish between reflectance changes and photometric shifts due to transparency. Thus the presence of color, which allows for the identification of shadows using a simple rule, does not similarly allow for the identification of transparency.

Accordingly, we did not constrain observers’ settings or provide feedback to observers based on any model of transparency. We simply asked them to make the display as consistent with homogeneous transparency as possible and assessed their reliability in doing so. The results of the first experiment indicate that the reliability of transparency percepts is greater when two transparency-consistent cues combine in a single display, even though combining cues does not influence the mean settings. It is interesting to note that recent psychophysical work has tested Metelli's quantitative predictions and found failures. In particular, the solution for α fails in general to predict perceived transmittance (Robilotto, Khang, & Zaidi, 2002; Singh & Anderson, 2002), despite the fact that Eq. 1 does in fact capture the lightness of surfaces seen through transparency (Singh, 2004). In contrast, we found that the quantitative predictions of the convergence model (and thus Metelli's model) proved accurate for the six-region display, as all but one observer made adjustments in accordance with the model. It is natural to expect that a strategy based on equating the ratio of contrasts, and one based on equating Metelli's α (i.e., ratio of luminance differences) should result in different predictions. It turns out, however, that in the context of 6-region displays the two strategies lead mathematically to the same predicted setting for the third inner sector (see Singh, 2004). There is thus a principled reason behind why Kasrai & Kingdom (2001) obtained equally good fits to their data with the two models.

In Experiments 2 & 3, six out of seven naïve observers adopted the strategy of the convergence model. The initial cue combination-like findings of Experiment 1 were challenged, however, by an asymmetry in the reliability of the settings: the color settings remained more reliable in the combined cue conditions, whereas the luminance settings were more reliable in the achromatic single-cue conditions. The mean settings for these observers revealed highly accurate performance in the luminance settings, but poor performance (with respect to the convergence model) in the color settings, particularly in the combined cue conditions. One anomalous observer, however, adopted a strategy of uniformity within the three sectors of the filter region. This observer showed an increase in setting reliability for both cues in the combined-cue display. The mean settings for this observer indicated a single adjustment strategy for both luminance and color settings.

A single explanation can account for these two sets of results: the reliability of perceived transparency is greater when the settings for each of the cues are made in accordance with an observer's own internal model of transparency. This follows suit with cue combination, as multiple redundant sensory signals yield more reliable percepts than singular ones.

It is puzzling, though, that the six observers who adopted the strategy of the convergence model for all luminance settings and for the color settings of the **C** displays, were unable to produce accurate color settings for the **L+C** and **Lα+C** conditions of Experiments 2 and 3. Manipulating the relative filter-background contrast for the chromatic and achromatic configurations did not alter performance indicating that the highly-saturated settings are not the result of an attempt to boost the filter-background contrast in the color portion of the stimulus. Instead, this may simply reflect an inherent weakness in the ability of the mechanisms responsible for deriving transparency percepts to use color information when luminance information is present.

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REFERENCES

Adelson, E.H. & Anandan, P. (1990). *Ordinal characteristics of transparency.* Paper presented at the AAAI-90 Workshop on Qualitative Vision, Boston, MA.

Anderson, B.L. (1997). A theory of illusory lightness and transparency in monocular and binocular images: The role of junctions. *Perception, 26,* 419-453.

Anderson, B.L., & Winawer, J. (2005). Image segmentation and lightness perception. *Nature, 434,* 79-83.

Backus, B.T. & Banks, M.S. (1999). Estimator reliability and distance scaling in stereoscopic slant perception. *Perception, Special Depth Perception 2, 28,* 217-242.

Beck, J. & Ivry, R. (1988). On the role of figural organization in perceptual transparency. *Perception & Psychophysics, 44,* 585-594.

Beck, J., Prazdny, K., & Ivry, R. (1984). The perception of transparency with achromatic colors. *Perception & Psychophysics, 35,* 407-422.

Boyaci, H., Doerschner, K., & Maloney, L.T. (2005). Cues to an equivalent lighting model. (under review).

Brainard, D.H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10,* 433-436.

Chen, V. & D'Zmura, M. (1998). Test of a convergence model for color transparency perception. *Perception, 27,* 595-608.

Da Pos, O. (1989). *Trasparenze* [Transparency]. Padua, Italy: Icone.

D'Zmura, M., Colantoni, P., Knoblauch, K., & Laget, B. (1997). Color transparency. *Perception, 29,* 471-492.

Faul, F., & Ekroll, V. (2002). Psychophysical model of chromatic perceptual transparency based on subtractive color mixture. *Journal of the Optical Society of America, 19,* 1084-1095.

Gerbino, W., Stultiends, C., Troost, J. & de Weert, C. (1990). Transparent layer constancy. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 3-20.

Hagedorn, J. & D'Zmura, M. (2000). Color appearances of surfaces viewed through fog. *Perception, 29,* 1169-1184.

von Helmholtz, H. (1910/1962). *Helmholtz's treatise on physiological optics.* New York: Dover.

Kasrai, R., & Kingdom, F.A.A. (2001). Precision, accuracy, and range of perceived achromatic transparency. *Journal of the Optical Society of America, A, 18,* 1-11.

Khang, B.-G., & Zaidi, Q. (2002). Accuracy of color scission for spectral transparencies. *Journal of Vision, 2,* 451-466.

Kingdom, F.A.A., Beauce, C. & Hunter, L. (2004). Color vision brings clarity to shadows. *Perception, 33,* 907-914.

Koffka, K. (1935). *Principles of Gestalt Psychology.* New York: Harcourt Brace.

Metelli, F. (1970). An algebraic development of the theory of perceptual transparency. *Ergonomics, 13,* 59-66.

Metelli, F. (1974a). Achromatic color conditions in the perception of transparency. In R. B. MacLeod & H. L. Pick (Eds.) *Perception: Essays in honor of J. J. Gibson* (pp. 95-116). Ithaca, NY: Cornell University Press.

Metelli, F. (1974b). The perception of transparency. *Scientific American, 230,* 90-98.

Nakuchi, S., Silfsten, P., Parkkinen, J., & Ussui, S. (1999). Computational theory of color transparency: Recovery of spectral properties for overlapping surfaces. *Journal of the Optical Society of America, A, 16,* 2612-2624.

Oruc, I., Maloney, L.T., & Landy, M.S. (2003). Weighted linear cue combination with possibly correlated error. *Vision Research, 43,* 2451-2468.

Pelli, D.G. (1997). The Video toolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10,* 437-442.

Robilotto, R., Zhang, B.-G., & Zaidi, Q. (2002). Sensory and physical determinants of perceived achromatic transparency. *Journal of Vision, 2,* 388-403.

Singh, M. (2004). Lightness constancy through transparency: internal consistency in layered surface representations. *Vision Research, 44,* 1827-1842.

Singh, M. & Anderson, B.L. (2002). Toward a perceptual theory of transparency. *Psychological Review, 109,* 492-519.

FIGURE CAPTIONS

Figure 1: Perceived transparency. A. A six-region surface that is perceived as three regions partly covered by a transparent filter. B. A rotation and displacement of the central three regions eliminates the percept of transparency.

Figure 2: ***Metelli's model***. A. A four-region stimulus after Metelli. The background regions are labeled b_1 and b_2 and the corresponding filtered regions are labeled f_1 and f_2. B. A schematic diagram demonstrating that, even with the constraints imposed by Metelli's equations in a display with only two pairs of regions b_1, f_1 and b_2, f_2, the settings of three of the regions do not determine that of the fourth. Given, for example, b_1, b_2, f_2, there are multiple possible values of f_1 consistent with Metelli's equations.

Figure 3: Schematic representation of the convergence model. A. A six-region stimulus after Kasrai & Kingdom (2001). B. The corresponding convergence model diagram. Three background luminances b_1, b_2, b_3 are plotted on a vertical axis and the corresponding filter region luminances f_1, f_2, f_3 plotted on a second vertical axis, offset from the first. The condition for transparency in the convergence model is that the lines passing through pairs of corresponding points b_i, f_i, $i = 1,2,3$ meet in a single point. The degree of convergence of the fixed background luminances contracted in towards their respective fixed filter luminances is $1-\alpha$. The point of convergence has luminance *t.*

Figure 4. Application of the convergence model to equiluminant color. The format is identical to that of Figure 3. Instead of luminance values, the model uses saturations of an equiluminant hue.

Figure 5. ***Example of a pair of achromatic stereoscopic stimuli used in Experiment 1.*** The pair on the left is for crossed fusion (X), the pair on the right for uncrossed (U).

Figure 6. ***Violations of Metelli constraints.*** A. A four-region stimulus used by Metelli that violates the polarity constraint. The two filter regions are *polarity-reversing,* and therefore do not elicit a percept of transparency. B. Example of a six-region stimulus that is also polarity-reversing: f_2 and f_3 have been reversed.

Figure 7. Monocular examples of each of the four stimulus types used in the course of the study. A. An achromatic, **L,** stimulus. B. A superimposed achromatic and chromatic, **L+C,** stimulus. C. A superimposed achromatic configuration with a polarity-reversing chromatic configuration, **L+iC,** stimulus. D. An equiluminant yellow, **C,** stimulus.

Figure 8. ***Experiment 1: Reliability data comparisons with 95% confidence intervals***. A: 7 observers' adjustment reliability for the **L+C** condition versus the adjustment reliability for the **L** condition. B: adjustment reliability for the **L+C** condition versus the adjustment reliability for the **L+iC** condition. C: adjustment reliability for the **L+iC** condition versus the adjustment reliability for the **L** condition.

Figure 9. ***Experiment 1: Mean settings.*** Mean settings for each of the three filter sectors for each of the seven observers plotted among the settings predicted by the convergence model (blue line). A. Settings made in the **L** condition. B. Settings made in the **L+C** condition. The settings for one anomalous observer are marked with red dashed circles. See text.

Figure 10. ***Experiment 1: Mean settings.*** A. Mean settings collapsed over the six "converging" observers. Black symbols: **Lα** condition; Green symbols: **Lα+C**

condition. Blue solid line: predicted settings. B. Convergence model diagram: **L** condition (upper graph); **L+C** condition (lower graph).

Figure 11. Experiment 2: Reliability data comparisons with 95% confidence intervals. A: Reliability of the color settings made in the **L+C** condition versus the reliability of the color settings made in the **C** condition. B: Reliability of the luminance settings made in the **L+C** condition versus the reliability of the luminance settings made in the **L** condition. The two data points marked with red asterisks represent the anomalous observer (see the text for details).

Figure 12. Experiment 2: Mean luminance settings. A: Black symbols: Mean luminance settings collapsed over the six "converging" observers. Black symbols: **L** condition; Green symbols: **L+C** condition; Blue solid line: predicted settings. B. Mean color settings collapsed over the six "converging" observers. Black symbols: **C** condition; Green symbols: **L+C** condition; Blue solid line: predicted settings.

Figure 13. Experiment 2: Convergence model diagrams of the collapsed mean settings. A. Mean luminance settings of the **L** condition. B. Mean color settings of the **C** condition. C. Mean luminance settings of the **L+C** condition. D. Mean color settings of the **L+C** condition.

Figure 14. Experiment 3: Reliability data comparisons with 95% confidence intervals. A. Reliability of the color settings made in each of the **Lα+C** conditions versus the reliability of the color settings made in the **C** condition. B. Reliability of the luminance settings made in each of the **Lα+C** conditions versus the reliability of the luminance settings made in each of the **Lα** conditions. Red symbols: α_L = 0.25; Blue symbols: α_L = 0.4; Black symbols: α_L = 0.55.

Figure 15. Experiment 3: Mean luminance settings. A. α_L = 0.55. B. α_L = 0.4. C. α_L = 0.25. Black symbols: **Lα** condition. Green symbols: **Lα+C** condition. Blue solid line: predicted settings.

Figure 16. Experiment 3: Mean color settings. A. Settings made in the **C** condition. Black symbols: “converging” observers; Green symbols: anomalous observer; Blue solid line: predicted settings. B. Settings made in the **L+C** conditions, collapsed over all seven observers. Red symbols: α_L = 0.25; Blue symbols: α_L = 0.4; Black symbols: α_L = 0.55.

TABLES

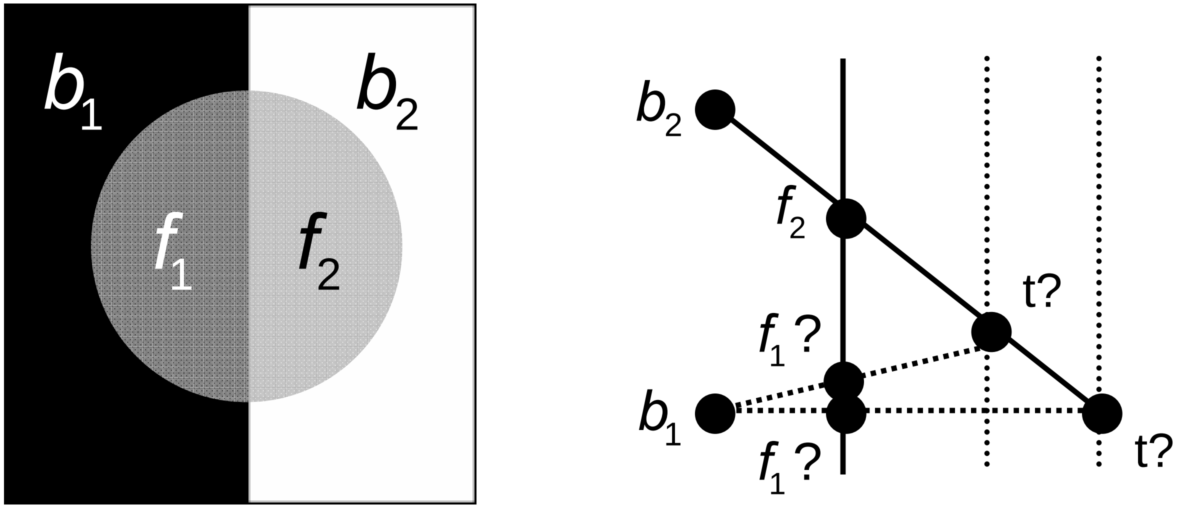
RMS	0.25	0.4	0.55
L	0.0168	0.0194	0.0286
C	0.0225	0.0286	0.0682

Table 1. Table of the RMS values for the luminance settings for the three α_L conditions of Experiment 3.

A

B

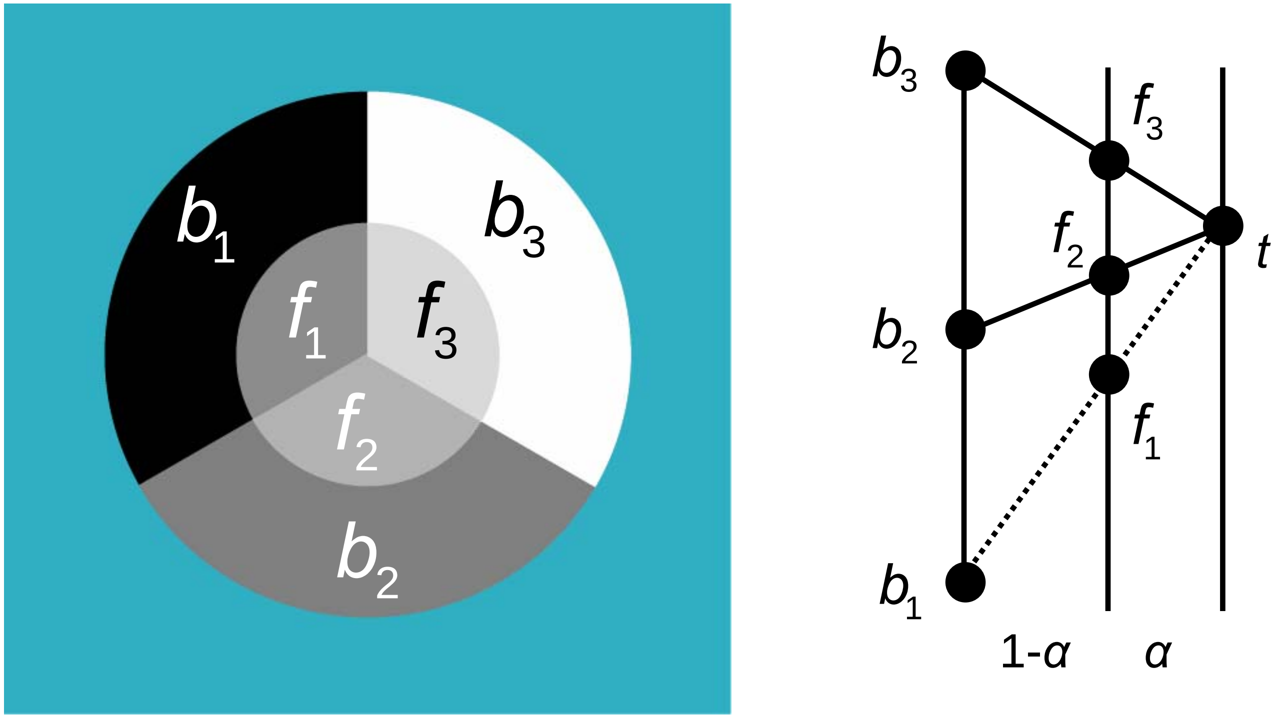
Figure 1



A

B

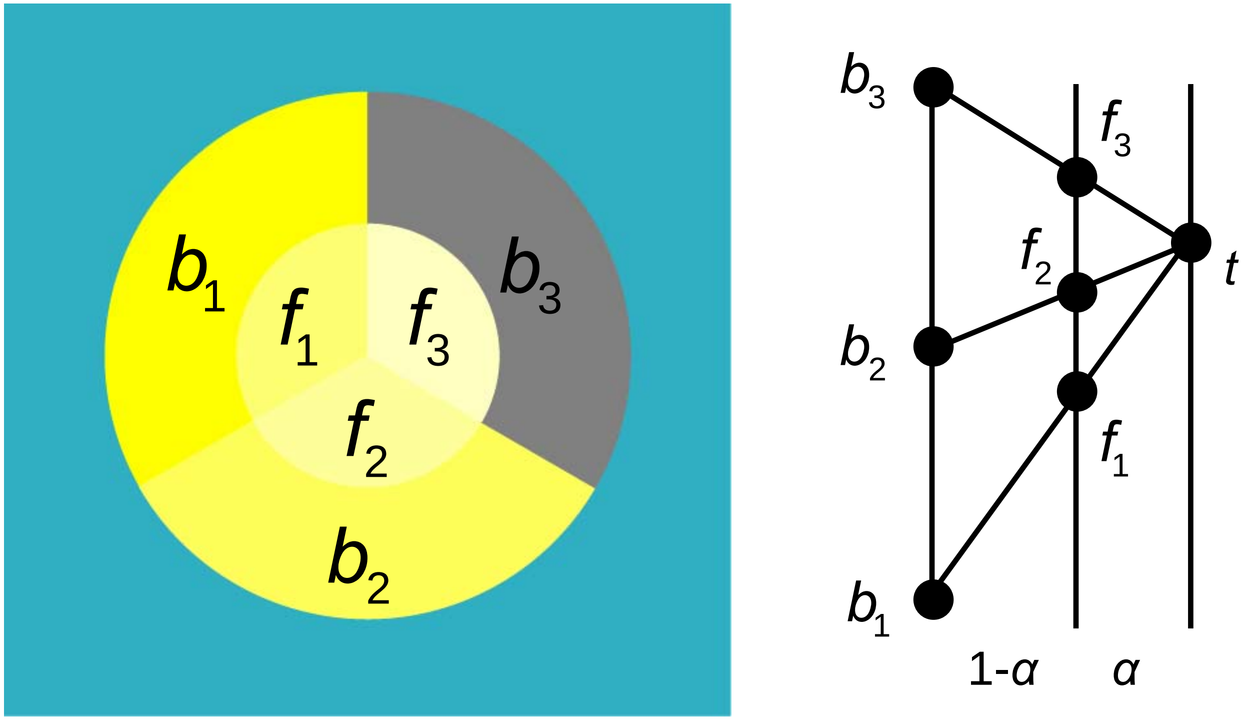
Figure 2



A

B

Figure 3



A

B

Figure 4

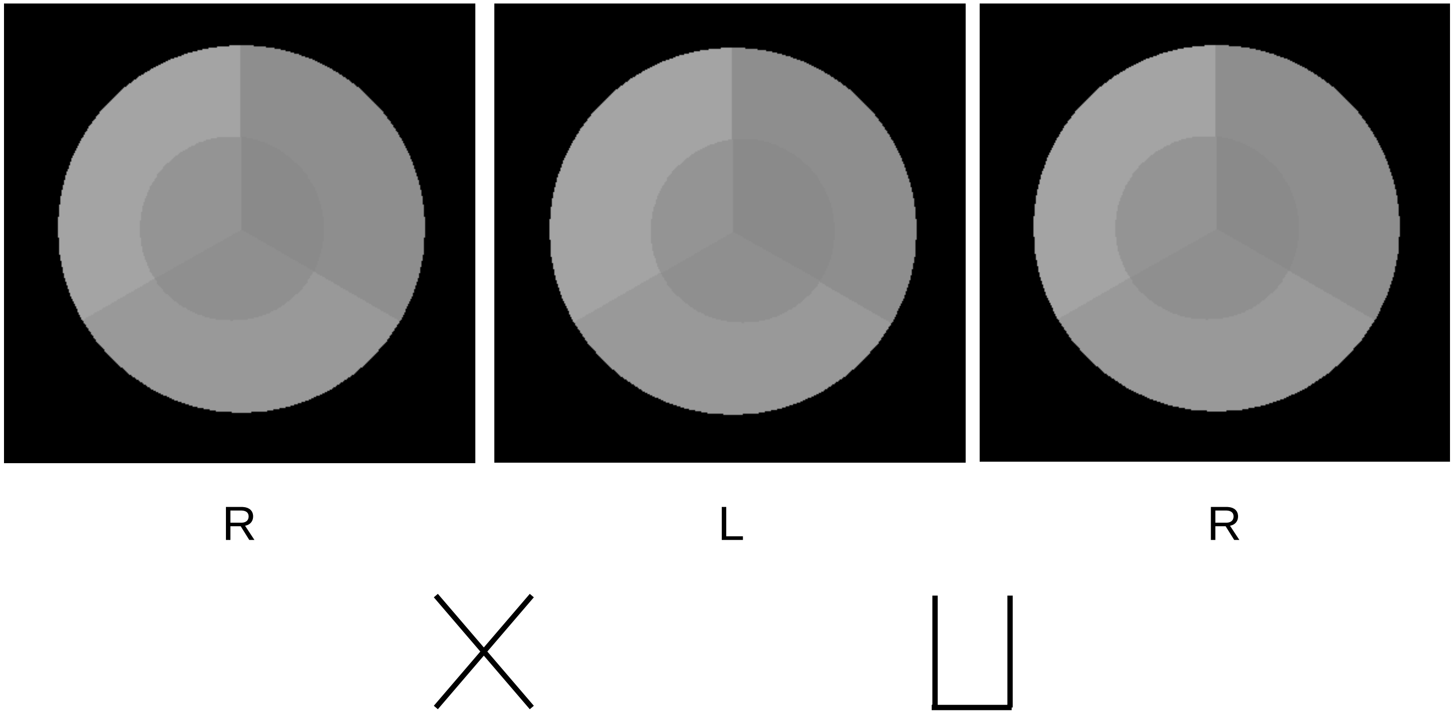
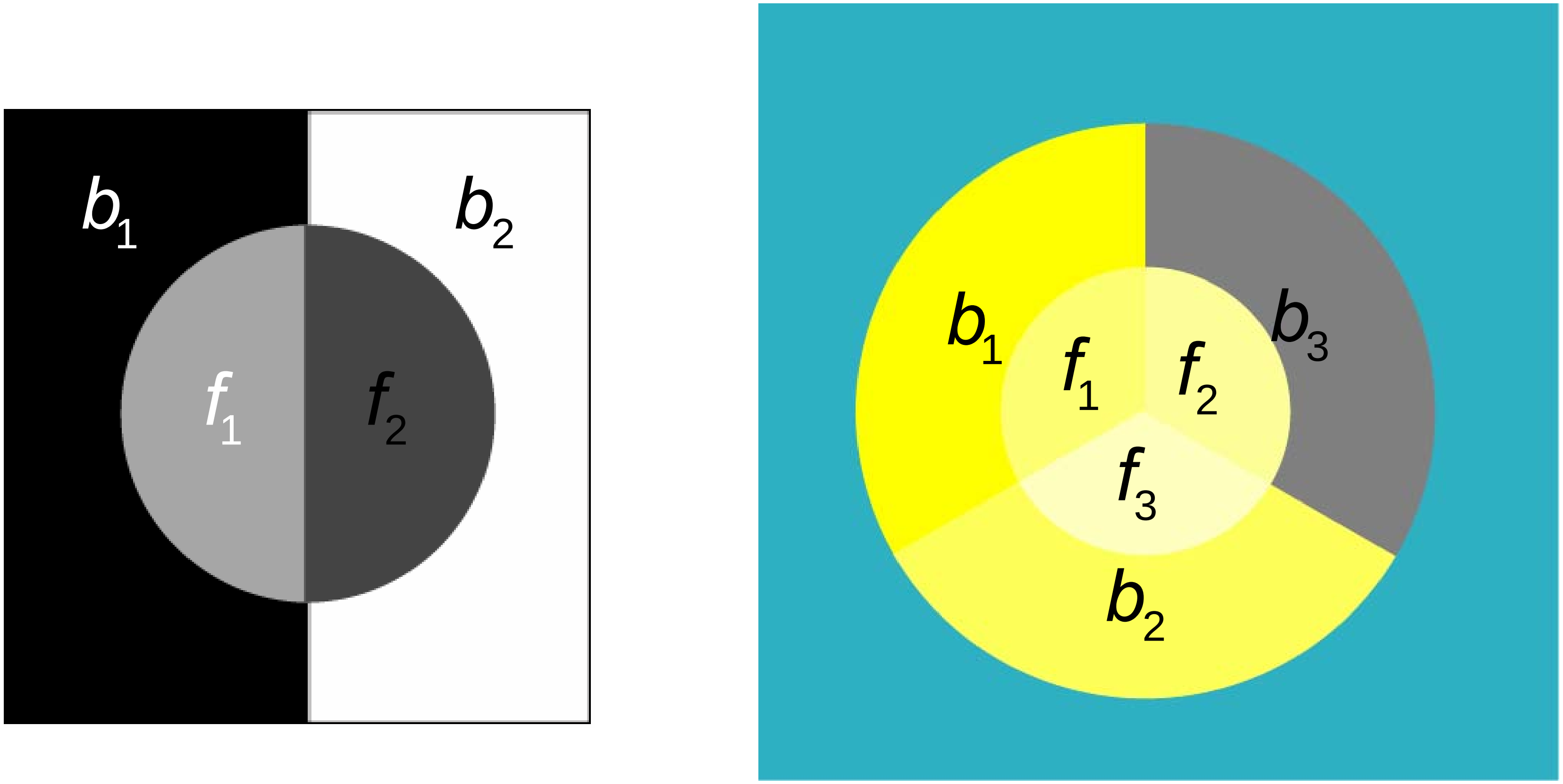


Figure 5



A

B

Figure 6

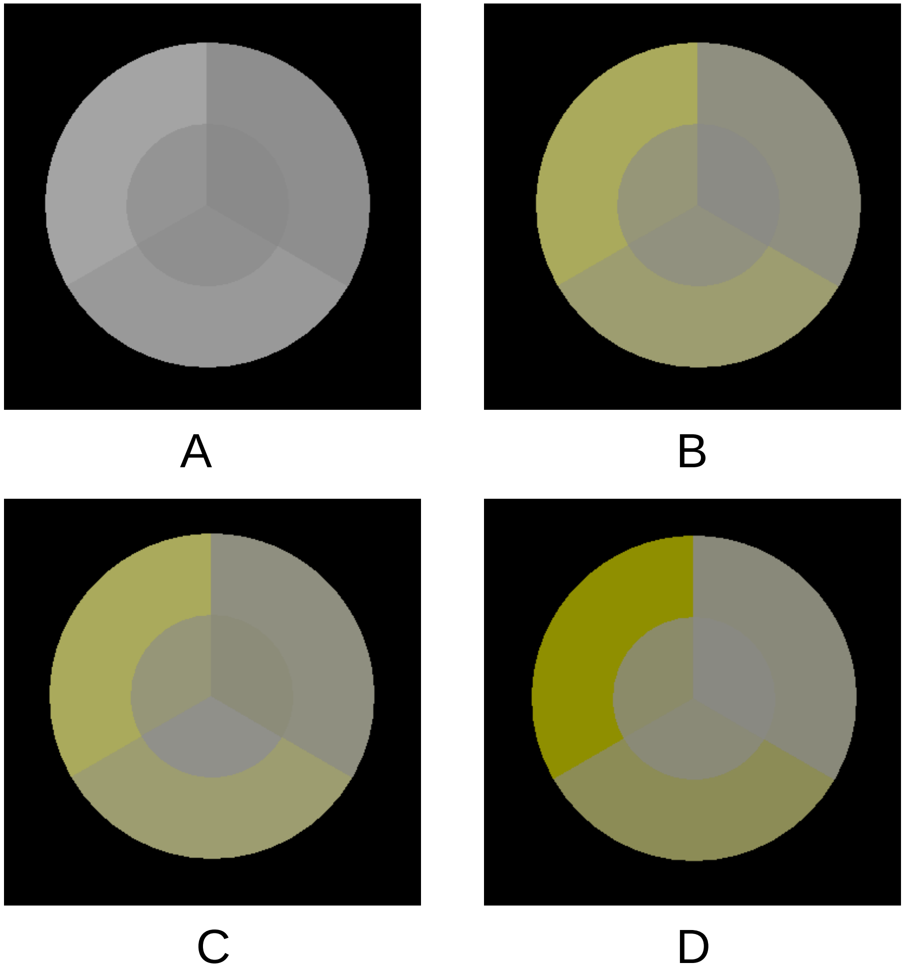
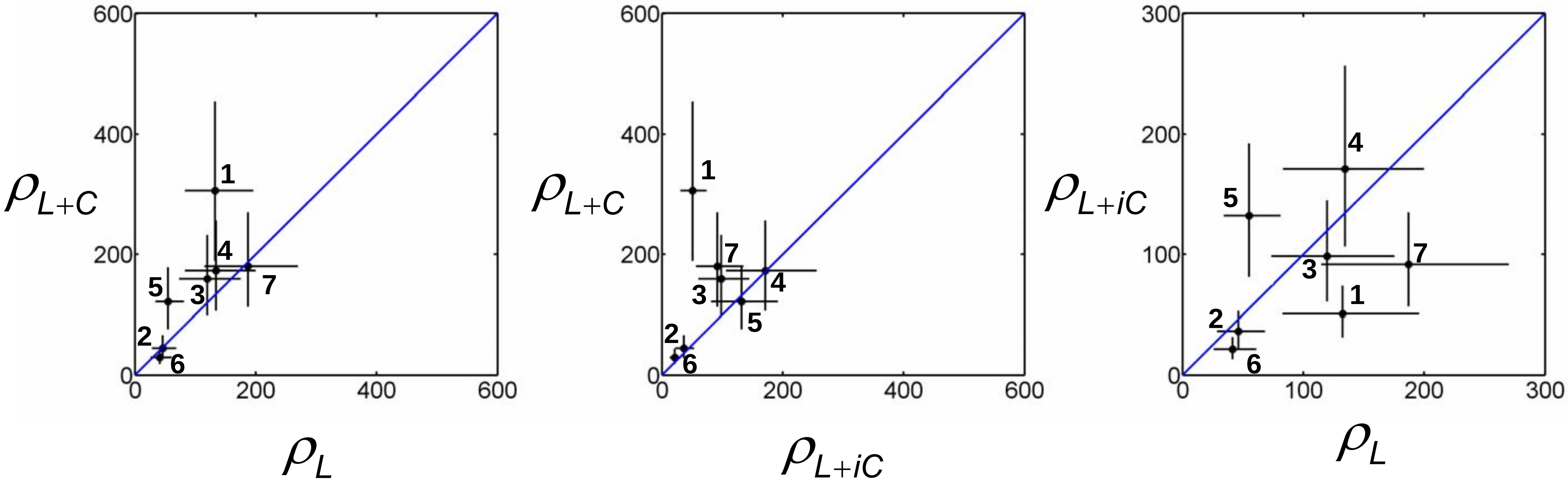


Figure 7

Reliability (ρ)



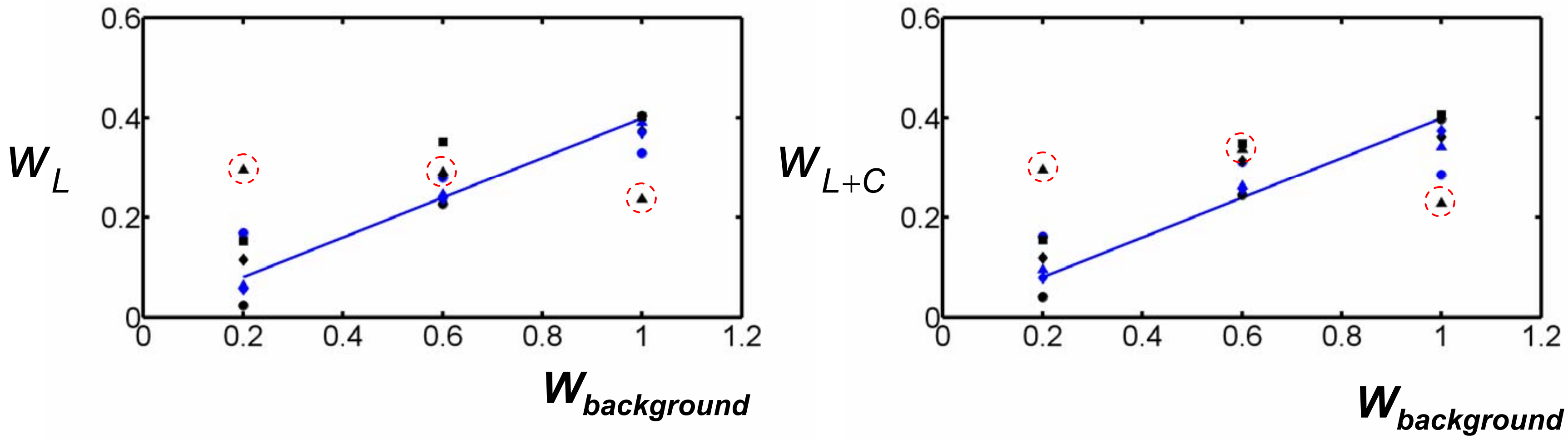
A

B

C

Figure 8

Mean settings (***w***)



A

B

Figure 9

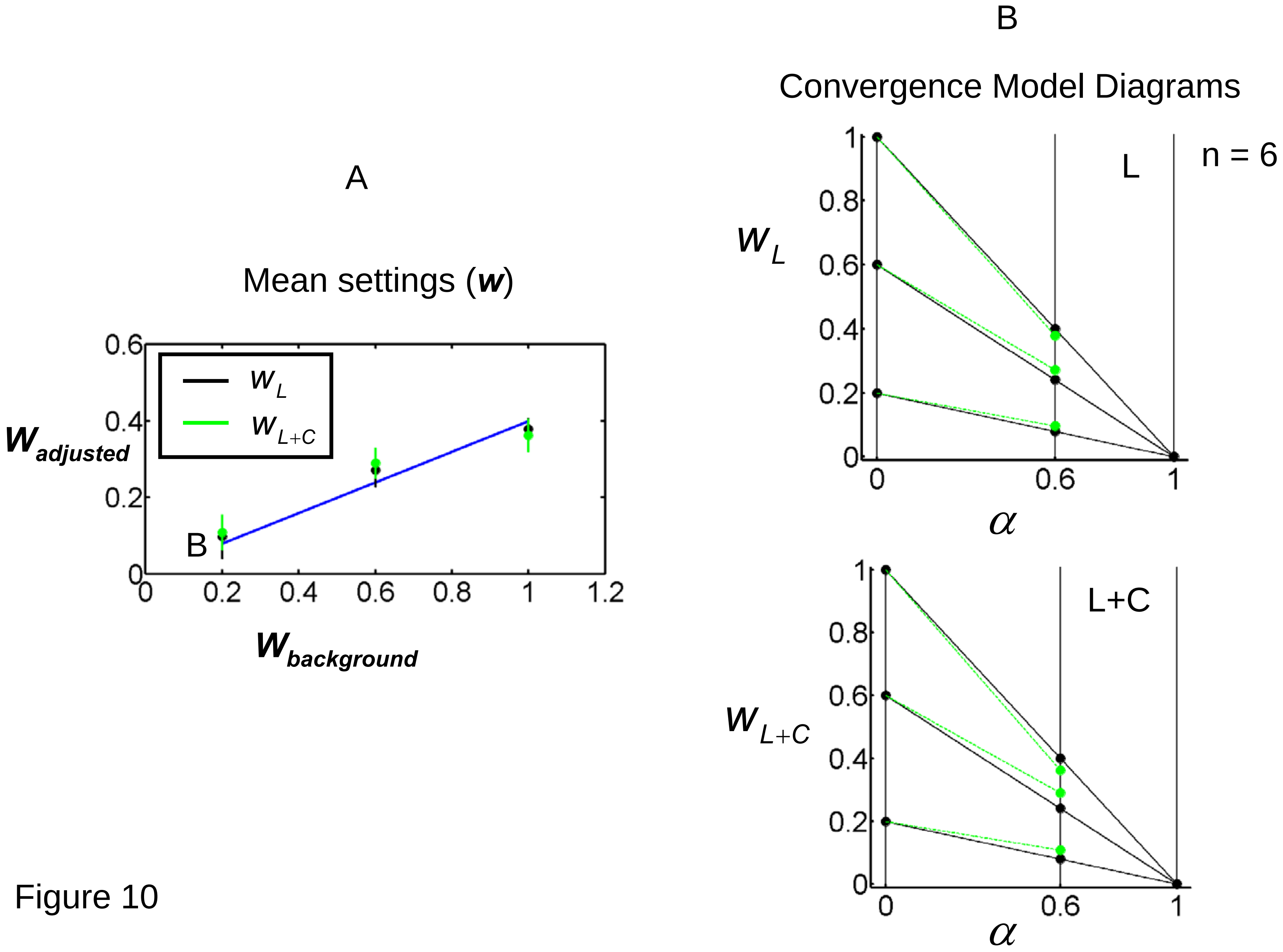
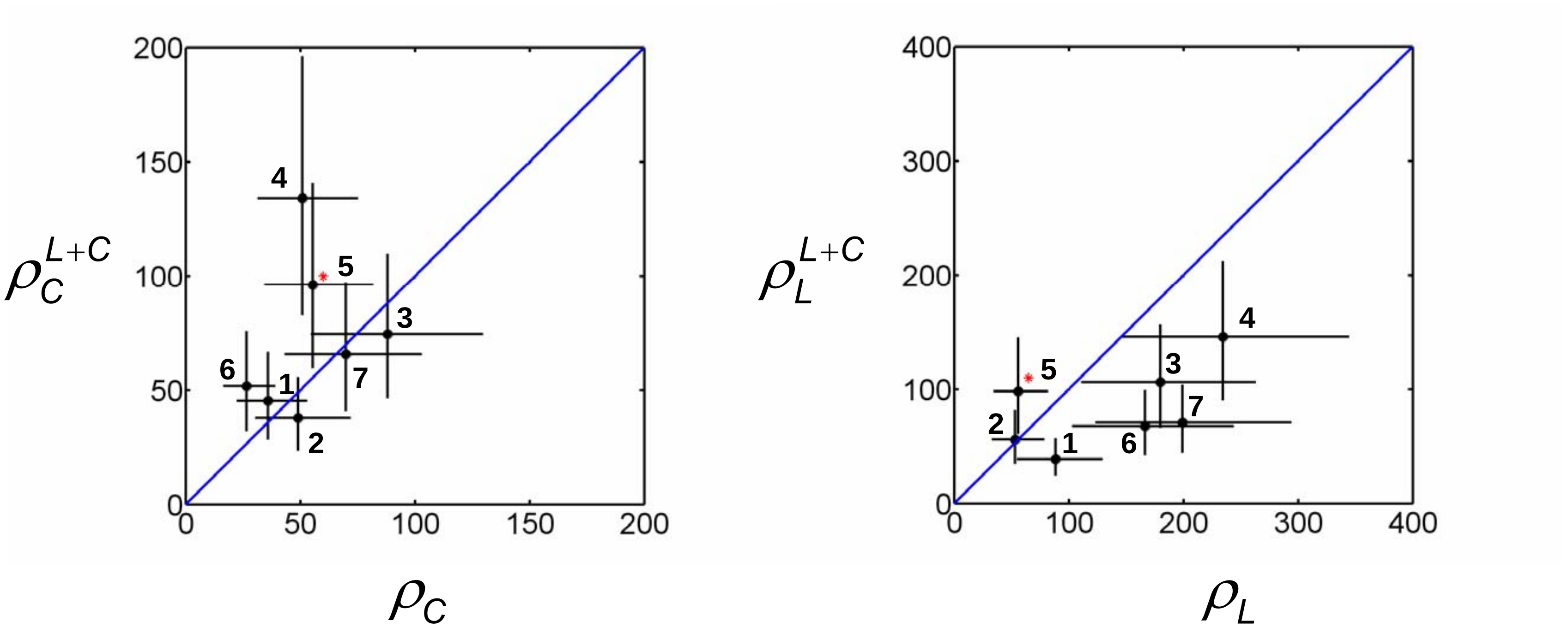

A
Mean settings (*w*)
$W_{adjusted}$
0.6
0.4
0.2
0
w_L
w_{L+C}
B
0
0.2
0.4
0.6
0.8
1
1.2
$W_{background}$
B
Convergence Model Diagrams
n = 6
L
W_L
1
0.8
0.6
0.4
0.2
0
0
0.6
1
α
L+C
W_{L+C}
1
0.8
0.6
0.4
0.2
0
0
0.6
1
α

Figure 10

Reliability (ρ)



A

B

Figure 11

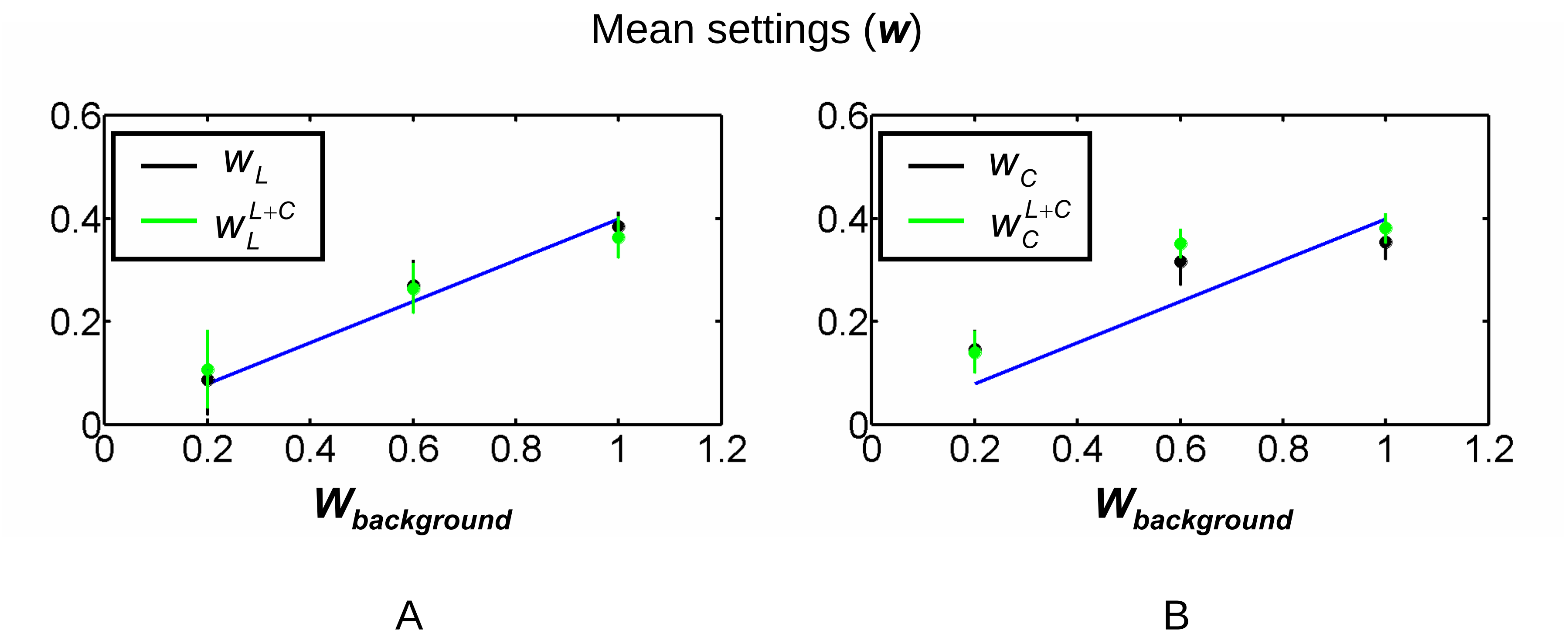

Mean settings (w)
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
W_background
w_L
w_L^{L+C}
A
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
W_background
w_C
w_C^{L+C}
B

Figure 12

Convergence Model Diagrams

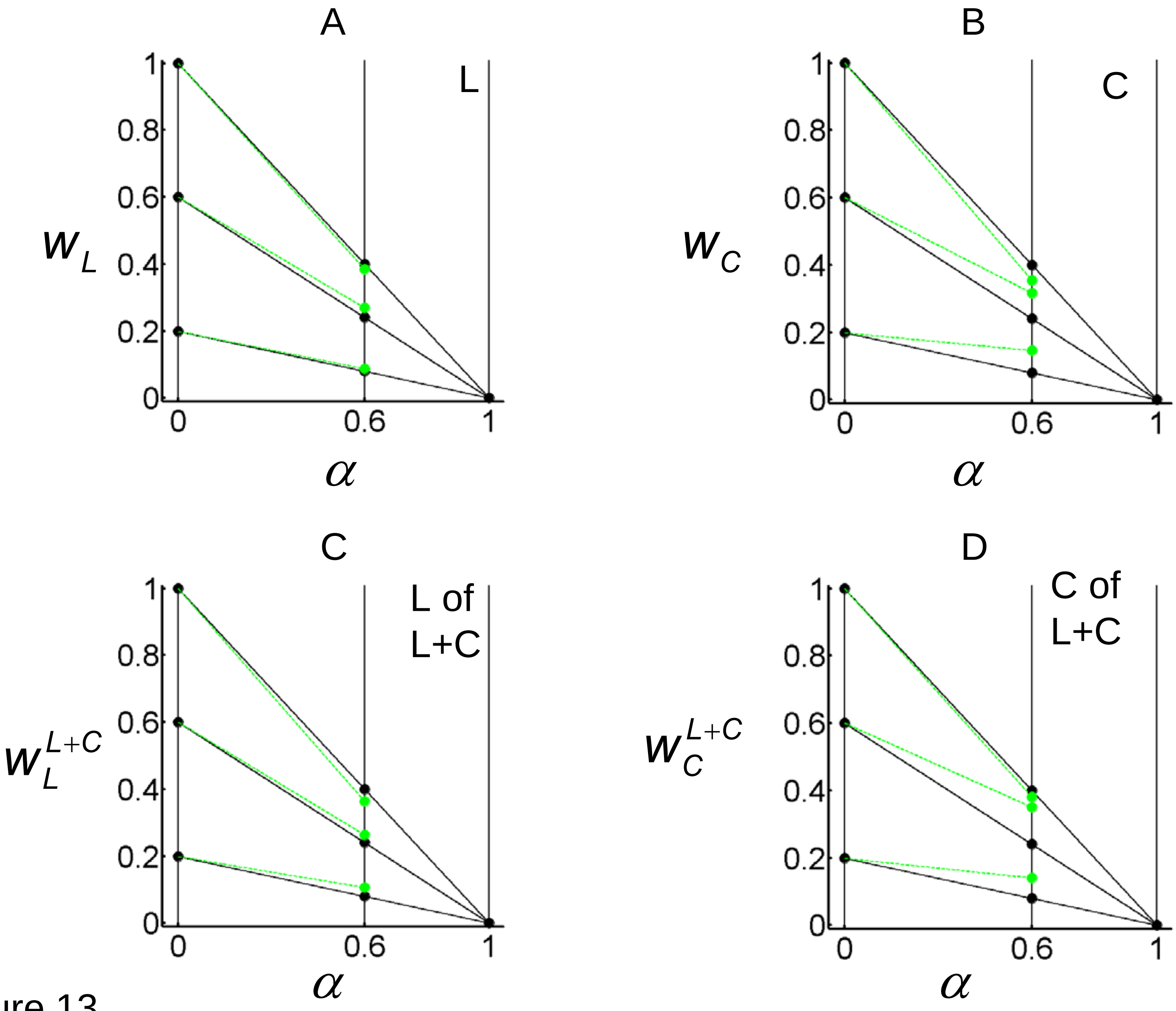


Figure 13

Reliability (ρ)

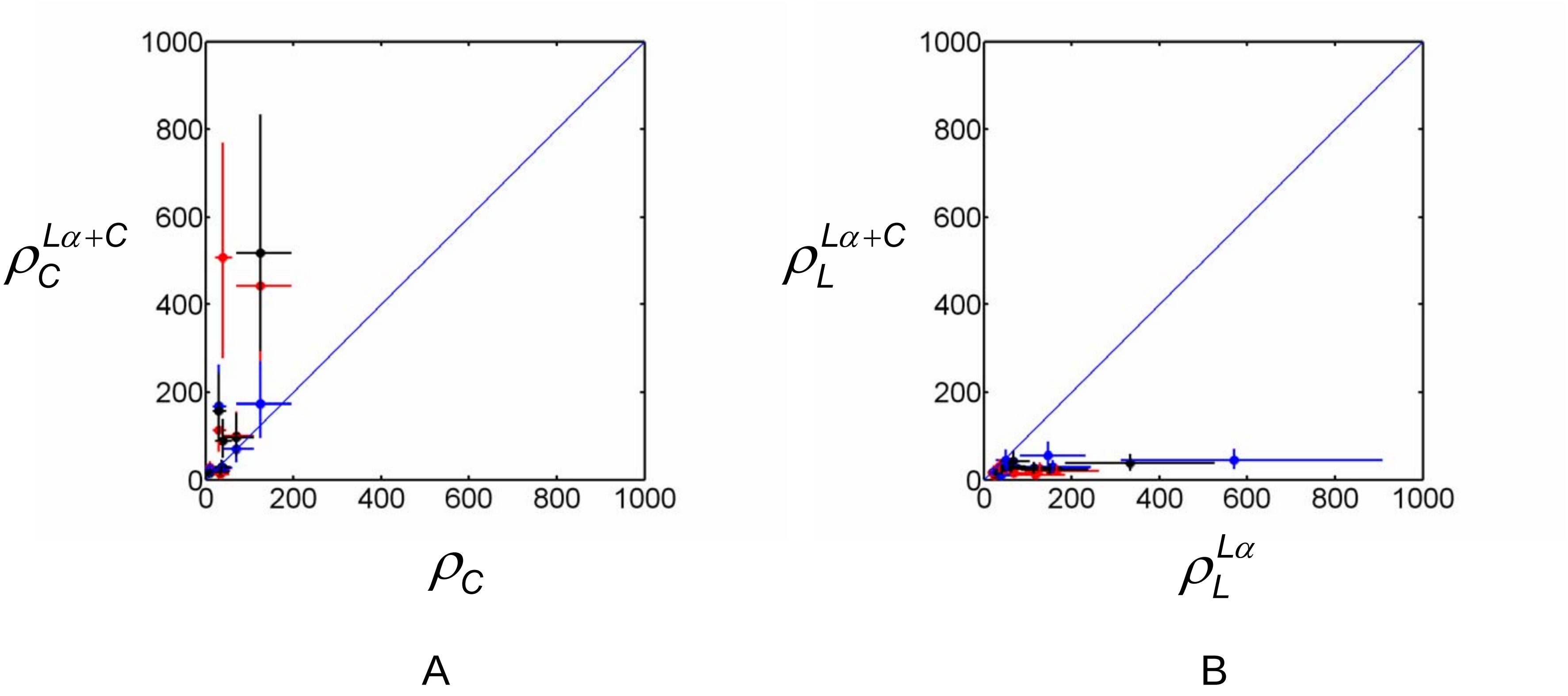


Figure 14

Mean luminance settings (***w***)

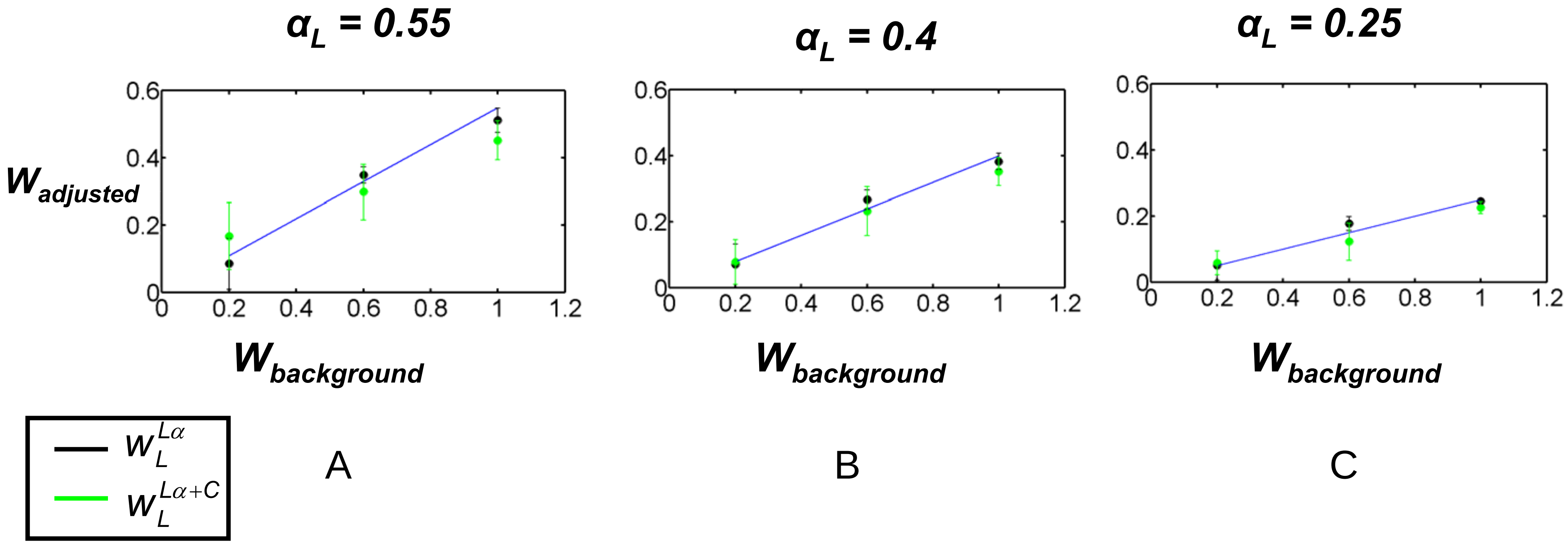
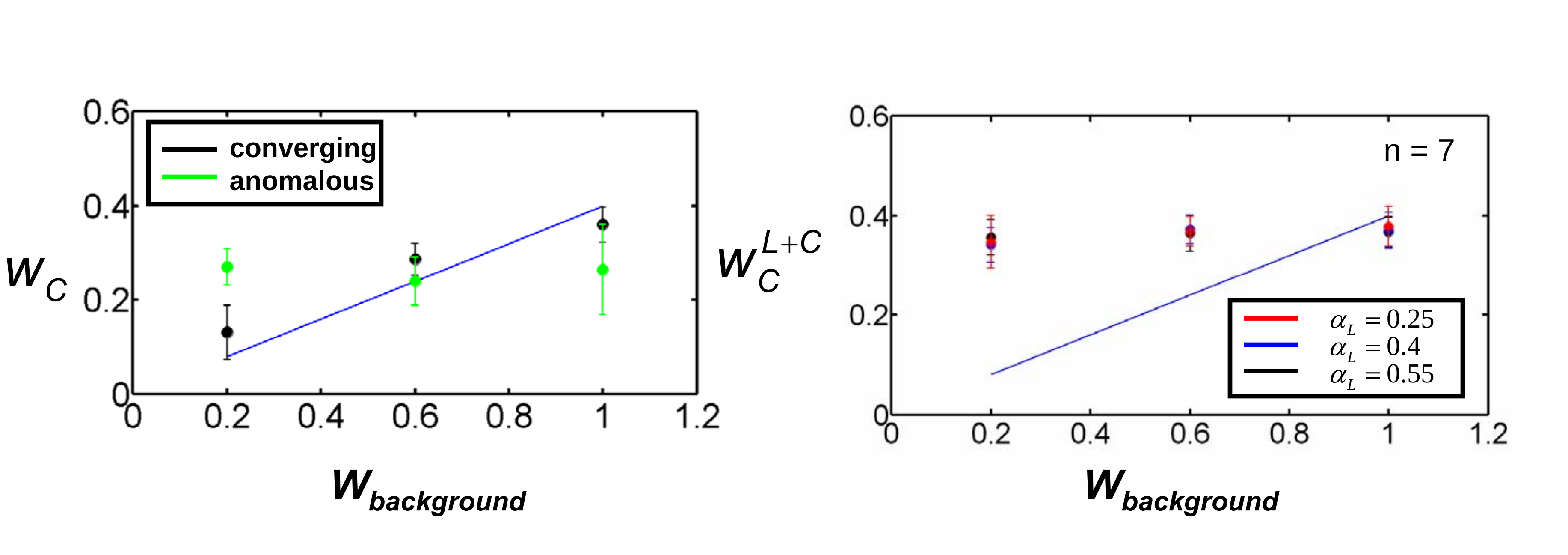


Figure 15

Mean color settings (***w***)



A

B

Figure 16