Perceived transparency of neutral density filters across dissimilar backgrounds

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We examine how the luminance distributions of overlaid surfaces affect the perception of transparency of neutral density filters. Pairs of neutral density filters were generated overlying variegated backgrounds of varying luminance distributions, and observers adjusted a single parameter of one filter until the pair appeared equally transparent. Physically identical filters appeared equally transparent on similar backgrounds, but did not appear equally transparent when backgrounds differed in luminance or contrast. Reducing luminance or contrast of the background decreased perceived transparency of the overlaying filter by a multiplicative factor. Observers matched perceived transparency of physically dissimilar filters by applying a linear trade-off between reflectivity and inner transmittance. In a second experiment, filters had their spatial structure altered in order to abolish the perception of transparency and appeared as patterned opaque disks, and observers equated perceived contrast of the two overlaid areas. Match settings gave results similar to the previous experiment, indicating that, in general, perceived transparency corresponds closely to the perceived contrast of the overlaid region.

Keywords: perceived transparency, perceived contrast, filter models

Introduction

In a previous study (Robilotto, Khang, & Zaidi, 2002a), we studied the phenomenal experience of transparency by asking observers to match the perceived transparency of physically different filters placed on identical backgrounds. We showed that matched perceived transparency is a one-dimensional percept that corresponded closely to matched perceived contrast of the overlaid region. We also showed that physically distinct filters perceived as equally transparent had very similar *transmittance, t* (proportion of incident radiant flux that passes through the entire filter), but could vary widely in *reflectance, r* (proportion of incident radiant flux reflected back from the filter). In the current study, we ask whether these determinants of perceived transparency generalize to cases where standard and matching filters are placed on dissimilar backgrounds, and whether physically identical filters appear equally transparent over variegated backgrounds that differ in mean luminance or contrast. We examine whether perceived transparency across dissimilar backgrounds remains a one-dimensional percept that corresponds to the perceived contrast of the overlaid region. We also test whether there is a systematic relation between perceived transparency and filter transmittance across dissimilar backgrounds.

Most early work on transparency perception simulated transparent layers with episcotisters, rapidly spinning disks with open wedge sectors. These devices simulate transparencies in accordance to an algebraic formula of color scission based on Talbot's law (Equation 1).

$$p = \alpha a + (1-\alpha)e \quad (1)$$

Here, the color of an overlaid region, p, is specified by a proportion, α, coming from the opaque layer's color, a, and the remaining proportion, $1 - \alpha$, coming from the filter's color, e. This model has been used to describe the perception of transparency based on physical reflectance values (Metelli, 1974a, 1974b, 1985), lightness values as nonlinear functions of reflectance (Beck, Prazdny, & Ivry, 1984), luminance values (Gerbino, Stultiens, Troost, & de Weert, 1990; Kasrai & Kingdom, 2001; Masin, 1997), subtractive color mixtures (Beck, 1978; Faul & Ekroll, 2002), and cone excitation ratios (Ripamonti & Westland, 2003; Westland & Ripamonti, 2000).

In this study, an algebraic formula that more closely approximates the natural properties of a real filter was used (Nakauchi, Silfsten, Parkkinen, & Usui, 1999). Neutral density filters were simulated from two independent physical properties: *reflectivity* and *inner transmittance* (Figure 1). *Reflectivity, β*, is a property of each air-filter interface and is dependent upon the index of refraction of the filter material. It is defined by the ratio of radiant flux reflected at a change in index, which occurs both at the front and back surface of a filter. *Inner transmittance, θ*, is a property of the filter media and is dependent upon the path length and absorptivity of the media. It is defined as the ratio of radiant flux reaching the back surface of the filter to the flux that enters the filter at the front surface (Wyszecki & Stiles, 1982). It is important to emphasize that β and θ are physically independent of each other with potential ranges of 0.0 to 100%. These two physical properties are used in this

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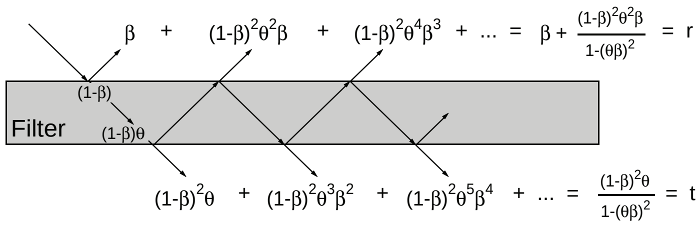

Figure 1. Model of a neutral density filter described by two independent properties: *reflectivity*, β, and *inner transmittance*, θ. β is defined by the ratio of radiant flux reflected at a change in index, and is factored in at both the front and back surface of a filter. θ is defined as the ratio of radiant flux reaching the back surface of the filter to the flux that enters the filter at the front surface, and is factored in during each internal pass. From these two properties, *reflectance*, *r*, the sum of all reflected radiant flux, and *transmittance*, *t*, the sum of all transmitted radiant flux, are determined.

study to define filter *reflectance*, *r*, and *transmittance*, *t* (Equations 2 and 3).

$$r = \beta + \frac{(1-\beta)^2\theta^2\beta}{1-(\theta\beta)^2} \tag{2}$$

$$t = \frac{(1-\beta)^2\theta}{1-(\theta\beta)^2} \tag{3}$$

Equations 2 and 3 show that whether β or θ is altered, both r and t are affected. When a filter is placed over an opaque surface with reflectance a, the transmitted light is reflected by the surface back at the filter and undergoes a series of reflections between the filter and the surface (Figure 2). At every pass through the filter (the first pass being indicated by the circled region), light again undergoes a complete series of internal reflections and transmissions. This model assumes that the filter's distance from the underlying surface is small relative to its distance from the illuminant. This makes the amount of light straying into or out of the overlaid region from the edges negligible. The

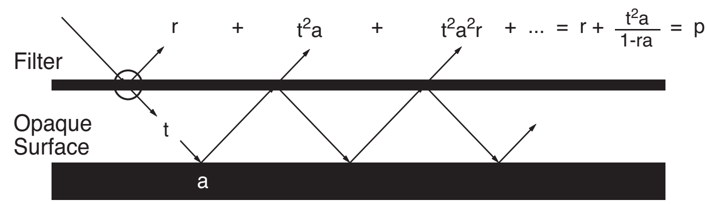

Figure 2. Model of the neutral density filter from Figure 1 overlaying an opaque surface with reflectance *a*. Transmitted light is reflected by the surface back at the filter and undergoes a series of reflections between the filter and the surface. At each pass through the filter (the first pass being indicated by the circled region), light again undergoes a complete series of internal reflections and transmissions. The total proportion of incident light reflected back from the overlaid area is indicated by *p*.

total proportion of incident light reflected back from the overlaid area is indicated by p (Equation 4).

$$p = r + \frac{t^2 a}{1-ra}$$

$$= \left[\beta + \frac{(1-\beta)^2\theta^2\beta}{1-(\theta\beta)^2}\right] + \frac{\left[\frac{(1-\beta)^2\theta}{1-(\theta\beta)^2}\right]^2 a}{1-\left[\beta + \frac{(1-\beta)^2\theta^2\beta}{1-(\theta\beta)^2}\right]a} \tag{4}$$

In this study, two filters were presented side by side (Figure 3). The standard filter had both its reflectivity and inner transmittance fixed throughout a given trial. The match filter had one of these two parameters fixed while the other was adjusted by the observer. In the first experiment, the observer was instructed to match the perceived transparency of the two filters. In the second experiment, the spatial arrangement of the overlaid area was manipulated so that transparency cues were abolished and the filters appeared as opaque disks (Figure 6). Observers were instructed to match the perceived contrast within the two disks to each other. In both experiments, filters were gener-

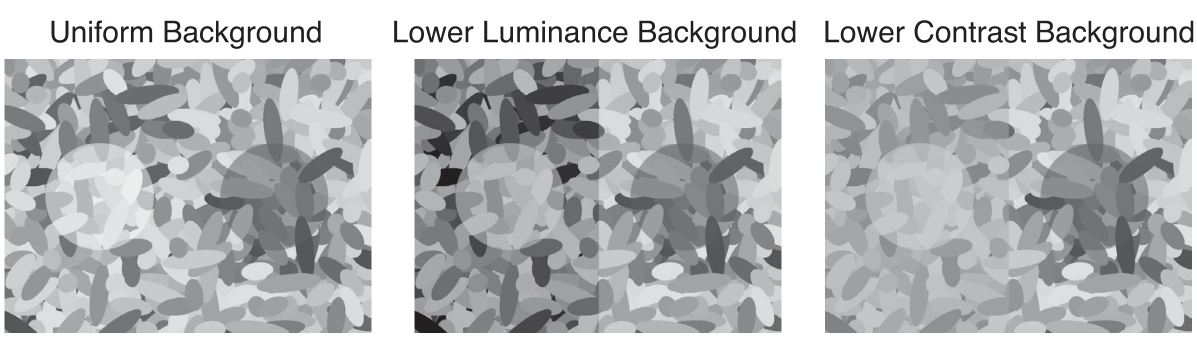

Figure 3. Examples of stimuli used in Experiment 1. The left side of each display contained the standard filter specified by a fixed β and θ value. The right side of each display contained the match filter, which had one of its properties fixed while the other was adjusted by the observer. The standard was presented over one of three background conditions, uniform, lower luminance, or lower contrast. Notice the X-junctions around the edges of the filters leading to transparency cues. Click on the figure to view a movie of a stimulus.

ated over different types of background conditions. In the uniform background conditions, both sides of the variegated background had the same luminance distribution. In the dissimilar background conditions, the side containing the standard filter had either the mean luminance or the contrast of its background reduced.

In the previous study (Robilotto et al., 2002a), filters were generated in a similar manner and presented over variegated backgrounds of uniform luminance distributions. Under these conditions, when the match filter had its fixed property, β or θ, set equal to that of the standard, observers accurately equated its variable property when matching perceived transparency. When the match filter had its fixed property set different from that of the standard, observers adjusted its variable property so that the settings formed linear functions in which reflectivity and inner transmittance were traded-off. The resulting matches were equated in filter transmittance, identifying it as the physical determinant of perceived transparency. It was also found that these functions of transparency match settings corresponded closely to functions of contrast match settings, indicating that perceived contrast is the likely sensory determinant of perceived transparency. We now extend this approach to conditions where physically different filters are placed over dissimilar backgrounds.

Experiment 1: Matching perceived transparency

Equipment

Stimuli presentation and data collection were computer controlled. Stimuli were displayed on the 36° x 27° screen (1024 × 768 pixels) of a Nokia Multigraph 445 Xpro 21" color monitor at a viewing distance of 60 cm. The refresh rate was 70 frames/s. Images were generated using a Cambridge Research Systems Visual Stimulus Generator (CRS VSG2/3), running in a 400-MHz Pentium II-based system. The system was calibrated for the use of 12-bit digital-analog converters with a Spectra-Scan PR-704 photospectroradiometer. After gamma correction, the VSG2/3 was able to generate 2861 linear gray levels. Any 256 gray levels could be displayed during a single frame. By cycling through pre-computed lookup tables, we were able to update the entire display each frame. During the experiment, observers looked through a dark box that masked off the monitor frame around the CRT screen, and room lights were kept off. Observer adjustments were made with a Cambridge Research Systems three-switch experiment response box.

Stimuli

Background materials were simulated as randomly sized, randomly oriented, overlapping ellipses with major axis lengths ranging from 2.2° to 6.6° and minor axis lengths of 1.8° (Figure 3). Seven different spatial layouts were drawn in image memory and a different layout was randomly chosen as the background on each trial. There were a total of 576 ellipses drawn in a layout, some of which were partially or completely occluded by others. On each trial, ellipses were randomly assigned one of 40 reflectance ratio values, a_i, ranging from 0.02 to 0.80 in 0.02 steps, with a mean of 0.41. The simulated illuminant was equal energy white, with CIE coordinates (0.33, 0.33). The display's maximum luminance of 48.51 cd/m^2 corresponded to a surface with 100% reflectance. For all other surfaces, luminance corresponded to this maximum value multiplied by the surface's reflectance ratio. The resulting luminance of the 40 ellipses ranged from 0.97 to 38.81 cd/m^2 in 0.97 cd/m^2 steps, with a mean of 19.89 cd/m^2.

A virtual boundary vertically bisected the background into a right and left half, and three separate background conditions were generated: *uniform*, *lower luminance*, and *lower contrast*. In the uniform background conditions, both halves of the background had the same luminance distribution. In the lower luminance conditions, all the surfaces on the left half of the display had their reflectance values reduced in half ($a'_i = a_i/2$), generating a mean luminance of 9.95 cd/m^2. In the lower contrast conditions, all surfaces on the left half of the display had their reflectances compressed in half around the mean ($a'_i = a_i/2 + \text{mean}\ (a_i)/2$). This decreased the contrast while keeping mean luminance the same.

For each trial, two filters were simulated, one on each half of the screen, as overlaying circular regions with diameters of 6.6°. Notice the X-junctions in Figure 3 that act as cues for transparency. The two overlaid regions moved in a synchronized clockwise motion along circular paths with 3.3° radii. Filters moved at a rate of one full circular path every 3.3 s. The advantages of moving a filter were multifold: a moving filter can overlay more materials than a static filter, increasing the probability of the overlaid materials being unbiased in a given set of materials, and the movement of filters greatly enhances the emergence of transparent layers (D'Zmura, Rinner, & Gegenfurtner, 2000; Khang & Zaidi, 2002). In Figure 3 the filters have been enlarged and centered on their respective halves of the display.

Filters were defined by their reflectivity, β, and inner transmittance, θ. The filter on the left was always one of nine standard filters designated by a combination of one of three β_s values (0.1, 0.2, 0.3) and one of three θ_s values (0.5, 0.6, 0.7). Both physical properties of the standard filter were held fixed in a given trial. The filter on the right was always the match filter. One of its physical properties was fixed while the other was adjustable by the observer. Either β_m was fixed at one of three values (0.1, 0.2, 0.3) and θ_m was adjustable, or θ_m was fixed at one of three values (0.5, 0.6, 0.7) and β_m was adjustable. The adjustable property in either case could be varied throughout its entire physical range of 0.0 to 1.0. In the dissimilar background conditions, it was always the match filter that was simulated over the lower luminance or lower contrast backgrounds.

Procedure

Observers were instructed to adjust the properties of the match filter until the two filters appeared equally transparent using a three-switch response box. Each of the three switches has a resting middle position and can be pressed either up or down. By pressing the left switch up and down, the match filter's adjustable parameter could be increased or decreased through its entire range. The right switch did the same, but more slowly, and was used to fine-tune the filter's appearance. If the observers were able to make a satisfactory match, they were instructed to press the middle switch up. If no matter how they adjusted the match filter, a satisfactory match could not be made, they were instructed to set the match filter as close as possible and then press the middle switch down. Once the middle switch was pressed in either direction, the display would freeze for 2 s, the setting would be recorded, and the next background with moving overlaid filters would appear.

Six match filters, three with different fixed reflectivity and three with different fixed inner transmittances, were matched to each of the nine standard filters, resulting in 54 conditions for each of the three background types. In a single session, each of the 54 conditions was presented once in a randomly determined sequence. Three observers with normal visual acuity participated in this study. For each background condition, observer RR completed 10 sessions, and observers SS and SC completed five sessions. There was no time limit on any part of this experiment and observers were allowed to take breaks at any time. Each session lasted approximately 40 min.

In the observers' instructions, no further definition of "transparency" was provided, and observers were not informed about the parameters that they were adjusting. We wanted to see whether observers could consistently match the perceived transparency of filters with physically different properties without a more stringent definition of the task. Before collecting data, observers were given a few practice runs in which they equated transparency across filters; some of which were similar, while others were quite different in appearance. All observers found it easy to equate their perception of degree of transparency for filters that were different in lightness or darkness. Note that RR is the first author while SS and SC were naive about the issues behind the study.

Results

The transparency match settings from Experiment 1 are plotted in Figure 4 in terms of reflectivity and inner transmittance. Each block of plots represents data from one of the three observers under one of the three background conditions. The nine subplots within each block represent the nine standard filters, whose reflectivities and inner transmittances are represented by the horizontal and vertical lines respectively. The six data points within each subplot represent the match settings for the six different match filter conditions for that standard. The three open blue triangles represent match filters whose inner transmittances were fixed and whose reflectivities were adjusted by the observer. The three open red circles represent match filters whose reflectivities were fixed and whose inner transmittances were adjusted by the observer. These two properties are independent of each other; therefore, as the observer adjusts the variable property, the triangles can only be shifted in the vertical dimension, while the circles can only be shifted in the horizontal dimension. Each data point represents the average of 10 match settings for observer RR and five match settings for observers SS and SC. Of the 3,240 match settings across the three observers under all conditions in Experiment 1, only 6 were judged as being not satisfactorily equal in perceived transparency after the best adjustment.

To help clarify Figure 4, it can be related to the example illustrated in Figure 3. In the first panel of Figure 3, the standard filter on the left has a high reflectivity (0.3) and a high inner transmittance (0.7). Within a given block of subplots in Figure 4, this standard corresponds to the upper right subplot (solid lines intersecting at $\beta = 0.3$, $\theta = 0.7$). The match filter on the right has its reflectivity fixed at a lower value (0.1), hence its lower luminance value, and is represented by the lowest circle in that subplot. The match filter appears more transparent than the standard, and in order to equate perceived transparency, the inner transmittance of the match is set lower than that of the standard. This results in the corresponding data point being shifted horizontally to the left.

Figure 4 shows that for each background condition, the pattern of match settings is similar across the three observers. Notice that in each subplot, one of the three variable β_m matches will have its θ_m fixed at a value identical to the standard's θ_s (indicated by the triangle on the vertical line), and one of the three variable θ_m matches will have its β_m fixed at a value identical to the standard's β_s (indicated by the circle on the horizontal line). Here it is possible to equate both properties between the filters and make veridical matches. These conditions act as controls and measure how accurately observers match physically identical transparent layers under the given task. For all other points, the fixed parameter of the match is set different from that of the standard. No matter how the adjustable property is set, even when perceived transparency is equated, the match will be physically different from the standard.

In the uniform background conditions, when the fixed properties of the two filters were equal, it is clear that observers were able to accurately equate the variable property. This is seen in each subplot by the circle fixed along the horizontal line being equated to its standard's θ, and the triangle fixed along the vertical line being equated to its standard's β. In other words, the data points fixed on each orthogonal line are set close to, or on top of, the intersection point of the lines, indicating that those match filters and their standard are physically the same.

In the uniform background conditions, when the fixed property of the match was set different to that of the standard, there was a consistent and linear trade-off between reflectivity and inner transmittance, when equating perceived transparency. When the fixed property of the match filter was set higher than that of the standard, observers set the match's variable property higher. When the fixed property of the match filter was set lower than that of the stan-

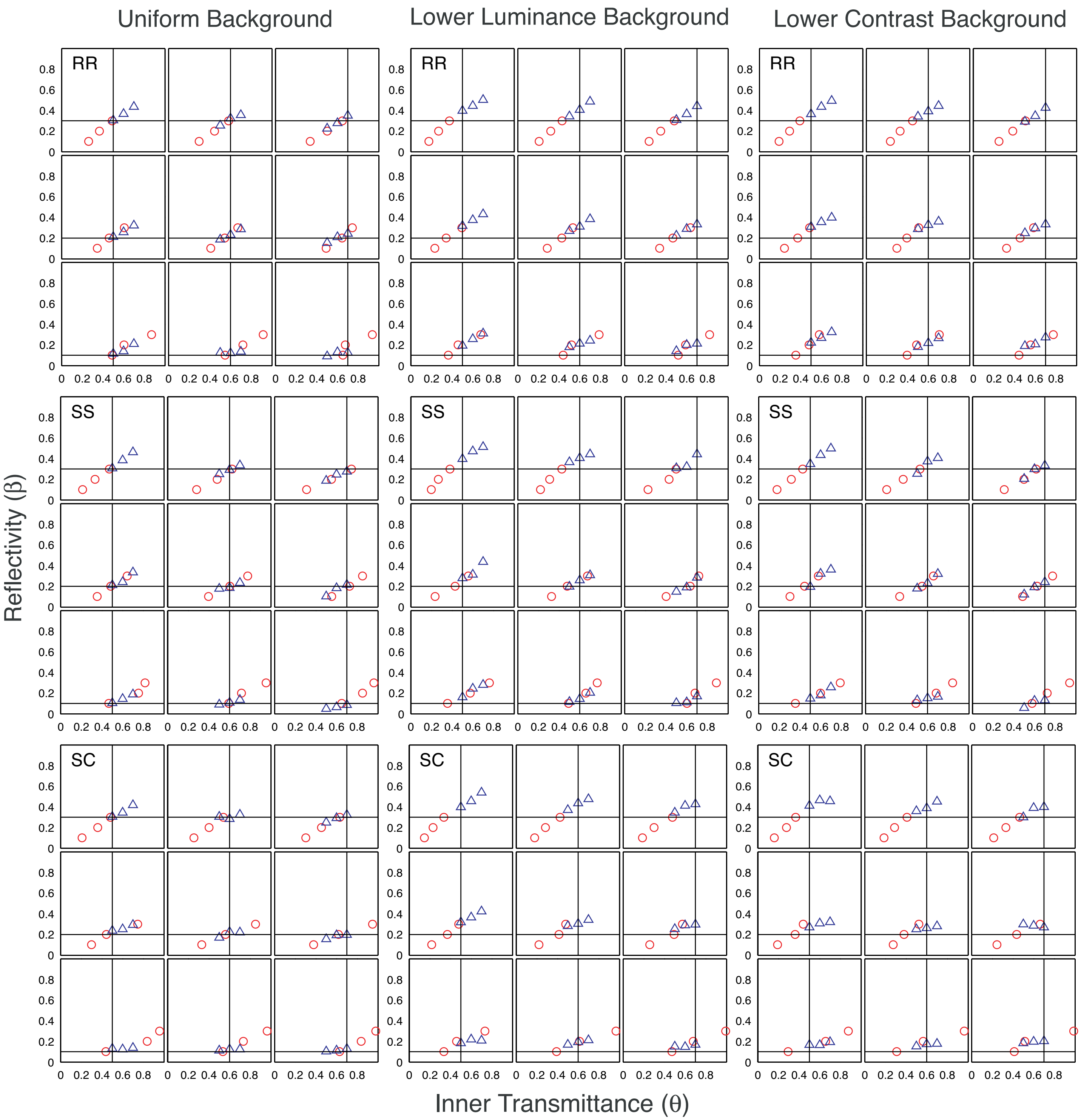

Figure 4. Mean match settings from Experiment 1 for the three observers under the three background conditions. The nine subplots within each block represent the nine standard filters. The properties of the standard filters are defined by the intersection of the orthogonal lines. For each standard, the three blue triangles represent match filters with fixed θ_m and adjustable β_m, and the three red circles represent match filters with fixed β_m and adjustable θ_m.

dard, observers set the match's variable property lower. These settings form linear functions that intersect the origins as specified by the standards. Conversely, in the lower luminance and lower contrast background conditions, when the fixed property of the match was different from that of the standard, observers did not equate the variable property. This is seen in the plots with the variable β_m settings shifted above the intersection points, and the variable θ_m settings shifted to the left of the intersection points. The remaining data points show a similar translation, resulting in consistent trade-offs between reflectivity and inner transmittance forming linear functions that do not intersect the origins specified by the standards.

Figure 5 further illustrates match settings for identical filters by presenting only settings from Experiment 1 in which the match filter had its fixed property set equal to that of the standard (conditions represented by symbols fixed on the orthogonal lines in Figure 4). Each pair of subplots represent a single observer under a given background condition. Left subplots represent the mean (±1 SD) of all adjustable θ_m settings versus θ_s, when β_m equaled β_s. Right subplots represent the mean (±1 *SD*) of all adjustable β_m settings versus β_s, when fixed θ_m equaled θ_s. The dashed lines represent the unit diagonal, or where the match filter's adjustable property would equal that of the standard. In these conditions, because the match filter's fixed property is already equal to that of the standard, any setting lying along the unit diagonal would make the two filters physically identical. In the uniform background conditions, mean settings are close to and almost always within 1 *SD* of the unit diagonal. This indicates that when fixed properties are equal, variable properties can be accurately equated as well. However, in the lower luminance and lower contrast conditions, mean match settings fall significantly below the unit diagonal for adjustable θ_m conditions, and significantly above the unit diagonal for adjustable β_m conditions. In other words, when observers equated perceived transparency of these filters, they either lowered the match filter's inner transmittance to a value less than its standard, or raised the match filter's reflectivity to a value greater than its standard. These actions both have the effect of decreasing the luminance range of the overlaid area and decreasing transmittance. Given that the variable parameter is not equated when the fixed parameter is equal, physically identical filters on different backgrounds do not appear equally transparent. This can also be demonstrated by clicking on Figure 3 to view an example movie. In the movie, the two filters are simulated with identical physical proper-

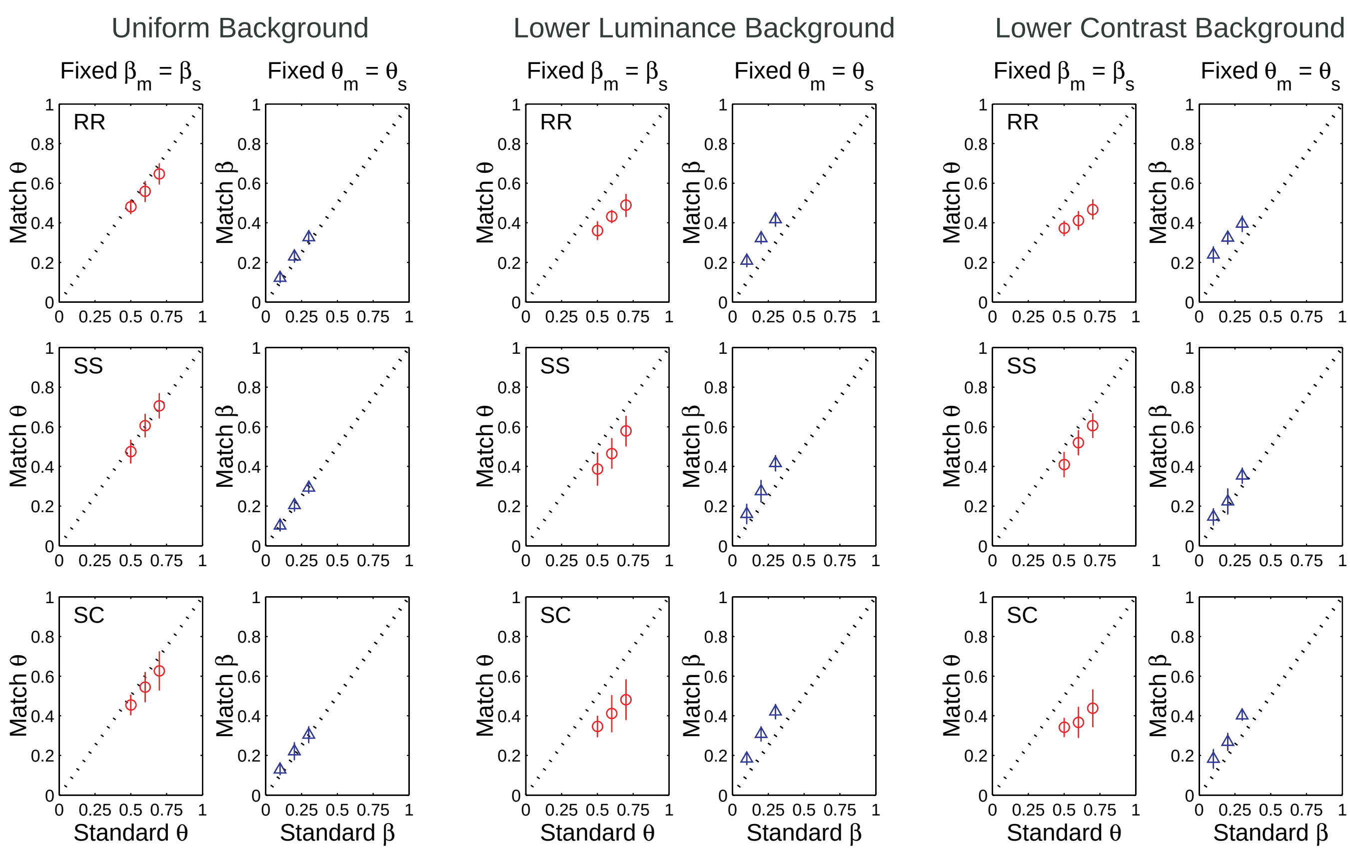

Figure 5. Mean match settings of adjustable properties (± 1 *SD*) versus standard properties for conditions where the fixed property of the match was set equal to that of the standard. Pairs of subplots are for the three observers in each of the three background conditions. For each pair, the left subplot represents all adjustable θ_m settings when fixed $\beta_m = \beta_s$. The right subplot represents all adjustable β_m settings when fixed $\theta_m = \theta_s$. Dashed lines represent the unit diagonal, where the setting would lie to equate both properties.

ties, yet the filter over the lower luminance background is perceived as less transparent. It can be concluded that decreasing a variegated background's mean luminance or contrast decreases the degree of perceived transparency of an overlaid filter.

The results of Experiment 1 also confirm the one-dimensionality of perceived transparency for broader conditions. In order for a percept to be considered one-dimensional, certain requirements must be met (Brindley, 1970; Zaidi, 1992): (1) one control should be sufficient to achieve a match, (2) perceived matches should be possible in all conditions within range, and (3) if two independent controls are used in two separate trials, the perceived matches should be the same or fall on the same function. In this experiment, all three requirements were met for matches of perceived transparency: (1) observers were able to achieve matches by adjusting either reflectivity, or inner transmittance, (2) matches were judged satisfactory by the observers in 3,234 out of 3,240 trials, and (3) the tradeoffs between reflectivity and inner transmittance form the same functions for reflectivity adjustments as inner transmittance adjustments. Match settings made by adjusting reflectivity overlap the match settings made by adjusting inner transmittance and would be indistinguishable if plotted with the same symbols.

Experiment 2: Matching perceived contrast

Varying the reflectivity of a filter has different effects on mean luminance and luminance range of overlaid areas than varying the inner transmittance of a filter. For a fixed reflectivity, when inner transmittance is increased, the overlaid region increases in mean luminance and luminance range. For a fixed inner transmittance, when reflectivity increases, the overlaid region increases in mean luminance but decreases in luminance range. In Experiment 1, even though the overlaid regions were often of disparate luminance, equating perceived transparency was almost always possible. This effectively rules out luminance as a determinant of perceived transparency.

In a previous study (Robilotto et al., 2002a), we found that perceived contrast was equated when observers matched perceived transparency. Other studies, using tripartite or sinusoidal backgrounds (Kasrai & Kingdom, 2001; Singh & Anderson, 2002b), have shown that Michelson contrast predicts perceived transparency. Due to our complex variegated background, Michelson contrast, as well as other standard contrast metrics (Moulden, Kingdom, & Gatley, 1990) are not sufficient predictors (Robilotto et al., 2002a). We now attempt to generalize the relationship between perceived contrast and perceived transparency to conditions of dissimilar backgrounds.

To test whether perceived contrast is the sensory determinant of perceived transparency, observers were asked to equate perceived contrast of similar filter stimuli over multiple background conditions. In order to separate perceived contrast from perceived transparency, the stimuli were altered to remove cues to transparency (Figure 6). If observers were using perceived contrast as the sensory determinant of perceived transparency, the match settings in Experiment 2 should be similar to the settings made in Experiment 1.

Procedure

The three background conditions in Experiment 2 were identical to those of Experiment 1, and two circular regions overlaid by filters were presented on either side of the display. Unlike Experiment 1 in which the spatial pattern of the overlaid layers corresponded to the background directly beneath them, the spatial pattern of the overlaid layers in Experiment 2 corresponded to fixed patches of background. These fixed patches came from each filter's respective side and from areas outside the observer viewing area. This had the effect of replacing transparency-inducing X-junctions along the edge of the filters in Figure 3 with occluding T-junctions, which break figural unity between the overlay and the background (Anderson, 1997; Kasrai & Kingdom, 2002; Watanabe & Cavanagh, 1993). During

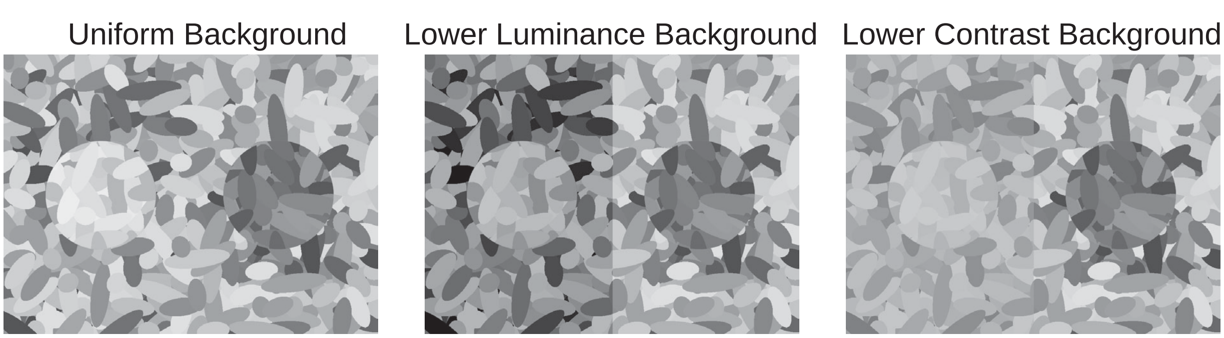

Figure 6. Examples of stimuli used in Experiment 2. The same filter model used in Experiment 1 determines the luminances of the overlaid areas, but the spatial configurations are consistent with opaque, patterned disks. Notice how the occluding T-junctions around the edges of the overlaid regions make the simulated filters appear as opaque patterned disks. Click on the figure to view a movie of a stimulus.

presentation, the overlaid regions moved in the same synchronized clockwork motion used in Experiment 1, but their spatial pattern remained unchanged. The resulting stimuli appeared as opaque, patterned disks moving over a variegated background. Click on Figure 6 to view an example movie. In the movie, the two disks have been simulated from filters with identical physical properties.

Experimental parameters were otherwise identical to those used in Experiment 1. The filter on the left was always one of nine standard filters designated by a combination of one of three β_s values (0.1, 0.2, 0.3) and one of three θ_s values (0.5, 0.6, 0.7). The match filter had either its β_m or θ_m fixed while the other was adjustable. The observer's task was to match the perceived contrast within the two opaque disks to each other. As in Experiment 1, the local luminances of the overlaid regions were calculated on the basis of the reflectivities and inner transmittances of the filters and the reflectances of the background surfaces in accordance to Equation 4. In this way, observers were adjusting perceived transparency in Experiment 1 and perceived contrast in Experiment 2 by adjusting the same two properties, β and θ. The adjustable property was varied using the same response box in the manner previously described.

Results

The data from Experiment 2 were analyzed in an identical fashion to the data from Experiment 1 and plotted in Figure 7. Again, each of the nine blocks of plots represents data from a single observer under a single background condition. The nine subplots within each block represent the nine standard filters, whose reflectivities and inner transmittances are represented respectively by the horizontal and vertical lines. The six data points in each plot represent the mean match settings for the six different match filter conditions for each standard. The three open blue triangles represent the three conditions where the match filter's inner transmittance was fixed and the observer adjusted reflectivity. The three open red circles represent the three conditions where the match filter's reflectivity was fixed and the observer adjusted inner transmittance. Each data point represents the average of 10 match settings for observer RR and five match settings for observers SS and SC.

In Experiment 2, under uniform background conditions, observers were able to accurately equate the variable property when the fixed property of the two filters was equal. This is shown by data points on the orthogonal lines being set close to the intersection point. When the fixed properties were different, there was a consistent and linear trade-off between reflectivity and inner transmittance. For conditions of dissimilar backgrounds, when the fixed properties of the two filters were equal, observers did not equate the variable property. In other words, identical filters over dissimilar backgrounds appear different in perceived contrast. Instead of equating the variable property, observers set the match filter's reflectivity higher and inner transmittance lower than that of the standard. These both have the effect of making the match filter more opaque and lowering its contrast. This counters the lower contrast within the standard's overlaid area due to the reduction of mean luminance or contrast of the standard's background.

For comparison of perceived transparency and perceived contrast, the match settings from Experiment 1 are superimposed on the plots as dots in Figure 7. The pattern of results is almost identical between the two experiments. In almost all conditions, the dots representing match settings for perceived transparency fall within or near the symbols representing match settings for perceived contrast. Figure 7 makes it clear that observers make the same settings when asked to match contrast as they did when asked to match perceived transparency. Given that the same settings are made, it is likely that perceived contrast of the overlaid regions is the sensory determinant of perceived transparency, even for conditions of dissimilar backgrounds.

Discussion

The question underlying this study is, can physically different filters be ranked or equated on a perceptual dimension such as "degree of perceived transparency"? In some cases where one is asked to isolate one quality from multi-quality stimuli, the conceptual unity of a quality may not be a perceptual unity. Despite this, we were curious about the quality that is called transparency in the vernacular. So in our previous paper (Robilotto et al., 2002a), we asked observers to match two physically different filters for "transparency," while giving them control over one of two independent physical parameters of the stimulus. The observers could have done a number of things: rejected any match (this happened a few times where the controls were lacking in range), matched the mean luminance of the overlaid sections, matched the lightest or darkest shades of the overlaid sections, matched the perceived contrast, or used some higher order image statistics. We provided minimal instructions and no feedback to our observers to see if they could carry out the task in a consistent and meaningful manner. The results showed consistency within and across observers. A second experiment showed that the transparency matches were also perceived contrast matches. In addition, although observers could only adjust reflectivity, β, or inner transmittance, θ, to equate perceived transparency, they actually equated transmittance, t, of the filters, irrespective of reflectance, r, (see Figure 10 of Robilotto et al. (2002a)). Thus perceived transparency corresponded closely to a meaningful physical property of the filters, t, which in turn is a function of both β and θ. These results suggested that judging perceived transparency seems to be a fairly natural task that has simple sensory and physical correlates. We used identical instructions and similar stimuli in this study to examine the sensory and physical correlates of per-

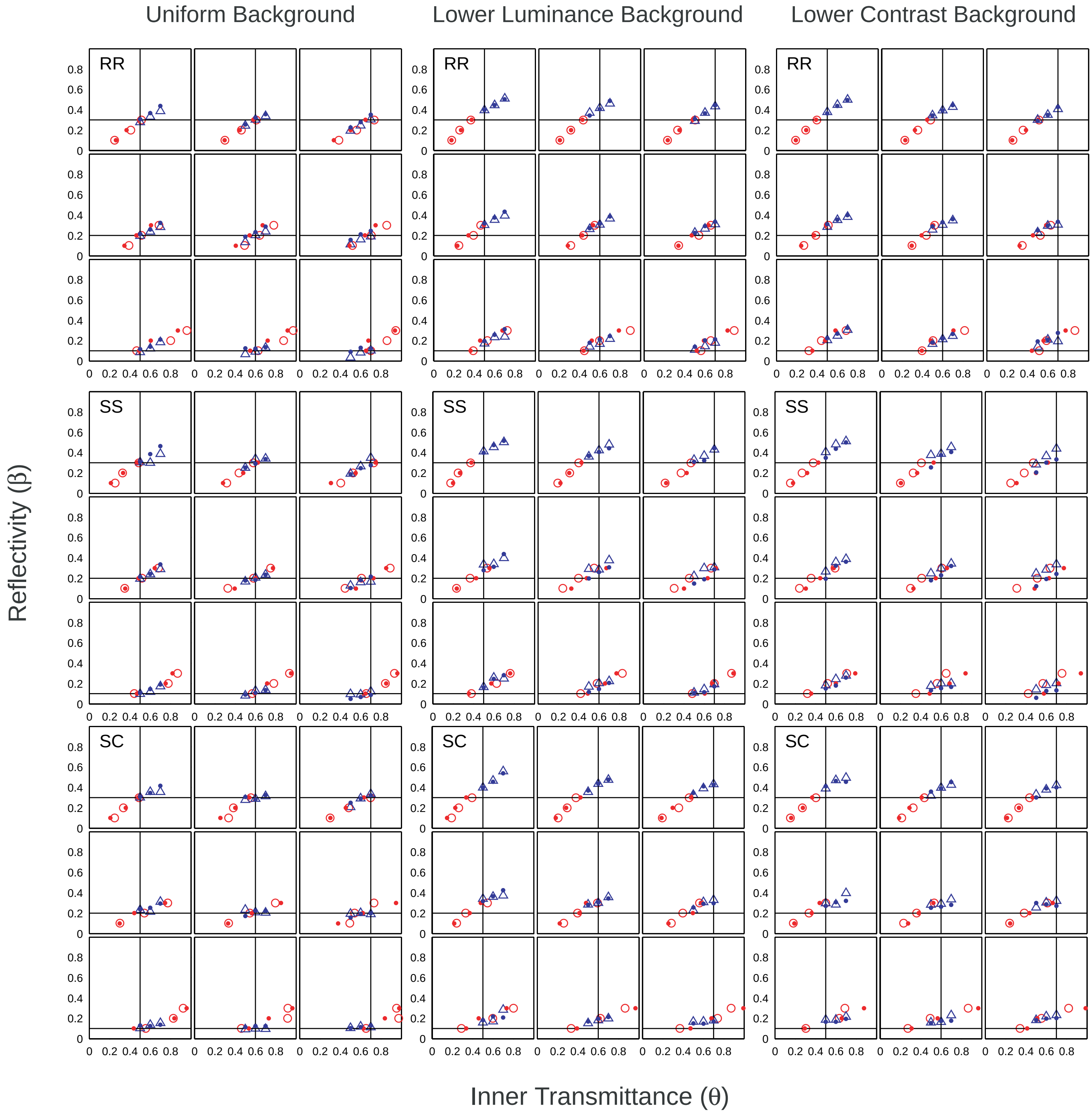

Figure 7. Mean match settings from Experiment 2 for the three observers under the three background conditions plotted in an identical manner as Figure 4. The nine subplots within each block represent the nine standard filters. The properties of the standard filters are defined by the intersection of the orthogonal lines. For each standard, the three blue triangles represent match filters with fixed θ_m and adjustable β_m, and the three red circles represent match filters with fixed β_m and adjustable θ_m. For comparison, match settings from Experiment 1 are superimposed over the plots as dots.

ceived transparency when filters are placed on dissimilar backgrounds.

The results show that even across dissimilar backgrounds, observers use contrast to equate for transparency. This seems to be a sensible strategy in everyday perception. Experience with transparency is fairly common There is ample opportunity to judge clarity of water if you fish, swim, or dive, and in colder climates there is fog. It makes sense that the clarity of outlines or patterns through fog or water is the functionally important quality; so perceived contrast is the natural metric. If one moves though such a transparency toward an object, one also gets feedback about the actual sharpness of the outlines and patterns as one gets closer to the object. It seems that the visual system learns to make use of readily available image variables/statistics to estimate surface attributes without requiring a detailed physical model.

Although β and θ are physically independent properties that characterize a neutral density filter, neutral density filter properties can be more easily measured in terms of filter reflectance and transmittance. It is important to realize that r and t were not used as the adjustable properties because they are not independent of each other (Figure 1). r and t are values that describe proportions of the total original incident light, and their sum must be less than or equal to 1.0. The remaining proportion of incident light is absorbed within the filter. β and θ are values that describe the surface reflecting and media absorbing properties of the material, and can independently vary between 0.0 and 1.0.

In order to assess the degree to which the physical determinant of transmittance predicts perceived transparency, match settings from Experiment 1 were transformed from β and θ into r and t according to Equations 2 and 3. For each observer under each background condition, transmittances of the match filters are plotted versus transmittances of their respective standards in Figure 8. Each data point represents the mean transmittance (±1 *SD*) of all matches made to one of the nine standards. From the nine mean data points, slopes (represented by the solid lines) were determined that best fit the data by minimizing the sum of the squared errors of a one-parameter model through the origin (Box, Hunter, & Hunter, 1978). Best-fit slope values and their SEs are listed inside each plot. The 95% confidence intervals were determined by multiplying the SE by the critical t value (2.306) of a two-tailed test with a 0.05 level of significance and 8 deg of freedom. Confidence intervals are represented by the shaded areas around the slopes. Dashed lines indicate the unit diagonal with a slope of 1.0, where the transmittance of the match and standard would be equal. In all conditions, linear slopes fit well with small SEs. For two of the three observers under uniform background conditions (SS and SC), the confidence interval fell around the unit diagonal, indicating that match filters were generally judged as equally transparent to standard filters when their transmittance was equated. For the third observer under uniform background conditions (RR), confidence interval fell slightly below the unit diagonal. Under conditions of lower contrast and lower luminance, observers consistently adjusted β_m or θ_m so that the transmittance of the match filter was significantly less than that of the standard. This is seen by the confidence intervals falling well below the unit diagonal for all observers. These lower transmittance values agree with the translation of data points seen in Figure 4 toward higher reflectivity and lower inner transmittance settings, and compensate for the decreased perceived transparency of the standards.

The transformed data from Experiment 1 were also replotted in terms of r and t in Figure 9 to show that for each standard, match filters had very similar transmittances despite varying substantially in reflectance. In Figure 9, each block of subplots for the three different background conditions represents the transformed average match settings from the three observers in Figure 4. Each subplot represents one of the nine standard filters specified by the intersections of the solid orthogonal lines. Again, open blue triangles represent match settings with adjustable reflectivities, and open red circles represent match settings with adjustable inner transmittances. Settings are restricted to the physically realizable space to the left of the diagonal where $r + t \leq 1.0$. Under uniform background conditions, match settings line up vertically along the transmittance of their standards. Under the low luminance and low-contrast background conditions, settings still line up vertically along a given transmittance, but are consistently shifted to the left of their standards' transmittance. This further attests to the decreased degree of perceived transparency when a filter is placed on a background of lower mean luminance or contrast.

Note that transmittance is not independent of reflectance for a filter, but is easier to measure with optical means than inner transmittance or reflectivity. It should be pointed out that all of our simulations were for glasslike clear filters (i.e., filters that do not scatter light). In a different paradigm, Singh and Anderson (2002a) ran opacity matching experiments with square-wave-background transparency displays that included blur in the lower contrast region (simulating translucency); observers' opacity matches no longer corresponded to their contrast matches. In particular, incrementally increasing the degree of blur led to a much greater decrease in perceived transmittance, and a relatively small decease in apparent contrast. So, in contexts involving image blur due to the light-scattering properties of translucent layers, the clean correspondence between perceived transmittance and apparent contrast may no longer obtain.

Although contrast sensitivity varies considerably with changes in observation conditions, such as mean luminance, spatial frequency, and retinal eccentricity, studies have shown that apparent contrast of suprathreshold patterns are much less affected by such changes (Georgeson & Sullivan, 1975; Kulikowski, 1976). This phenomenon of contrast constancy has been shown to hold true over a wide range of conditions, but fails for patterns viewed under natural conditions with low luminance and high spatial frequency (i.e., Gabor patches of 8c/deg or higher and 2cd/m^2 or less; Peli, Arend, & Labianca, 1996; Peli, Yang, Goldstein, & Reeves, 1991). The stimuli used in the current study have greater mean luminances and lower spatial frequencies than those shown necessary for failure of contrast constancy.

It is clear from Figure 8 that the data points are well fit by straight lines through the origin in all the plots, with slopes near 1.0 for uniform background conditions, and slopes significantly different than 1.0 for dissimilar backgrounds. This indicates that reducing luminance or contrast of the background decreases perceived transparency of the overlaying filter by a multiplicative factor. In addition, because perceived transparency corresponds closely to perceived contrast, these results show that in complex gray-scale configurations, halving mean luminance of a back-

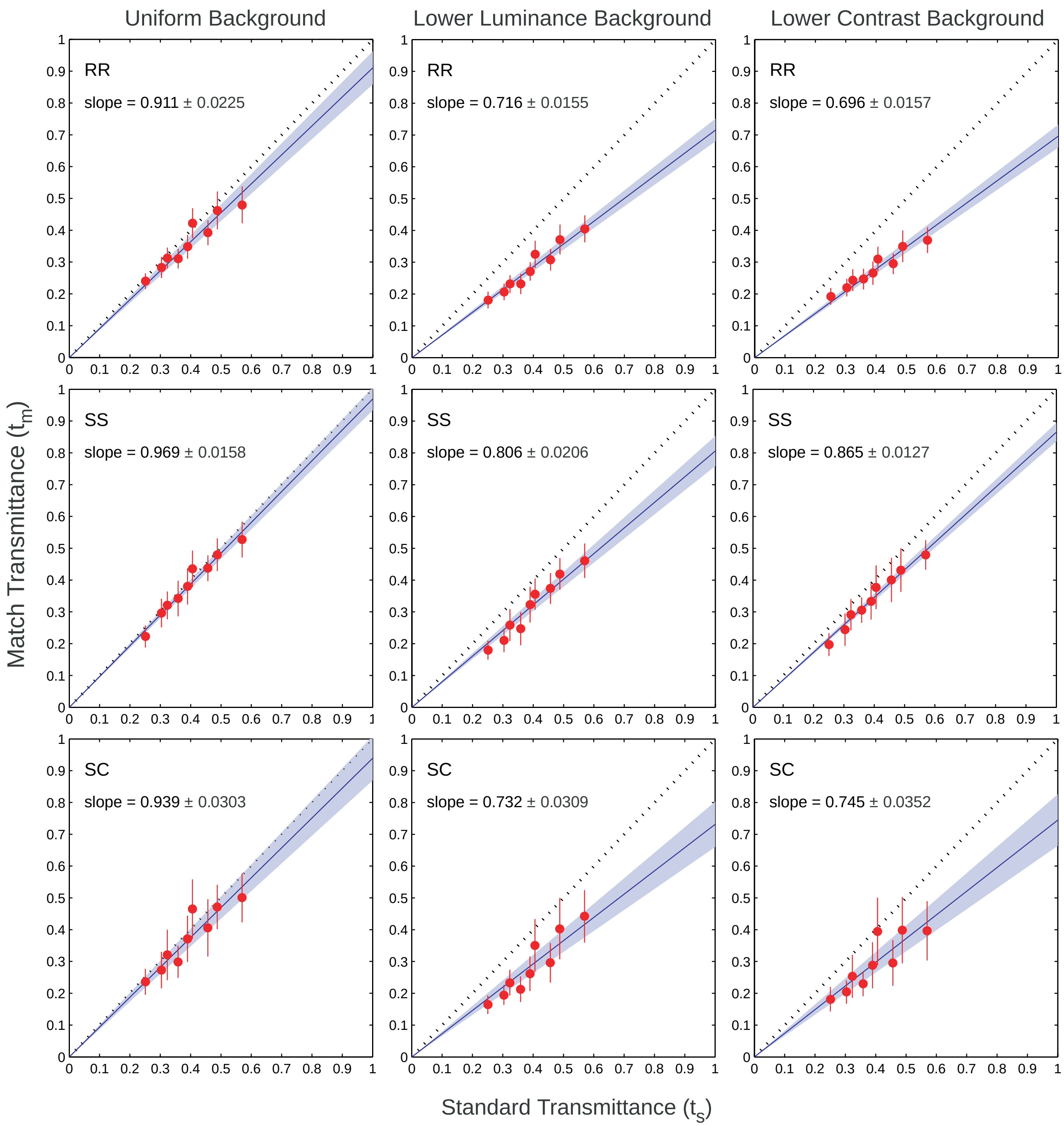

Figure 8. Match settings from Experiment 1 are replotted in terms of transmittance, *t*. Each data point represents the mean transmittance (± 1 *SD*) of all matches made to one of the nine standards. Solid lines represent slopes fit to the mean data points and the shaded areas correspond to their 95% confidence intervals. Dashed lines indicate the unit diagonal, where settings of equal transmittance would lie. Best-fit slope values and their SEs are listed inside each plot.

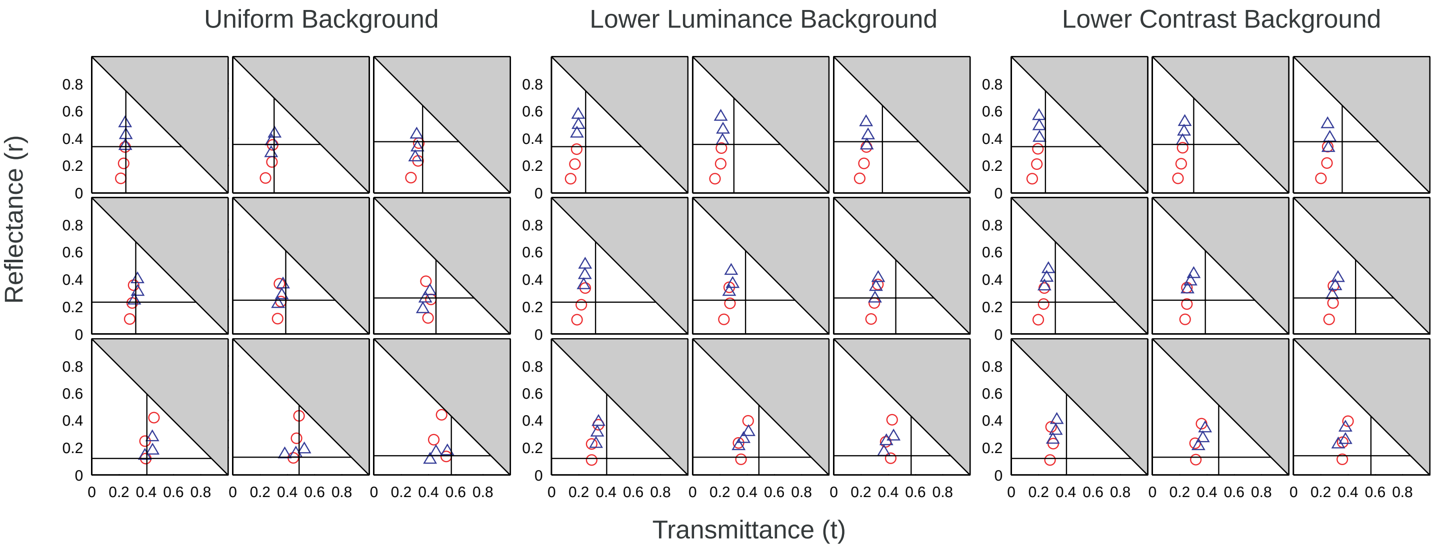

Figure 9. Mean match settings from Experiment 1 replotted in terms of reflectance, *r*, and transmittance, *t*. Settings are averaged across the three observers. As in Figure 4, each subplot represents one of the nine standard filters specified by the intersection of the solid orthogonal lines. For each standard, triangles represent adjustable β_m match settings, and circles represent adjustable θ_m match settings. Settings are restricted to the physically realizable space left of the diagonal where $r + t \leq 1.0$.

ground's surface distribution has a very similar effect to compressing the distribution in half around the mean luminance. In other words, perceived contrast is not independent of mean luminance.

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