

# Sensory and physical determinants of perceived achromatic transparency

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What are the physical and sensory determinants of perceived transparency? To explore this question, we simulated pairs of physically different neutral density filters on a CRT and asked observers to match their perceived transparency. Matching was accomplished by adjusting one of two physically independent filter properties, reflectivity and inner transmittance. Results show that observers can make reliable matches through a linear trade-off of these two properties. In a separate experiment, observers matched the perceived contrast of the overlaid regions. The reflectivity and inner transmittance values for contrast matches are similar to those of perceived transparency matches, suggesting that perceived image contrast is the sensory determinant of perceived transparency. In variegated displays, neither Michelson contrast nor other standard contrast metrics predicts contrast appearance. When perceived transparency is plotted in terms of filter reflectance and filter transmittance, perceived transparency corresponds closely to filter transmittance.

**Keywords:** transparency, perceived transparency, perceived contrast, contrast metrics

## Introduction

The perception of transparency occurs when an observer is aware not only of surfaces in the visual world but also of the media through which the surfaces are viewed, for example, viewing surfaces through filters, meshes, or fog. Physically, the intensities contributed by surfaces and the transparent media are collapsed into single values at each point on the retina. It is the visual system's task to segregate or "scission" these values into their individual components. Through the manipulation of these components and the analyses of their perceptual effects, it is our hope to better understand how sensory and physical properties determine our perception of transparency.

Here we have simulated pairs of neutral density filters over variegated achromatic backgrounds. These filter layers were generated according to a model that more closely approximates the physical properties of real filters than the filter models of previous studies. In the first experiment, we examined the physical determinants of perceived transparency by asking observers to match the transparency of physically different filters. Adjustment was constrained to one of two physical properties, reflectivity or inner transmittance. In the second experiment, we examined the sensory determinants of perceived transparency by asking observers to match the contrast of the overlaid regions. Adjustment was constrained in the same manner as in the first experiment.

For most of the past three decades, [Metelli's \(1974a, 1974b\)](#) episcotister model has been used as the standard paradigm for transparency perception (see "Discussion" for details). When an episcotister, an opaque disk with an open wedge sector, is rotated at a high enough rate in front of a surface, the opaque and open sectors appear to fuse together, resulting in the percept of a transparent layer over a background. In the case of a bipartite background, an episcotister will create an overlaid region with two different luminances. According to Metelli's model, it is the difference in luminance between these two overlaid regions, or luminance range, that governs the degree of transparency perceived.

Expanding further on Metelli's model, [Beck, Prazdny, and Ivry \(1984\)](#) examined constraints on the perception of transparency and reasoned that the computations carried out by the visual system in perceiving transparency are in terms of lightness values rather than in Metelli's terms of reflectance. Perceived transparency has also been studied as a constancy problem by [Gerbin, Stultiens, Troost, and de Weert \(1990\)](#), whose results corresponded well with episcotister model predictions. Metelli's episcotister model is not, however, without flaws. Whereas episcotister model equations predict that perceived transparency matching should be independent of mean luminance, [Singh and Anderson \(2002\)](#) show that luminance ranges of matching filters increase monotonically as their mean luminance increases. For Singh and Anderson's displays, the critical variable for perceived transparency was found to be Michelson

contrast. Kasrai and Kingdom (2001) measured the accuracy and precision of perceived transparency and found that predictions from the luminance-based formulation of Metelli’s episcotister model as well as predictions from a variation of Singh and Anderson’s Michelson contrast ratio model provided reasonable fits to the data. This is despite the fact that there was a reasonably wide range of adjustable patch luminances that gave rise to at least some degree of perceived transparency.

All of the aforementioned experiments treat transparent layers as being generated from simple models based on episcotisters over bipartite, tripartite, or sinusoidal backgrounds. Here we generate pairs of physically different filters that are based on a model that more closely represents their physical properties (*reflectivity* and *inner transmittance*), and present them over complex, variegated backgrounds. With the two filters, we ask first if observers can reliably equate their perceived transparency by adjusting a single parameter in only one of the filters. This single adjustable parameter was always one of two independent physical filter properties. Second, we ask if observers can match perceived contrast of the overlaid areas by adjusting again, one of the same single parameters in only one of the filters. If equating transparency or contrast is possible, what is the relationship between the two filter properties at the point of a match, and how do the relationships differ between equated transparency and equated contrast? Lastly, given the physical properties, is there a simple sensory metric that can predict the degree of perceived transparency and perceived contrast for filters over variegated backgrounds?

### Simulation of Filter Properties

Neutral density filters can be described by two independent physical properties: *reflectivity* and *inner transmittance* (Figure 1). Reflectivity ( $\beta$ ) is a property of the air-filter interface and is dependent upon the index of refraction of the filter material,  $n$ , in accordance with Fresnel’s law of reflection:

$$\beta = \left( \frac{n-1}{n+1} \right)^2 . \tag{1}$$

The term  $\beta$  is factored not only when the original incident light reflects off the front surface but also at each change in media (each time light is internally reflected between the filter’s front and back surface). A typical glass or plastic absorption filter has a reflectivity of .04 to .05 (Nakauchi, Silfsten, Parkkinen, & Usui, 1999). Inner transmittance ( $\theta$ ) is a property of the filter 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).  $\theta$  is dependent upon the path length,  $d$ , and absorptivity of the media,  $m$ , in accordance with Bouguer’s law:

$$\theta = 10^{-dm} . \tag{2}$$

Again,  $\theta$  is factored not only when the original incident light initially passes through the front surface but each time internally reflected light passes through the filter. As shown in Figure 1, light reflected from the filter consists primarily of a single  $\beta$  term, plus multiple sets of even number passes through the filter that exit from the front surface. These secondary components, due to internal reflection, account for the fact that reflected light is partially dependent on the inner transmittance. It is to be stressed, however, that unlike the total reflected light, light reflected at each surface,  $\beta$ , is independent of inner transmittance.

When the first reflected term  $\beta$  is summed along with the infinite power series of the secondary components, the total light reflected back from the filter is equal to  $\beta + [(1-\beta)^2 \theta \beta / (1-(\theta\beta)^2)]$ . When the infinite power series of the components that leave through the back surface of the filter is summed, the total light transmitted is equal to  $(1-\beta)^2 \theta / (1-(\theta\beta)^2)$ . The series of reflections and transmissions in Figure 1 occur at each point throughout the filter. When the 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 internal reflections between the filter and the surface, and partially transmits back through the filter (Figure 2). At every pass through the filter in Figure 2 (the first pass being indicated by the circled region), light undergoes the entire series of reflections and transmissions in Figure 1.

The total proportion ( $p$ ) of incident light reflected back from the overlaid area consists of two additive components (Equation 3). The first additive component is the proportion of incident light reflected from the filter without passing through the back surface. This reflected light (from the circled region of Figure 2) is the sum of all reflected light in Figure 1. The first pass through the filter (from the circled region of Figure 2) is the sum of all transmitted components in Figure 1, and is internally reflected between the filter and the opaque surface. Each time this light reflects back to the filter, a proportion passes back out and the internally reflected portion becomes smaller. The sum of the infinite power series of these proportions that are retransmitted back out through the filter make up the second additive component of Equation 3:

$$p = \left[ \beta + \frac{(1-\beta)^2 \theta^2 \beta}{1-(\theta\beta)^2} \right] + \frac{\left[ \frac{(1-\beta)^2 \theta}{1-(\theta\beta)^2} \right]^2 a}{1 - \left[ \beta + \frac{(1-\beta)^2 \theta^2 \beta}{1-(\theta\beta)^2} \right] a} . \tag{3}$$

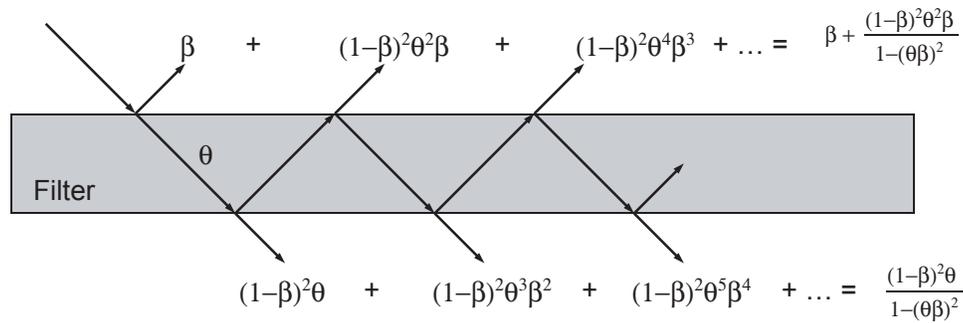


Figure 1. Neutral density filters can be described by two independent physical properties,  $\beta$  and  $\theta$ .  $\beta$  is the surface reflectivity of the air-filter interface.  $\theta$  is the inner transmittance, defined as the ratio of radiant flux reaching the back surface of the filter to the flux that enters the filter at the front surface (Wyszecki & Stiles, 1982).

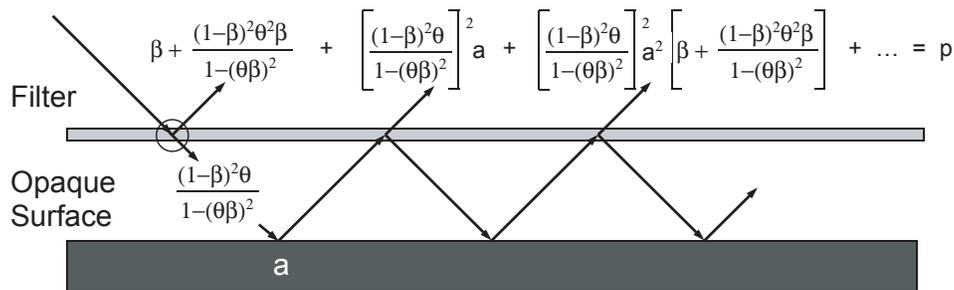


Figure 2. Model of a neutral density filter over an opaque surface. A proportion of incident light is reflected from the filter, while another proportion is transmitted through. The transmitted proportion is reflected between the filter and the underlying surface and decreases with each additional reflection. Each pass through the filter (the first, indicated by the circled region) includes the entire series of reflections and transmissions in Figure 1.

Simulating filters based on the model presented in Figure 2 is an attempt to replicate physically realistic transparent layers. Metelli’s model ignores internal reflections within filters as well as internal reflections between the back surface of filters and the background. This study consists of two experiments in which we manipulate the two physical properties,  $\beta$  and  $\theta$ , in order to examine the sensory and physical determinants of perceived transparency. In the first experiment, two transparent filters are generated over a variegated background and observers are asked to match the perceived transparency of a variable Matching filter to the perceived transparency of a fixed standard filter. In the second experiment, two variegated opaque disks are generated over the same variegated background and observers are asked to match the perceived contrast within a variable matching disk to the perceived contrast within a fixed standard disk.

refresh rate was 70 frames/s. Images were generated using a Cambridge Research Systems Visual Stimulus Generator (CRS VSG2/3) (Rochester, Kent, England), 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 (Photo Research, Chatsworth, CA). 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 precomputed 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 by a Cambridge Research Systems 3-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

## General Methods

### Equipment

All stimulus presentation and data collection were computer controlled. Stimuli were displayed on the 36” x 27” screen (1,024 x 768 pixels) of a Nokia Multigraph 445 Xpro 21” color monitor at a viewing distance of 60 cm. The

occluded by others. On each trial, ellipses were randomly assigned one of 40 flat reflectance values ranging from 0.1076 to 0.5726 with a mean of 0.3001. The simulated illuminant was Equal Energy White and the mean background luminance was 14.56 cd/m<sup>2</sup>. The normalized luminance distribution of the 40 ellipses is represented by Figure 4.

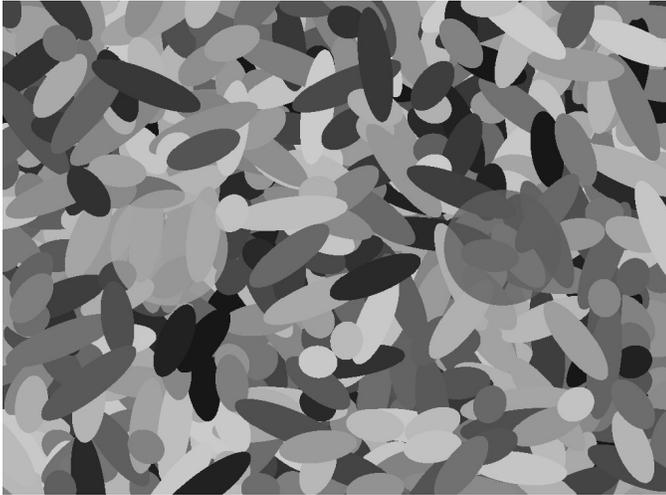


Figure 3. Movie of typical stimuli used in Experiment 1. The two filters are simulated over a variegated achromatic background. Although the filter on the left is considerably brighter than the other, their perceived transparencies are similar. Notice also the X-junctions around the edges of the filters leading to transparency cues.

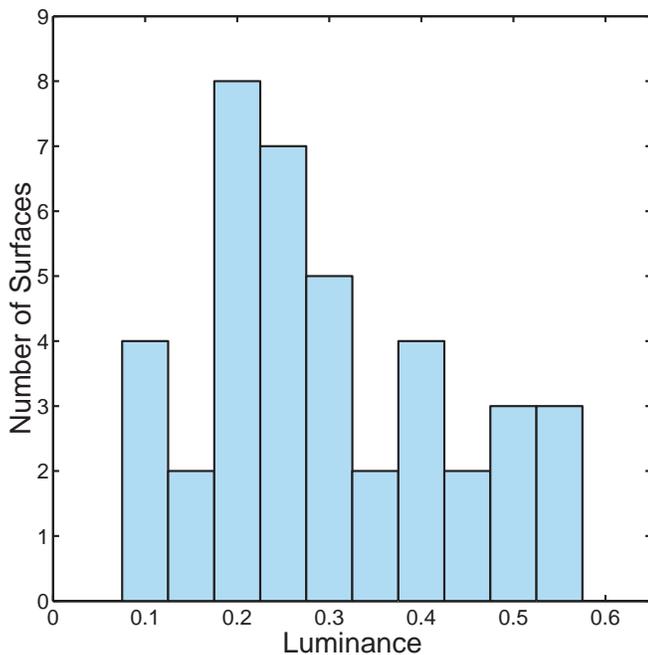


Figure 4. Normalized luminance distribution of the 40 background materials.

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 manifold: 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).

The luminance values of each pixel,  $P$ , on the display were calculated using the physical parameters of the filters, background, and illumination. The luminance values of the pixels pertaining to the background ellipses were calculated by simply multiplying the reflectance of ellipse materials,  $a$ , by the illumination,  $I$ :

$$P_{background} = aI . \tag{4}$$

The luminance values of the pixels pertaining to the regions overlaid by the filters were calculated by multiplying the overall reflectance of the overlaid area,  $p$ , by the illumination,  $I$ :

$$P_{overlaid} = pI$$

$$= \left[ \beta + \frac{(1-\beta)^2 \theta^2 \beta}{1-(\theta\beta)^2} \right] I + \frac{\left[ \frac{(1-\beta)^2 \theta}{1-(\theta\beta)^2} \right]^2 a}{1 - \left[ \beta + \frac{(1-\beta)^2 \theta^2 \beta}{1-(\theta\beta)^2} \right] a} I . \tag{5}$$

## Observers

Three observers with normal visual acuity participated in the study. All three were experienced psychophysical observers, but only R.R., the first author, was aware of the nature and purpose of the study.

## Experiment 1. Characteristics of Perceived Transparency

In everyday situations, we have no trouble saying whether something is more transparent than something else. The question is, is this a quantifiable percept, and if so, what is its dimensionality? To test this, in Experiment 1, we first measured whether observers could consistently equate the transparency of physically different filters. Then we compared the properties of equally transparent filters to test dimensionality.

## Procedure

Two filters, defined by their reflectivity  $\beta$  and inner transmittance  $\theta$ , were presented together over a background on the screen. The luminances of overlaid ellipses were calculated according to Equation 5. The filter on the left was always one of 9 standard filters designated by a combination of one of three  $\beta_s$  values (0.1, 0.2, 0.3) and one of three  $\theta_s$  values (0.5, 0.6, 0.7). Both physical properties of the standard filter were held fixed in a given trial. The match filter on the right always had one of its physical parameters fixed while the other was adjustable by the observer. Either  $\beta_m$  was fixed at one of three values (0.1, 0.2, 0.3) and  $\theta_m$  was varied or  $\theta_m$  was fixed at one of three values (0.5, 0.6, 0.7) and  $\beta_m$  was varied. The adjustable parameter in either case could be varied throughout the entire physical range from 0.0 to 1.0. Observers were told to adjust the match filter using a 3-switch response box, until the two filters appeared equally transparent. The left switch varied the adjustable parameter throughout 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, the display would freeze for 2 s, the setting would be recorded, and the next background with moving overlaid filters would appear.

The nine standard filters were each matched by six match filters (three with fixed reflectivities of 0.1, 0.2, or 0.3, and three with fixed inner transmittances of 0.5, 0.6, or 0.7), resulting in 54 conditions. Each of these conditions was presented in a single session, and each observer completed 5 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 filter matching would be consistently possible without a more stringent definition of the task, and also whether observers could match the perceived transparency of filters with physically different properties.

## Results

The results of Experiment 1 are plotted in Figure 5 in terms of reflectivity and inner transmittance. Each of the three blocks of plots represents data from a single observer. The nine plots within each block represent the matches made to the nine standard filters. The

reflectivities and inner transmittances of the nine standards are represented respectively by the horizontal and vertical solid black lines. The six data points in each plot represent the match settings for the six different match-filter conditions for each standard. The three open blue triangles represent the three different conditions where the match filter's inner transmittance was fixed and the observer adjusted reflectivity. The three open red circles represent the three different conditions where the match filter's reflectivity was fixed and the observer adjusted inner transmittance. These two properties are independent of each other; therefore, as the observer adjusts the variable parameter, the blue triangle data points can be shifted only in the vertical dimension, whereas the red circle data points can be shifted only in the horizontal dimension.

The data point positions are taken as the average setting from the satisfactory matches from five sessions of each condition. If, for any particular combination, observers judged less than three out of five matches as satisfactory, the data point was omitted and not used in any further analysis. Figure 5 shows that the pattern of the six data points is similar throughout different standard conditions and across the three observers. Notice that in one third of the conditions, the match filter will have either its  $\beta_m$  or  $\theta_m$  fixed at a value identical to the  $\beta_s$  or  $\theta_s$  values of the standard. For these conditions, it is possible for observers to set the adjustable parameter so that the two filters are physically the same. As seen in the data, observers were able to accurately equate the variable parameter when the fixed parameters of the two filters were equal (data points on the orthogonal solid lines are set close to the intersection point). These conditions act as controls to see how accurately observers can match physically identical transparent layers under the given task, and could also reveal potential artifacts or biases.

If the trade-off between reflectivity and inner transmittance was truly linear for each plot, and if a standard filter and a match filter were considered equivalent in terms of perceived transparency, then straight lines with slope  $m$  could be fit on the  $(\beta, \theta)$  plots, and would pass through the intersection specified by the standard filter's properties  $(\beta_s, \theta_s)$ . For each level of perceived transparency equivalent to standard  $(\beta_s, \theta_s)$ , there exists  $(\beta_i, \theta_i)$  in the equivalence set so that:

$$m = \frac{\beta_i - \beta_s}{\theta_i - \theta_s} \quad (\text{for fixed } \theta_i) \quad (6)$$

Let  $\theta'_i$  equal the fixed match  $\theta$  and  $\beta'_j$  equal the fixed match  $\beta_j$ . Then for  $i = (1, 2, 3)$  and for  $j = (4, 5, 6)$ :

$$\beta_i = \beta_s + m(\theta'_i - \theta_s) + \varepsilon_{\beta_i} \quad (\text{for fixed } \beta_j) \quad (7)$$

$$\theta_j = \theta_s + 1/m(\beta'_j - \beta_s) + \varepsilon_{\theta_j} \quad (8)$$

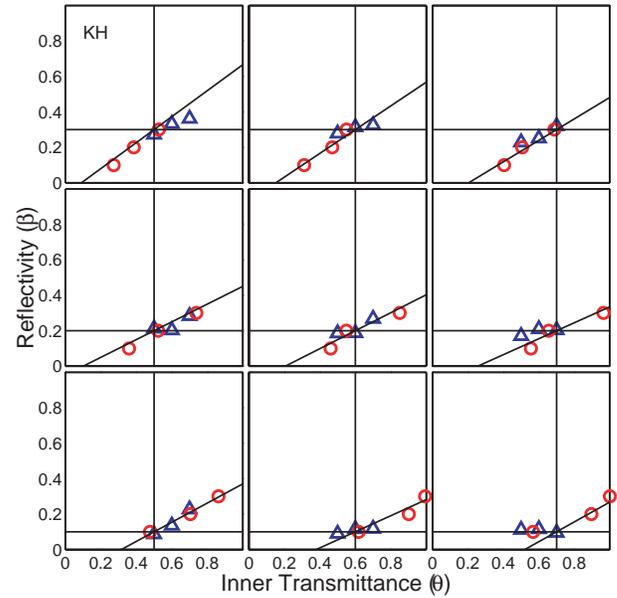
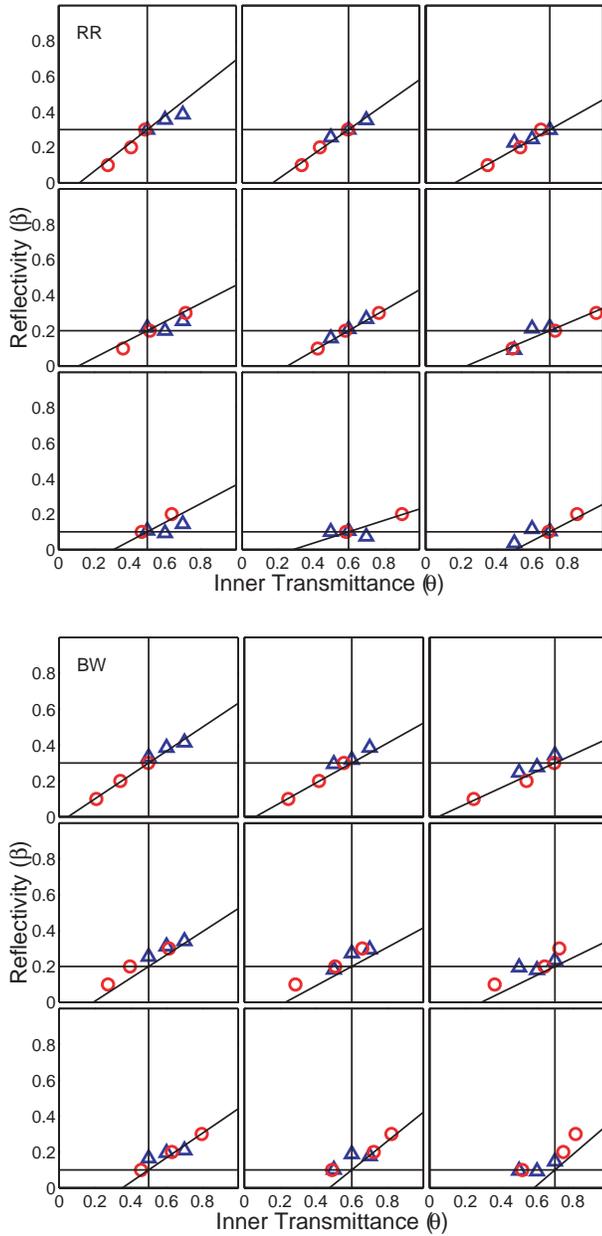


Figure 5. Results from Experiment 1 for the three observers. Each of the nine plots per observer represents one of the nine standard filters. The standard filters' properties are marked by the orthogonal solid lines and are held fixed during a given trial. The data points in each plot represent the match settings for the six different match filter conditions for each standard. The three open blue triangles represent the conditions where observers adjusted reflectivity. The three open red circles represent the conditions where observers adjusted inner transmittance. Oblique straight lines through the intersection point are fit to the data to minimize the squared error.

The two error components were equally weighted and a slope was found that minimized the sum of squared errors ( $S$ ) for Equation 9:

$$S = \sum_{i=1}^3 ((\beta_i - \beta_s) - m(\theta'_i - \theta_s))^2 + \sum_{j=4}^6 ((\theta_j - \theta_s) - 1/m(\beta'_j - \beta_s))^2 \tag{9}$$

For most conditions, the oblique straight lines fit well. Small deviations are seen when the standard filter is of low reflectivity and high transmittance (bottom right plots in Figure 5). With these parameters, the standard filters have the least effect in altering the luminance of the overlaid surfaces. In these conditions, compared to

expected settings predicted from the fits, observers tend to set the variable reflectivity too high when fixed transmittance is low, and tend to set variable reflectivity too low when fixed transmittance is high. This makes the left most data points line up horizontally in these plots.

Table 1 shows the square root of the averaged sum of squared error ( $\sqrt{S_{avg}}$ ) for different conditions. Conditions ( $\beta_i = \beta_s$ ) represent the nine data points per observer where the fixed match filter's reflectivity equals that of the standard's. Under these settings, observers can adjust inner transmittance so that the filters are physically identical. Conditions ( $\beta_i \neq \beta_s$ ) represent the 18 data points per observer where the fixed match filter's reflectivity is different from that of the standard. Under these settings, the filters will be physically different no matter how inner transmittance is adjusted. Conditions

$(\theta_i = \theta_s)$  and  $(\theta_i \neq \theta_s)$  represent equivalent conditions but in terms of inner transmittance. As shown in the bottom two rows of Table 1, whether the filters have the same or different inner transmittances, the reliability of reflectivity settings is similar when matching transparency. As shown in the upper two rows, when observers vary the inner transmittance to match transparency, settings are more reliable (lower  $\sqrt{S_{avg}}$ ) when the filters have the same reflectivity than when they are different.

Table 1. Number of Conditions in Which the Fixed Match Filter Parameter ( $\beta_i$  or  $\theta_i$ ) and the Same Fixed Standard Parameter ( $\beta_s$  or  $\theta_s$ ) Were Equal and Unequal

Condition	n	Square Root of $S_{avg}$		
		R.R.	K.H.	B.W.
$\beta_i = \beta_s$	9	0.0095	0.0155	0.0548
$\beta_i \neq \beta_s$	18	0.0440	0.0521	0.0592
$\theta_i = \theta_s$	9	0.0241	0.0548	0.0894
$\theta_i \neq \theta_s$	18	0.0293	0.0451	0.0793

For each condition and observer, the table lists the square root of the averaged sum of squared error ( $\sqrt{S_{avg}}$ ) between the data and the straight line fit. Lower values indicate a better fit to the model.

Experiment 1 shows that two filters may appear to be of identical perceived transparency to an observer despite being of physically distinct reflectivity and inner transmittance, and despite the overlaid regions appearing different. Among all observers, only three data points (out of a possible 162) were omitted due to the inability of an observer to make at least three out of five satisfactory matches for a given condition. These occurred only for observer R.R. in conditions where the standard filter had a reflectivity of 0.1 and the match filter had a fixed reflectivity of 0.3 (notice that the bottom three plots for R.R. in Figure 5 have only five data points). For 13 of the 15 sessions in these three conditions, the variable transmittance of the match filters was set to 1.0 or 100%, but R.R. still did not perceive the two filters as equally transparent. In these cases, the extent of the standard filters' perceived transparencies was out of the range, regardless of the match filters' transmittance.

## One-Dimensionality of Perceived Transparency

In order for a percept to be considered n-dimensional, certain requirements must be met. For example, human color vision is considered three-dimensional because the adjustment of three independent controls makes an exact color match

possible whereas two are generally not enough (Brindley, 1970). Based on the matching results from Experiment 1, it appears that perceived transparency is a one-dimensional percept. To be considered one-dimensional, the following requirements must be met: (1) one control should be sufficient to achieve a match, (2) 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) Out of 810 trials, 785 were judged satisfactory by the observers. Of the remaining 25 matches judged unsatisfactory, 9 involved conditions where the parameters of the match predicted by the linear fits were beyond the physically realistic range of the CRT. (3) The tradeoffs between reflectivity and inner transmittance form the same function for reflectivity adjustment and inner transmittance adjustment. Matches made by adjusting reflectivity and matches made by adjusting inner transmittance overlap each other and would be indistinguishable if plotted with the same symbols. This is true even in those segments where the data deviate from linearity.

In Figure 6, the matching data for Experiment 1 were averaged across the three observers. All matches that were not judged satisfactory by the observer were omitted. For each of the nine standard filter conditions, straight lines were refit according to the method described above, and are presented together. The fit lines all pass through their respective origin,  $(\beta_s, \theta_s)$ , specified by their standard filter's properties, and are marked by the nine intersection dots. For the sake of clarity, individual data points representing matches were left out.

The straight lines for all nine standards are close to parallel and have a mean slope of 0.592 with a standard deviation of 0.091. In other words, when reflectivity is increased by 1 unit, inner transmittance must be increased by just over 2 units in order to maintain its degree of perceived transparency, regardless of the standard parameters. This means that perceived transparency can be set to any value within a given range simply by adjusting one of these two properties. Simulated filters were confined to the lower right of the two dimensional space in Figure 6 due to physical and sensory constraints. If reflectivity was adjusted too high, the luminance of the overlaid regions would pass above the range of the monitor. If inner transmittance was adjusted too low, the overlaid region would appear too dark to make reliable matches.

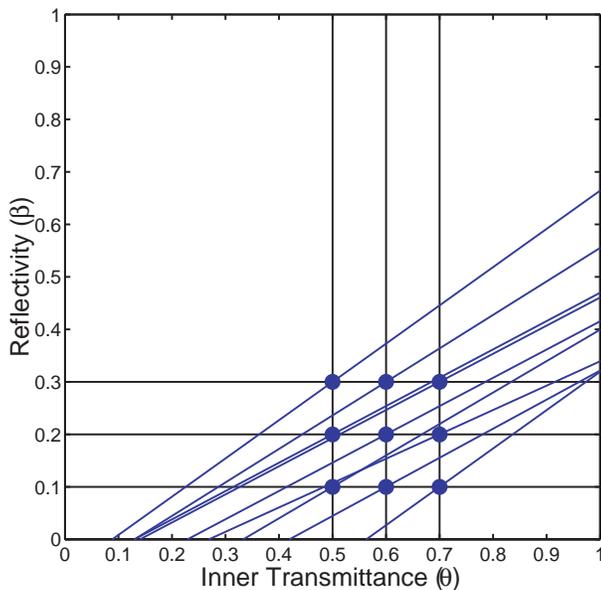


Figure 6. The matching data for Experiment 1 were averaged across the three observers, and oblique straight lines were refit to each of the nine standard filter conditions. The fit lines all pass through their respective origin,  $(\beta_s, \theta_s)$ , specified by their standard filter's properties, and are marked by the nine intersection dots.

## Experiment 2. Characteristics of Perceived Contrast

Varying the reflectivity of a filter has perceptually different results on mean luminance and luminance range ( $L_{\max} - L_{\min}$ ) 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 the previous experiment, 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 Experiment 2, we tried to identify the sensory information used in matching perceived transparency by testing whether observers were equating perceived contrast. In order to separate perceived contrast from perceived transparency, the stimuli were altered to remove cues to transparency. Luminance distributions of the overlaid areas and observers' methods of adjustment remained the same, but the spatial pattern of the overlaid areas corresponded to portions of the background outside the viewing area and remained fixed beneath the filters (Figure 7). This had the effect of abolishing the percept of transparency. The moving transparent filters now appeared as moving opaque disks. 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 stimulus background in Experiment 2 was identical to that of Experiment 1, and two circular regions overlaid by filters were presented on either side of the display. However, 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 out of view from the observer (Figure 7). This had the effect of replacing transparency induced X-junctions with occluding T-junctions, which broke figural unity between the overlay and the background. During presentation, the overlaid regions moved in a synchronized clockwork motion but their spatial pattern remained unchanged. The resulting stimuli appeared as opaque, patterned disks moving over a variegated background.



Figure 7. Movie of typical stimuli used in Experiment 2. The luminances of the overlaid areas are determined by the filter model used in Experiment 1, but the spatial configurations are consistent with opaque, patterned disks. Notice the occluding T-junctions around the edges of the overlaid regions make the simulated filters appear as opaque disks.

Experimental parameters were identical to Experiment 1. The nine combinations of standard disks were again based on  $\beta_s$  of 0.1, 0.2, or 0.3 and  $\theta_s$  of 0.5, 0.6, or 0.7. The match disk had either its  $\beta_m$  or  $\theta_m$  fixed while the other was varied. The observers' task was to match the perceived contrast within the two opaque disks. 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 5. In this way, observers were adjusting perceived transparency in Experiment 1 and perceived contrast in Experiment 2 by adjusting the same two parameters,  $\beta$  and  $\theta$ . The adjustable parameter was varied using the same 3-switch box with identical response effects.

## Results

The data from Experiment 2 were analyzed in an identical fashion to the data from Experiment 1 and are plotted in Figure 8 in terms of reflectivity and inner transmittance. Again, each of the three blocks of plots represents data from a single observer. The nine plots within a block represent the nine standard filters with their two parameters represented by the horizontal and vertical lines. The six data points in each plot represent the 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. These settings were the average taken from the satisfactory matches from five sessions of each condition. If less than three out of five matches were judged unsatisfactory to the observers, the averaged data point was omitted. For each plot, a straight solid line was fit to the data, passing through  $(\beta, \theta)$ , using Equations 6 - 9 to minimize the sum of squared error ( $S$ ) as in Experiment 1.

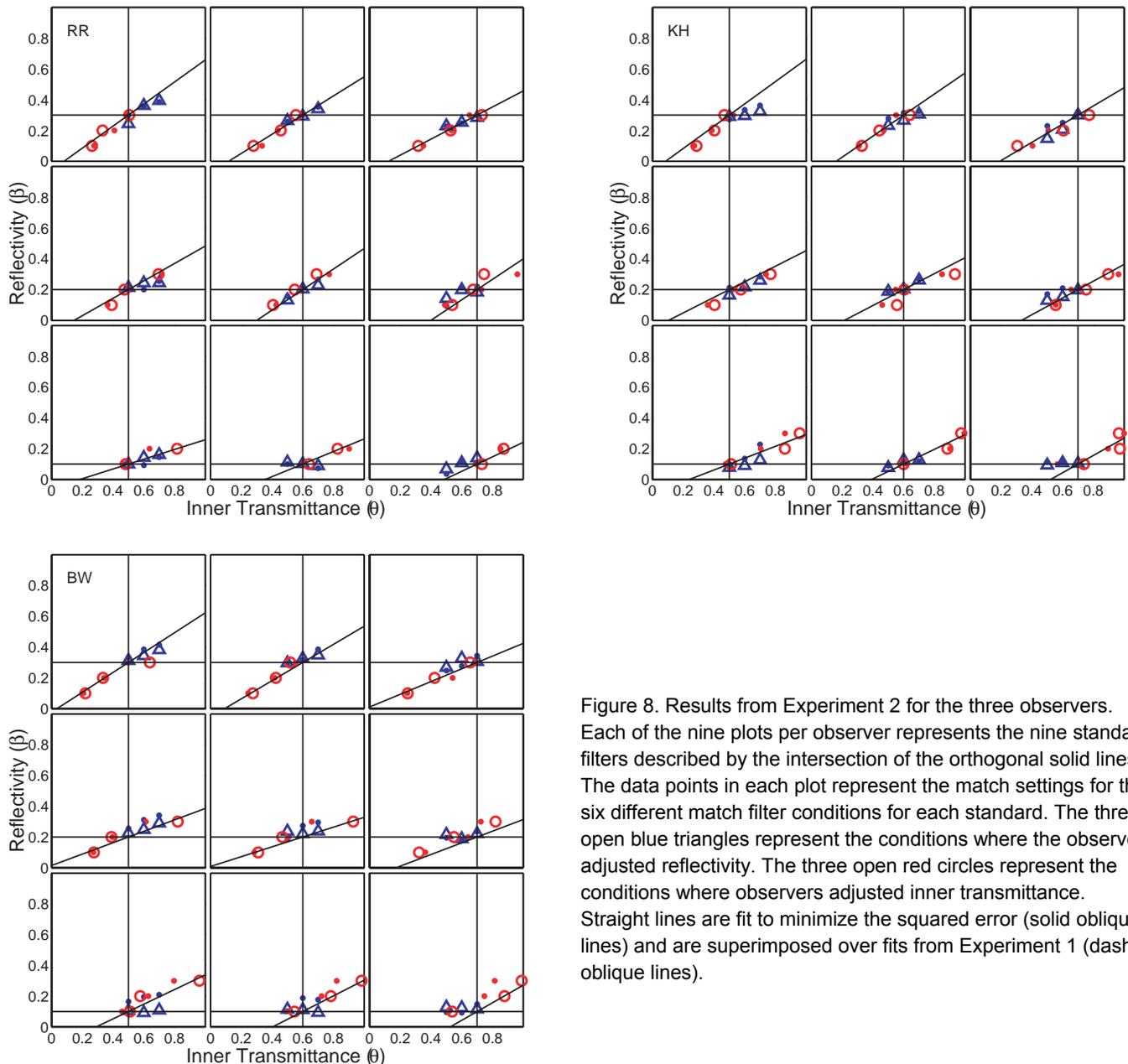


Figure 8. Results from Experiment 2 for the three observers. Each of the nine plots per observer represents the nine standard filters described by the intersection of the orthogonal solid lines. The data points in each plot represent the match settings for the six different match filter conditions for each standard. The three open blue triangles represent the conditions where the observer adjusted reflectivity. The three open red circles represent the conditions where observers adjusted inner transmittance. Straight lines are fit to minimize the squared error (solid oblique lines) and are superimposed over fits from Experiment 1 (dashed oblique lines).

In Experiment 2, observers were able to accurately equate the variable parameter when the fixed parameter of the two filters was equal. When the fixed parameters were different, there was a consistent linear trade-off between reflectivity and inner transmittance. When the match filter had a fixed reflectivity higher than that of the standard filter, observers increased the inner transmittance of the match filter to match perceived contrast. When the match filter had a fixed reflectivity lower than that of the standard filter, observers decreased the inner transmittance of the match filter to match perceived contrast.

For most conditions, the straight lines fit well. As in Experiment 1, small deviations are seen when the standard filter is of low reflectivity and high transmittance (bottom right plots in Figure 8). In these conditions, compared to expected settings predicted from the fits, observers tend to set the variable reflectivity too high when fixed transmittance is low, and tend to set variable reflectivity too low when fixed transmittance is high. Despite small deviations of the individual regression lines to the data, the pairs of regression lines from the two experiments overlap each other well, indicating that equal perceived transparency corresponds to similar combinations of reflectivity and inner transmittance as equal perceived contrast.

It is also interesting to note that, among all observers, only three data points out of 162 were omitted due to the inability of an observer to make at least three out of five satisfactory matches for a given condition. These were the same three cases omitted in Experiment 1 and occurred only for observer R.R. in the three conditions where the standard filter had a reflectivity of 0.1 and the match filter had a fixed reflectivity of 0.3. For 14 of the 15 sessions in these three conditions, the variable transmittance of the match filters was set to 1.0 or 100%, but R.R. still did not perceive the two filters as equal in contrast. In these cases, the extent of the standard filter overlay's perceived contrast was out of the range, regardless of the match filters' transmittance.

For comparison of perceived transparency and perceived contrast, in Figure 8, the results of Experiment 1 are superimposed on the plots as dots. 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 8 makes it clear that observers make the same settings when asked to match contrast as they did when asked to match perceived transparency. This indicates that even in variegated settings, perceived contrast is the determinant of perceived transparency. This argument would only count as being based on correlation if some simpler sensory determinant underlay both types of matches. It is difficult to conceive of a simpler sensory variable than contrast.

## Physical Determinants

From the results of Experiment 1, it appears that perceived transparency is one-dimensional. Could there be a simple physical property that corresponds to this dimension? Though  $\beta$  and  $\theta$  are physically independent properties that characterize a neutral density filter, neutral density filter properties can also be measured in terms of filter *reflectance*,  $r$ , the proportion of incident radiant flux reflected back from the filter, and *transmittance*,  $t$ , the proportion of incident radiant flux passing through the filter. Both of these are functions of both reflectivity,  $\beta$  and inner transmittance,  $\theta$ ,

$$t = \frac{(1 - \beta)^2 \theta}{1 - (\theta\beta)^2} \tag{10}$$

$$r = \beta + \frac{(1 - \beta)^2 \theta^2 \beta}{1 - (\theta\beta)^2} \tag{11}$$

Through these equations, the filter model in Figure 2 can be simplified to Figure 9.

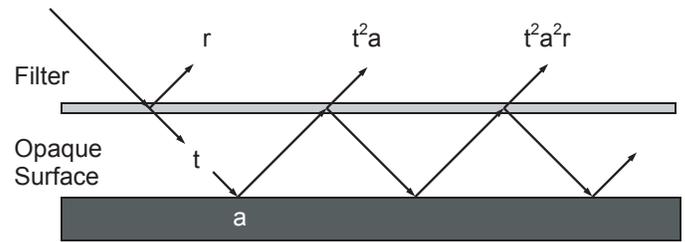


Figure 9. Neutral density filter properties are more simply measured in terms of filter reflectance  $r$ , the proportion of incident radiant flux reflected back from the filter, and transmittance  $t$ , the proportion of incident radiant flux passing through the filter. These are both functions of  $\beta$  and  $\theta$ , and take into account multiple internal reflections between the front and back surfaces of the filter (Nakauchi et al., 1999).

It is important to realize that  $r$  and  $t$  were not used as the adjustable parameters in this study because they are not independent of each other.  $r$  and  $t$  are values that describe proportions of the total original incident light, and their sum must be less than 1.0.  $\beta$  and  $\theta$  are values that describe the light reflecting and absorbing properties of the material, and can independently vary between 0.0 and 1.0. Using the terms  $r$  and  $t$ , the luminance value of a single overlaid pixel from Equation 5 can be simplified to:

$$P_{overlaid} = rI + \frac{t^2 a}{1 - ra} I \tag{12}$$

Matching data from Experiment 1 were plotted in terms of reflectivity,  $\beta$ , and inner transmittance,  $\theta$ , in Figure 5. When these data are transformed into reflectance,  $r$ , and transmittance,  $t$ , through Equations 10

and 11, and plotted in its new two-dimensional space, the result is Figure 10. Unlike reflectivity and inner transmittance, reflectance and transmittance are not physically independent of each other. Their sum must be equal to or less than 1.0 and matches are restricted to the physically realizable region left of the diagonal line in Figure 10. Solid lines depict reflectance and transmittance of the nine standard filters.

Notice that unlike Figure 5, where  $\beta_s$  is constant across horizontal panels and  $\theta_s$  across vertical panels,  $r_s$  and  $t_s$  vary from panel to panel. This is because as either  $\beta$

or  $\theta$  of a filter changes, so do both its reflectance and transmittance. Open blue triangles represent conditions where the match filter's inner transmittance was fixed and the observer adjusted reflectivity, and open red circles represent conditions where the match filter's reflectivity was fixed and the observer adjusted inner transmittance. Reflectance and transmittance are dependent on both  $\beta$  and  $\theta$ . During a trial, as an observer adjusts either  $\beta_m$  or  $\theta_m$ , both reflectance and transmittance are altered and the corresponding data point is shifted in both the vertical and horizontal dimensions in the plot.

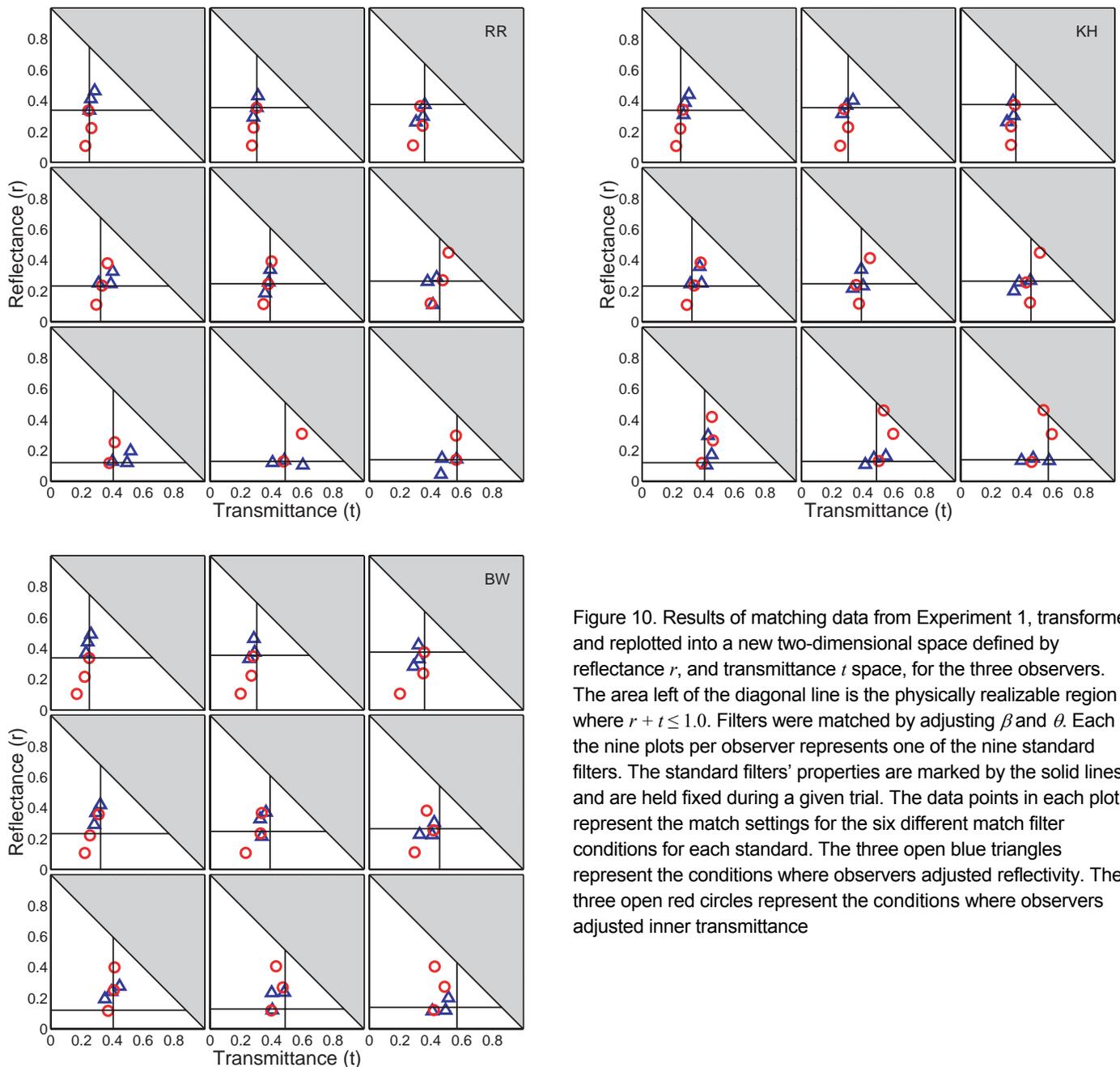


Figure 10. Results of matching data from Experiment 1, transformed and replotted into a new two-dimensional space defined by reflectance  $r$ , and transmittance  $t$  space, for the three observers. The area left of the diagonal line is the physically realizable region where  $r + t \leq 1.0$ . Filters were matched by adjusting  $\beta$  and  $\theta$ . Each of the nine plots per observer represents one of the nine standard filters. The standard filters' properties are marked by the solid lines and are held fixed during a given trial. The data points in each plot represent the match settings for the six different match filter conditions for each standard. The three open blue triangles represent the conditions where observers adjusted reflectivity. The three open red circles represent the conditions where observers adjusted inner transmittance

Figure 10 shows that data points generally line up in a vertical fashion along the transmittance of the standard filter, indicating that equal perceived transparency corresponds closely to the physical property of equal transmittance. There is, however, some departure from vertical, with many of the data points lining up along paths with positive slopes slightly less than vertical. In other words, there is a trend to adjust  $\beta$  and  $\theta$  so as to increase  $t$  when  $r$  is high.

## Metrics for Perceived Contrast

Experiment 2 shows that observers can reliably equate perceived contrast of physically different filters over variegated backgrounds. The trade-offs between reflectivity and inner transmittance are very similar to the trade-offs that equate perceived transparency in Experiment 1. Singh and Anderson (2002) have shown that for transparent disks over sinusoidal backgrounds, perceived transparency can be predicted by the ratio of Michelson contrast within the transparent region to the Michelson contrast of adjacent regions. If a metric could be found that would adequately predict perceived contrast, it would likely be able to predict perceived transparency as well.

Our understanding of perception of image contrast is mainly based on narrow-band images, such as sine-wave gratings or plaids (Georgeson & Shackleton, 1994; Peli, 1997; Singh & Anderson, 2002). Two variegated images could have the same maximum and minimum luminances, hence identical Michelson contrast, yet have completely different histograms and perceived contrasts. A number of studies have looked at metrics for more complex or natural stimuli (Moulden, Kingdom, & Gatley, 1990; Peli 1990; Chubb & Nam, 2000; Nam & Chubb, 2000; Bex & Makous, 2002), but none predicts perceived contrast adequately. In this section, we analyze observers' contrast matching data using variants of the six metrics compiled by Moulden et al. (1990). These metrics try to incorporate the complete distribution of luminances. The first two metrics calculate the standard deviation of the luminances, or the standard deviation of the logarithms of luminances. The last four calculate local contrasts between luminances or log luminances of all possible pairs of ellipses, and use their average as a metric of image contrast. In all of the following equations, normalized luminance values are represented by  $a_i, a_{i+1}, \dots, a_n$  ( $n = 40$ ).

(i) Standard deviation of the luminances:

$$SD = \left[ \frac{1}{n} \sum_{i=1}^n (a_i - \bar{a})^2 \right]^{1/2} \tag{13}$$

(ii) Standard deviation of the log of luminances:

$$SDLG = \left[ \frac{1}{n} \sum_{i=1}^n (\log a_i - \log \bar{a})^2 \right]^{1/2} \tag{14}$$

(iii) Space-average Michelson contrast of the luminances:

$$SAM = \frac{1}{n^2} \sum_{i=1}^n \sum_{j=1}^n \left| \frac{a_i - a_j}{a_i + a_j} \right| \tag{15}$$

(iv) Space-average Michelson contrast of the log of luminances:

$$SAMLG = \frac{1}{n^2} \sum_{i=1}^n \sum_{j=1}^n \left| \frac{\log a_i - \log a_j}{\log a_i + \log a_j} \right| \tag{16}$$

(v) Space-average Whittle contrast of the luminances:

$$SAW = \frac{1}{n^2} \sum_{i=1}^n \sum_{j=1}^n \left| \frac{a_i - a_j}{\min(a_i, a_j)} \right| \tag{17}$$

(vi) Space-average Whittle contrast of the log of luminances:

$$SAWLG = \frac{1}{n^2} \sum_{i=1}^n \sum_{j=1}^n \left| \frac{\log a_i - \log a_j}{\min(\log a_i, \log a_j)} \right| \tag{18}$$

Table 2 lists the ratios of contrast within regions overlaid by the standards to contrast within the background for each of the six metrics. The ratios are ordered by mean luminance of the nine standard overlaid regions. The table shows that of the nine standard filters, five lead to overlaid regions with a lower mean luminance than the background, whereas four lead to overlaid regions with a higher mean luminance than the background. By all of these measures, contrast is reduced considerably (max contrast = 0.4304, min contrast = 0.0399). The correlations between the different measures are 0.8927 or better (mean correlation = 0.9630).

To test whether any of these metrics provides an adequate estimate of perceived contrast, for each metric the average ratio of contrast within the region overlaid by the match to contrast within the region overlaid by the matching standard was calculated for each observer from the match settings of Experiment 2. Figure 11 presents these ratios using the six metrics. The minimum requirement for a satisfactory metric is that for every perceived contrast match, calculated values must be identical for the areas overlaid by the standard and match filters. In Figure 11, this would result in contrast ratios (match/standard) equal to 1.0. Mean luminance of the region overlaid by the standard filter is plotted on the abscissa. The asterisk represents the mean luminance of the background.

The plots show that none of the metrics provides a satisfactory measure of perceived contrast for variegated gray-level images. According to these metrics, observer K.H. is consistently underestimating, whereas observer B.W. is consistently overestimating, the contrast of the standard regions. For this paradigm, SD, SAMLG, and SAWLG are closely correlated, as are SDLG, SAM, and SAW.

Table 2. Standard Filters Ordered by Their Physical Properties (Reflectivity,  $\beta$ , and Inner Transmittance,  $\theta$ )

Filter Properties		Standard Region / Background						
$\beta$	$\theta$	Lum	SD	SDLG	SAM	SAMLG	SAW	SAWLG
0.1	0.1	0.5731	0.1788	0.2885	0.3051	0.2105	0.2051	0.2556
0.1	0.2	0.6802	0.2597	0.3527	0.3725	0.2854	0.2582	0.3392
0.1	0.3	0.8079	0.3571	0.4083	0.4304	0.3707	0.3067	0.4303
0.2	0.1	0.8881	0.1228	0.1286	0.1357	0.1243	0.0849	0.1548
0.2	0.2	0.9888	0.1804	0.1691	0.1784	0.1784	0.1136	0.2185
0.2	0.3	1.1104	0.2513	0.2092	0.2207	0.2448	0.1431	0.2940
0.3	0.1	1.1964	0.0800	0.0625	0.0656	0.0775	0.0399	0.0979
0.3	0.2	1.2877	0.1191	0.0863	0.0906	0.1155	0.0557	0.1442
0.3	0.3	1.3997	0.1689	0.1122	0.11780	0.1652	0.0732	0.2030

For each filter, ratios of standard region to background are listed for luminance (Lum) and the six contrast metrics (SD, SDLG, SAM, SAMLG, SAW, SAWLG). SD = standard deviation of the luminances; SAM = space-average Michelson contrast of the luminances; SAMLG = space-average Michelson contrast of the log of luminances; SAW = space-average Whittle contrast of the luminances; SAWLG = space-average Whittle contrast of the log of luminances.

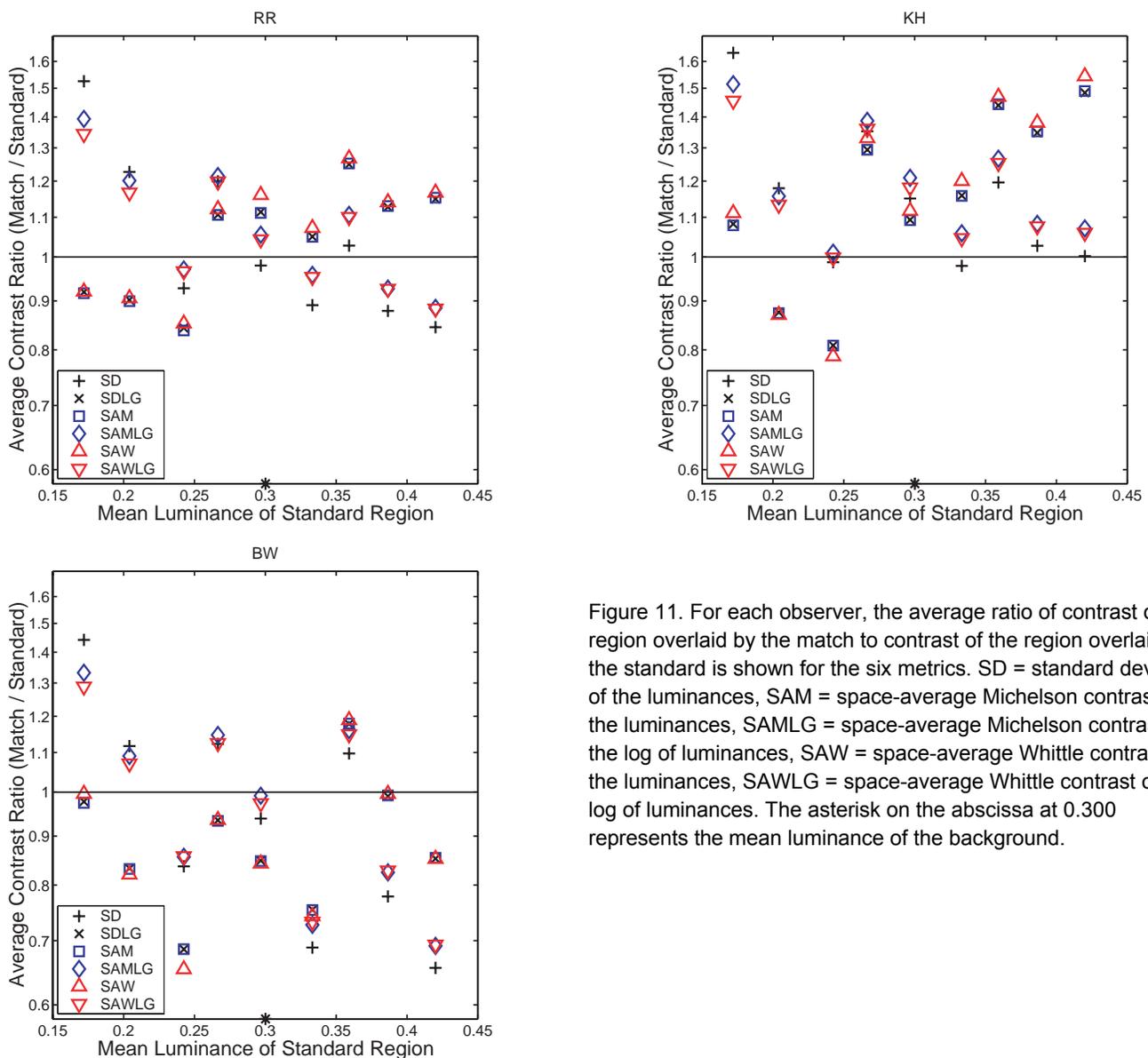


Figure 11. For each observer, the average ratio of contrast of the region overlaid by the match to contrast of the region overlaid by the standard is shown for the six metrics. SD = standard deviation of the luminances, SAM = space-average Michelson contrast of the luminances, SAMLG = space-average Michelson contrast of the log of luminances, SAW = space-average Whittle contrast of the luminances, SAWLG = space-average Whittle contrast of the log of luminances. The asterisk on the abscissa at 0.300 represents the mean luminance of the background.

## Discussion

Historically, models of perceived transparency have been based on Metelli's (1974a, 1974b) model of a rotating episcotister. An episcotister is an opaque disk of reflectance  $e$  with an open wedge sector with a fractional area  $\alpha$ . When rotated at a high enough rate in front of a bipartite background of reflectances  $a$  and  $b$ , the opaque and open sectors appear to fuse together, resulting in the percept of a transparent layer over a background (Figure 12). The three reflectances and the fractional area all have proportional values between 0 and 1. For these parameters, Metelli used Talbot's law to obtain the overall reflectances of the overlaid regions,  $p$  and  $q$ , corresponding to the background regions  $a$  and  $b$ , respectively (Equations 19 and 20).

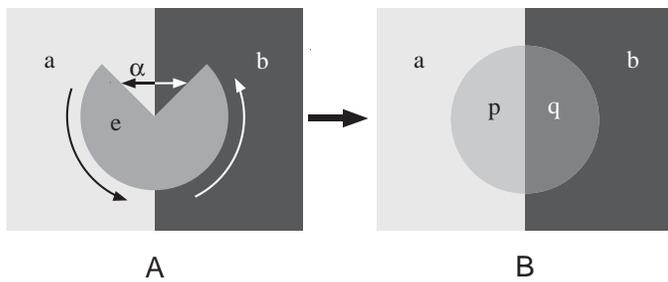


Figure 12. Model of a transparent layer based on an episcotister, an open wedged disk that rapidly rotates in front of a background. A.  $a$  and  $b$  are the reflectances of the two background patches.  $e$  and  $\alpha$  are the episcotister's reflectance and proportional area of open wedge respectively. B. When the disk is rotating at a high enough rate, the opaque and open sectors appear to fuse together, resulting in the percept of a transparent layer over the background with reflectances  $p$  and  $q$ .

$$p = \alpha a + (1 - \alpha)e \tag{19}$$

$$q = \alpha b + (1 - \alpha)e \tag{20}$$

Metelli respectively referred to  $\alpha$  and  $e$  as *transparency* and *color* of the transparent layer. Conversely, the values of  $a$ ,  $b$ ,  $p$ , and  $q$  can be used to solve for  $\alpha$  and  $e$ :

$$\alpha = \frac{p - q}{a - b} \tag{21}$$

$$e = \frac{\alpha q - bp}{(a + q) - (b + p)}. \tag{22}$$

Given  $a$ ,  $b$ ,  $p$ , and  $q$ , observers must extract  $\alpha$  and  $e$ . According to this model, for a given bipartite background, the luminance range,  $|p - q|$ , determines  $\alpha$ . Metelli claimed that this coefficient was the primary determinant of perceived transparency.

Expanding further on Metelli's model, Beck et al. (1984) examined constraints on the perception of

transparency. Because  $\alpha$  is restricted to values between 0 and 1, Equation 21 implies that (i) if  $a > b$ , then  $p > q$ ; and  $q > p$ , if  $b > a$ , and (ii) the absolute difference  $|b - a|$  must be greater than the absolute difference  $|q - p|$ . Because  $e$  is also restricted to values between 0 and 1, Equation 22 implies that (iii) if  $(a + q) > (b + p)$  then  $aq > bp$  and  $bp > aq$  if  $(b + p) > (a + q)$ , and (iv) the absolute difference  $|(a + q) - (b + p)|$  must be equal to or greater than the absolute difference  $|aq - bp|$ . Constraint (i) is a restriction on the order of the intensities and insures that  $\alpha$  is positive. Constraint (ii) is a restriction on the magnitude of the intensities and insures that  $\alpha$  is less than 1. Metelli (1974a) had previously demonstrated that the perception of transparency occurs when these two constraints are met and fails to occur when either of them is violated. Constraint (iii) insures that  $e$  is non-negative, and constraint (iv) insures that  $e$  is less than or equal to 1.0. Beck et al. (1984) showed that violations of these last two constraints do not adversely affect the perception of transparency. They argued that constraints (iii) and (iv) involve operations of addition and multiplication that are not readily interpretable by the visual system. They also argued that the degree of perceived transparency varies linearly, not with reflectance, but with lightness, a nonlinear function of reflectance.

Perceived transparency has also been studied as a constancy problem by Gerbino et al. (1990). They make an important point of distinguishing between Metelli's reflectance term,  $e$ , which they termed *material reflectance*, and *effective reflectance*  $f$ , where  $f = (1 - \alpha)e$ . In their experiment, observers were presented with two sets of luminance patterns, a standard and a match, similar to Figure 12b. The luminance relations of each set of patterns were different from each other and both always met the constraints that led to the perception of transparency. The observers' task was to vary the luminance of the central patches composing the transparent layer in the matching pattern so that the layer appeared most similar to the transparent layer of the standard pattern. The central patches composing the transparent layer in the matching pattern were automatically covaried in such a way that the matching layer transmittance was always kept constant and equal to the standard layer transmittance ( $\alpha' = \alpha$ ). Only the value of the common additive component  $f$  could be adjusted. Obtained values corresponded well with episcotister model predictions and results indicated that when  $\alpha$  is equated by the experimenter, the effective reflectance term  $f$  is what observers equated in order to match transparent layers. Alternative models based on local luminance or average contrast ratios accounted for less variability.

Metelli's episcotister model is not, however, without flaws. Singh and Anderson (2002) have pointed out Metelli's (1974b) footnote stating that a black episcotister appears more transparent than a white episcotister of the same fractional section  $\alpha$ . This implies that  $\alpha$  is not the

sole determinant of perceived transparency. In Singh and Anderson's experiments, observers stereoscopically viewed small transparent disks overlying sinusoidal backgrounds. Observers were asked to match the perceived transparency of the standard disks by adjusting the matching disks' luminance ranges ( $L_{\max} - L_{\min}$ ) while their mean luminances were kept fixed. Separately, observers were asked to match the lightness of the standard disks by adjusting the matching disks' mean luminances while their luminance ranges were kept fixed. Whereas Metelli's equations predict that perceived transparency should be independent of mean luminance, Singh and Anderson's results show that observers' settings of luminance ranges increase monotonically with mean luminance of the matching disks. This would explain Metelli's observation of systematically overestimating the transmittance of the darkening transparent layers, and systematically underestimating the transmittance of lightening transparent layers. For Singh and Anderson's displays, they found the critical variable for perceived transparency to be Michelson contrast  $|(p-q) / (a-b)|$ . In order to equate perceived transparency, observers set the luminance range of the matching disk so that its Michelson contrast matched that of the standard disk, independent of mean luminance.

In Experiment 1 of the present study, when the fixed parameters of the standard and match filter were different, the data show a consistent and linear trade-off between reflectivity and inner transmittance (Figure 5). When the match filter had a fixed reflectivity higher than that of the standard filter, observers increased the inner transmittance of the match filter to match perceived transparency. When the match filter had a fixed reflectivity lower than that of the standard filter, observers decreased the inner transmittance of the match filter to match perceived transparency. This result corroborates Singh and Anderson's (2002) results in which observers increased the luminance range of a matching layer monotonically as its mean luminance increased. When the matching results are transformed into terms of reflectance and transmittance (Figure 10), data points generally line up in a vertical fashion along the transparency of the standard filter, indicating that equal perceived transparency corresponds closely to the physical aspect of equal transmittance. There is, however, some departure from vertical with many of the data points lining up along paths with positive slopes slightly less than vertical. In other words, there is a trend to adjust  $\beta$  and  $\theta$  so as to increase  $t$  when  $r$  is high. This is again constant with Singh and Anderson's results as well as Metelli's (1974b) observation that a darkening episcotister looks more transmissive than a lightening one with the same transmittance term.

To measure the accuracy and precision of perceived transparency, Kasrai and Kingdom (2001) designed a stimulus with six luminance patches. A circular background was divided into three equally sized wedges.

Over the center of the background, a smaller circular filter was simulated, creating three overlaid wedge patterns. A traditional transparency figure based on the episcotister model is composed of four luminance patches (Figure 12b). In these traditional figures there exists a unique solution for either  $\alpha$  or  $f$  (but not both) when only one luminance patch is adjustable. If the figure consists of six patches (3 background + 3 overlaid), there exists a unique solution for both  $\alpha$  and  $f$  when only one luminance patch is adjustable. In Kasrai and Kingdom's experiment, the three background patches had their luminances fixed. Two of the overlaid patches had their luminances fixed with  $\alpha$  and  $f$  equated. The observers' task was to adjust the luminance of the third overlaid patch so that the three central wedge patterns appeared to be overlaid by a single homogeneous filter. Predictions from the luminance-based formulation of Metelli's episcotister model as well as predictions from a variation of Singh and Anderson's model based on ratios of Michelson contrasts provided reasonable fits to the data. This is despite the fact that there was a reasonably wide range of adjustable patch luminances that gave rise to at least some degree of perceived transparency.

It has been shown that perceived contrast predicts perceived transparency (Singh & Anderson, 2002), but only for sinusoidal backgrounds where contrast is defined by Michelson contrast. In our variegated display, Michelson contrast as well as the other standard contrast metrics tested, failed to predict contrast matching results, and thus also failed to predict matches for perceived transparency.

All of the aforementioned experiments have treated transparent layers as being generated from simple models based on episcotisters, and presented them on bipartite or tripartite or sinusoidal backgrounds. The layers were manipulated by adjusting transmittance  $\alpha$ , effective reflectance  $f$ , luminance range, or mean luminance. Here we generated filters based on models that more closely represent their physical properties, and presented them over complex, variegated backgrounds. The physical filter properties were manipulated during perceived transparency matching and perceived contrast matching experiments. Matches of perceived transparency between physically dissimilar filters enabled us to isolate sensory variables and physical properties that are responsible for the degree of perceived transparency.

The results from Experiment 1 show that by adjusting either reflectivity or inner transmittance, observers could reliably match perceived transparency for filters with different physical properties. Matches of perceived transparency involved a trade-off between reflectivity and inner transmittance that was generally linear. Because (1) only one control was sufficient to produce matches, (2) matches were possible in nearly 97% of trials, and (3) match settings made by adjusting reflectivity and match settings made by adjusting inner transmittance fell along the same functions, perceived transparency can be

thought of as a one-dimensional percept. When the data for equated perceived transparency were plotted in terms of filter reflectance and transmittance, a simple pattern emerged. To the extent that the points are aligned vertically along the standard filter's transmittance, equal perceived transparency corresponds closely to equal transmittance. It is therefore likely that transmittance is the physical determinant of perceived transparency.

The results from Experiment 2 show that by adjusting either reflectivity or inner transmittance, observers could reliably match perceived contrast for regions overlaid by filters with different physical properties. The settings of reflectivity and inner transmittance for matched contrasts were similar to those values set for matched perceived transparency. Given the similarity of the settings, it is likely that perceived contrast of the overlaid regions is the sensory determinant of perceived transparency.

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