Color Transparency: Geometry, Motion, Color, Scission, and Induction

Submitted by
Zhehao Huang

DISSERTATION

In partial satisfaction of the requirements of the degree of
Doctor of Philosophy

SUNY College of Optometry

December, 2021

Approved by the Dissertation Committee:

Dr. Robert McPeek (Chair) Signature Date 12/10/21
Dr. Qasim Zaidi (Advisor) Signature Date 12/10/21
Dr. Jose Manuel-Alonso Signature Date 12/10/21
Dr. Steve Shevell Signature Date 12/10/21
Dr. Bevil Conway Signature

Stewart Bloomfield, PhD
Associate Dean for Graduate Studies and Research
Dedication

To Su Jin and Huang Jiandong.
# Table of Contents

Table of Contents........................................................................................................ iii

Introduction..................................................................................................................... 1

Chapter 1 Perceptual scale for transparency: Common fate overrides geometrical and color cues........................................................................................................... 9

Abstract.......................................................................................................................... 9

Keywords......................................................................................................................... 10

Introduction..................................................................................................................... 11

Method............................................................................................................................ 15

Stimuli.............................................................................................................................. 15

Results............................................................................................................................. 28

Conclusion....................................................................................................................... 38

Acknowledgments........................................................................................................... 38

Reference......................................................................................................................... 38

Appendix......................................................................................................................... 44

Chapter 2 Testing invariance of perceived filter color across colored backgrounds: the case of colorless filters................................................................................................. 45

Introduction....................................................................................................................... 45

Methods.......................................................................................................................... 48

Stimuli.............................................................................................................................. 48

Experimental Procedure................................................................................................. 51
Introduction

In this section, I provided a short review on color transparency, and then describe what is innovated about the three studies I have done.

When our eyes receive light reflected from the surface, we can see the object, perceiving its color, shape and other properties. When surfaces are overlaid by a transparent filter, it’s a common thing that we could perceptually separate the colors of the image into the colors of the underlying surface and the color of the overlaying layer. Such ability was called perceptual scission. This ability is essential in our daily lives, enabling us to judge the color of transparent objects, and infer surface colors behind fog. However, the mechanism to the transparency perception and perceptual scission remains a mystery. Because of the physical characteristics of transparent layers, the spectral distribution and intensity of light coming from each point of the overlaid image is a composite of illuminant spectrum passed through the spectrum of an intervening medium, reflected from the surface spectrum, and passed again through the spectrum of the intervening medium, and does not in itself contain separable information about the characteristics of the components. Apart from spectral information, geometrical and moving information also influence our perception to transparency. In the following paragraphs, we will introduce the characteristics that lead us to perceive transparency, and how we perceive color under transparent filter.

Cues to Transparency

The continuation of contours from contours from exposed to overlaid regions creates X-junctions in the image, while the discontinuation creates T-junctions. X-junctions trigger transparency perception when there are multiplicative changes in contrast, and in achromatic stimuli, observers match the degree of transmittance to perceived contrast. However, X-junctions are not necessary for volumetric transparency, or if there is a continuation of pattern from exposed to overlaid regions. T-junctions, created by the opaque patch lying on a background, are generally considered to be cues for occlusion between opaque objects, but can elicit the impression of an illusory transparent layer under conditions of amodal completion.

Metzger mentions in a footnote that the law of common fate would add a contribution in cinema photography, but without details of the conditions or evidence. Previous measurements reported that motion seems to enhance the impression of

1
transparency in the presence of X-junctions, and enhances the perception of opacity in the presence of T-junctions. Such result is similar to its role in distinguishing reflections from paint, but this has not been critically tested. The effect of motion is not only limited to the contours and edges, as color change and apparent motion can create an illusory transparent layer. Further, dynamic image deformation can lead observers to report transparent water or hot air flowing above the background, and transparency is actually enhanced by the presence of T-junctions at the edge of the surface. Motion is thus likely to be a complex cue for transparency, and yet to be tested its relationship with perception of transparency.

When a surface is covered with a transparent layer, the spectra of lights from the exposed background differ from lights from the portion overlaid by a filter by a double pass through the transmission spectrum of the filter. However, when lights from exposed surfaces are absorbed in L, M, S cone-photopigments, and plotted against lights from identical surfaces overlaid by a filter, the change can generally be defined by a multiplicative constant for each cone class. Therefore, changes in spectra of lights transmitted through filters form a 3-D diagonal transform in cone space or an affine transform in cone-opponent space. The transformation provides a strong cue to the filter color, proving sufficient information for estimation.

The spectra information suggested veridical perception of the filter color could be used as a measure of the degree of scission, and Khang & Zaidi tested how accurately human observers separate the image into overlay and background components by placing moving transparent layers on chromatically different sets of background materials. They put filters on the left and right side of the screen and tested if the observers could tell if they are identical. During the trial, the observers adjusted the color of the filter on a gray-level background to match the filter on a colored background. For 6 different colored filters, placed on 6 different colored backgrounds, the matched chromaticity was close to the actual chromaticity of the test filter against a grey background, and differed significantly from the average chromaticity of the overlaid segment, providing ostensibly strong evidence for color scission. The same stimulus, with surround changed to black, gave an impression of a spotlight on a dark surface, not a transparent filter, and in this case, when observers matched the spotlight by a spotlight on a gray-level background, the light had the average chromaticity of the overlaid segment, which differed significantly from the actual chromaticity of the spotlight filter. The result suggested that the observers can accurately separate colors of transparent layers, supporting the
perception of filters, but not supporting the perception of spotlights. However, this interpretation is limited by the fact that the color of the filter creates color contrast from exposed to overlaid areas, with an increase towards the filter color on the overlaid area irrespective of the background colors, and observers could be responding to that rather than to a transparency percept.

Perceptual scission and color constancy

Gerbino et al. first asked observers to match the appearance of two transparent layers side-by-side, each against a background of different contrast. They considered it as a constancy problem, and their result was consistent with the prediction of episcotister model. Khang and Zaidi made a series of measurements of the perception in chromatic transparent layer. They simulated natural illuminants with color filters and various surfaces, and used force-choice procedure to measure thresholds for identifying filters and opaque patches. The result suggested that geometrical and color information helped the observer to identify similar overlays across different illuminants, and they concluded that the accuracy of inferred color constancy for ensembles of objects requires color scission between material reflectances and illuminant spectra. A later study used a similar configuration with a matching task, finding an incomplete constancy across multiple illuminants.

Khang and Zaidi continued to investigate, as they placed filters on various sets of chromatic materials and match filters on achromatic materials. Filter matching was close to veridical in most cases, however, was not possible in cases where the transmittance of the filter was highly dissimilar in shape to the reflectance of the background materials. The result suggested that the accuracy of color scission in transparency perception depends on the color composition of background surfaces. Faul and Ekroll expanded the measurement under multiple illuminants, and found a systematic deviation with different illuminants.

Khang and Zaidi further measured illuminant color estimation for spectrally filtered spotlights. Their results showed that the estimation was relatively accurate when the surroundings were illuminated, but the matching was biased when no illuminant other than the spotlight was presented. A heuristic model was proposed to suggest observers using additive or multiplicative model based on the relative surrounding luminance.
We plan to go beyond this in three ways:

In Chapter 1, we focused on the cues to the transparency. Although many types of cues (X or T-junctions, motion, color consistency) were studied in the previous studies, very few of them have designed the stimuli based on the cooperation or competition of the cues. We used the cues in cooperation or conflict to evoke gradations of perceived transparency, and asked observers to judge the probability of physical transparency in Likert-type paired comparisons. From these comparisons, we estimated a perceptual transparency scale for human observers using a Maximum likelihood variant of classical Thurstone scaling, which allowed us to quantitatively compare and analyze the factor influencing our transparency perception. We built a linear model with 5 latent factors, and have found that motion-related common fate took the most important role in transparency perception, suggesting a relation between motion and transparency different from past studies.

Previous measurements of color scission have limitations. For example, the color adjustment to match the target color is relatively accurate, but it’s also time consuming and suffers from long time adaptation bias. Force-choice judgment is quick and free from adaptation effect, but the selection of choices can be the source of bias. In Chapter 2, we examine the observers’ ability to estimate filter color with transparency with our improved method: we ask observers to make a judgement of the transparency region being red or green (or, blue/yellow). By doing this we could find the neutral point of the filter that the observers think colorless. We would also like to see how the observers perform scissions in our color inconsistent stimuli in Chapter 1, so we included them as part of the stimuli.

In Chapter 3, we designed novel isomeric stimuli: the same variegated achromatic background, in stimulus 1, we put under a yellow light with the light then passing through a circular cyan filter; in stimulus 2, we put it under a cyan light with the light then passing through the circular yellow filter. The lights coming to the eye from the two circular regions were identical, but they looked different. We compared isomeric stimuli with each other, also with single color filter and discovered color induction is responsible for the perception of transparency colors.

Reference
Chapter 1 Perceptual scale for transparency: Common fate overrides geometrical and color cues

Abstract

Objects that pass light through are considered transparent, and we generally expect that the light coming out will match the perceived color of the object. However, when the object is placed on a colored surface, the light coming back to our eyes becomes a composite of surface, illumination, and transparency properties. Despite that, we can often perceive separate overlaid and overlaying layers differing in colors. How neurons separate the information to extract the transparent layer remains unknown, but physical characteristics of transparent filters generate geometrical and color features in retinal images which could provide cues for separating layers. We estimated the relative importance of such cues in a perceptual scale for transparency, using stimuli in which X or T-junctions, different relative motions, and consistent or inconsistent colors, cooperated or competed in forced-preference psychophysics experiments. Maximum-likelihood Thurstone scaling revealed some new results: moving X-junctions increased transparency compared to static X-junctions, but moving T-junctions decreased transparency compared to static T-junctions by creating the percept of an opaque patch. However, if the motion of a filter uncovered a dynamically changing but stationary pattern, sharing common fate with the surround but forming T-junctions, the probability of seeing transparency was almost as high as for moving X-junctions, despite the stimulus being physically improbable. In addition, geometric cues overrode color inconsistency to a great degree. Finally, a linear model of transparency perception as a function of relative motions between filter, overlay, and surround layers, contour continuation, and color consistency, quantified a hierarchy of latent influences on when the filter is seen as a
separate transparent layer.

Keywords

transparency, perceptual scale, color scission, layers, relative motion, image junctions, latent factors
Introduction

All objects modify the light that strikes them, but we only become perceptually aware of that when the light reflected onto a second surface matches the perceived color and/or shape of the first object. Objects that pass light through are considered transparent, and the modification of light is more obvious. We expect that the modified light coming out will match the perceived color of the transparent object, but the situation is more complicated if the object is placed on a colored opaque surface so that the light coming back to an observer is the result of modifications by both the transparent object and the opaque surface. Perceptual scission occurs if the shapes and colors of the underlying surface are seen as separate from the shape and color of the overlaying layer. The ability to disentangle the color of the surface from the color of the medium is essential to the success of vision. Among other functions, it enables us to judge the color of transparent objects, and infer surface colors behind fog. In conditions where a transparent layer is lying on top of the background surface, the spectral distribution and intensity of light coming from each point of the overlaid image is a composite of illuminant spectrum passed through the spectrum of an intervening medium, reflected from the surface spectrum, and passed again through the spectrum of the intervening medium, and does not in itself contain separable information about the characteristics of the components. However, the physical characteristics of transparency also create geometrical and color image features that evoke scission, and sometimes there is relative motion from actual movement or changes of viewpoint, especially if the transparent layer has a volume or is in front of the surface. In this paper, we quantify the relative importance of these features in giving the impression of transparency.

The continuation of contours from exposed to overlaid regions creates X-junctions in the image. X-junctions trigger transparency perception when there are
multiplicative changes in contrast, and in achromatic stimuli, observers match the
degree of transmittance to perceived contrast. An opaque patch lying on a
background creates T-junctions at the edge, which are generally considered to be
cues for occlusion between opaque objects, but can elicit the impression of an
illusory transparent layer under conditions of illusory modal contours. In addition, X-
junctions are not necessary for volumetric transparency, or if there is a continuation
of pattern from exposed to overlaid regions. We test the efficacy of T-junctions
versus X-junctions when other cues are also present.

Relative motion has also been linked to transparency. Informal observations
suggest that motion seems to enhance the impression of transparency in the
presence of X-junctions, and enhances the perception of opacity in the presence of
T-junctions, similar to its role in distinguishing reflections from paint, but this has not
been critically tested. In addition, color change and apparent motion can create an
illusory transparent layer. Further, dynamic image deformation can lead observers to
report transparent water or hot air flowing above the background, and transparency
is actually enhanced by the presence of T-junctions at the edge of the surface.
Motion is thus likely to be a complex cue for transparency, and we test its effect on
the perceptual separation of layers.

When observers look at an overlaid surface through a transparent layer, the spectra
of lights from an exposed background differ from lights from the portion overlaid by a
filter by a double pass through the transmission spectrum of the filter, but remarkably,
when lights from exposed surfaces are absorbed in L, M, S cone-photopigments, and
plotted against lights from identical surfaces overlaid by a filter, the change can
generally be defined by a multiplicative constant for each cone class. Hence,
changes in spectra of lights transmitted through filters form a 3-D diagonal transform
in cone space or an affine transform in cone-opponent space. This transform
provides a strong cue to the color of the filter, showing that there is sufficient
information to estimate the color (not the spectrum) of the filter, and suggesting that
veridical perception of the filter color could be used as a measure of the degree of
scission.

To test this suggestion, Khang & Zaidi estimated how accurately human
observers separate the image into overlay and background components by placing
moving transparent layers on chromatically different sets of background materials. To
measure whether observers could tell whether the two filters are identical despite the
local colors of the two overlaid regions being different, observers adjusted the color
of the filter on a gray-level background to match the filter on a colored background.
For 6 different colored filters, placed on 6 different colored backgrounds, the matched
chromaticity was close to the actual chromaticity of the test filter against a grey
background, and differed significantly from the average chromaticity of the overlaid
segment, providing ostensibly strong evidence for color scission. The same stimulus,
with surround changed to black, gave an impression of a spotlight on a dark surface,
not a transparent filter, and in this case, when observers matched the spotlight by a
spotlight on a gray-level background, the light had the average chromaticity of the
overlaid segment, which differed significantly from the actual chromaticity of the
spotlight filter. These results suggest that observers can accurately scission colors of
transparent layers in geometric configurations that support the perception of filters
but not if they support the perception of spotlights against black surrounds. However,
the scission interpretation is limited by the fact that the color of the filter creates color
contrast from exposed to overlaid areas, with an increase towards the filter color on
the overlaid area irrespective of the background colors, and observers could be
matching the change in color with or without a transparency percept, thus veridical
filter color matching would not be a direct estimate of the degree of color scission.
To counter this limitation, we used the transparency cues described above in cooperation or conflict to evoke gradations of perceived transparency, and asked observers to judge the probability of physical transparency in Likert-type paired comparisons. From these comparisons, we estimated a perceptual transparency scale for human observers using a Maximum likelihood variant of classical Thurstone scaling.
Method

Stimuli

Materials
A 46°×26° (1920×1080 pixels) monitor screen was covered with a variegated background of randomly oriented elliptical patches centered on randomly chosen pixels on the monitor, with long axes randomly ranging from .85 to 1.56 degrees, and short axes randomly ranging from .35 to .65 degree. The total number of ellipses per image was 8192, which we had found previously provided complete coverage in every case, so no iterations were needed. Ten different sets of ellipses were generated and one set was chosen randomly on each trial. To simulate the colors of background surfaces, we used 280 reflectance spectra materials chosen from measurements of natural and man-made objects that were previously used by Khang & Zaidi and Smithson & Zaidi. From the MacLeod-Boynton chromaticity plot of all 280 materials under equal energy light (Error: Reference source not found), we selected four sets of 40 materials each from single quadrants of the color space, while the fifth set was equally balanced across the four quadrants, and the sixth set consisted of 40 achromatic materials. On each trial, reflectances from one set were randomly assigned to ellipses, and a central disk covered by one of 6 Kodak CC30 color filters, randomly chosen on each trial. The 6 filters are shown on the 6 background surfaces in Figure 2.
Figure 1 MacLeod-Boynton chromaticity of 280 reflectances of natural and man-made materials under equal-energy light, used to simulate background surfaces. Background surfaces consisted of four sets of 40 materials each from the single quadrants of the color space designated with approximate color names for convenience, while the fifth set was equally balanced across the four quadrants, and the sixth set consisted of 40 achromatic materials with a similar luminance distribution.
Figure 2 Six Kodak CC30 color filters (red, green, blue, cyan, magenta, yellow) placed on 6 backgrounds: Quadrant Red-Blue, Quadrant Red-Yellow, Quadrant Green-Yellow, Quadrant Green-Blue, Balanced, and Achromatic.

**Geometric configurations**

We constructed geometric and motion configurations that required the transparent “filter” layer, the “overlaid” background surface layer, and the exposed “surround” surface layer to be oriented and moved independently, so each stimulus was constructed from the three simulated layers (illustrated below), and we will refer to the layers with the names inside the quotation marks. By separately manipulating the
three layers, we simulated 7 geometric configurations that combined geometric, motion cues to transparency, while maintaining colors in the overlaid and exposed regions that were physically consistent with transparency (Videos in Figure 3 top):

“Static X-junctions”: stationary circular filter on the background. The construction in terms of the three layers is illustrated in Figure 4A, where the overlaid surface is just cut out from the exposed surround, so replacing it yields a surface with continuous ellipses. “Moving X-junctions”: the simulated filter moving back and forth horizontally over the surface. Both configurations contain X-junctions on the boundaries of the disks, as realistic cues for transparency. By asking observers to compare the first two configurations, we can quantify if motion enhances the perception of transparency.

“Static T-junctions”: the circular overlaid region is the mirror-reversed version of the static X-junction case, thus creating T-junctions at the boundary with the surround (Figure 4B) and allowing a comparison of static X-junctions versus T-junctions in transparency perception. “Moving T-junctions”: the simulated filter and overlaid background move together as if one layer, thus creating moving T-junctions on the boundary. By asking observers to compare the static and moving T-junction
conditions, we can quantify if motion also enhances the perception of opacity. Figure 5 left presents a comparison of Moving X and Moving T configurations and their separation into the three layers. Note that the overlaid surface changes on each frame of the Moving X configuration as if cut out from the background surface on each frame, which is physically equivalent to the filter moving over a continuous stationary surface. The overlaid surface in the Moving T configuration moves with the filter but is unchanging, which is physically equivalent to an opaque patch moving over a surface. “Dynamic T-junctions”: the moving circular region on every frame is the mirror-reversed version of the moving X-junction condition, so the filtered region moves as if it is covering a stationary but changing overlaid surface on each frame, thus creating dynamically changing T-junctions on the moving boundary as opposed to X-junctions. In this critical condition, the moving filter seems to uncover new areas of the background on every frame, but these are different from what was on the exposed surround in the same location. The main motivation for this condition is that the overlaid and surround layers share a motion-defined common fate, not shared with the moving filter, thus this condition can reveal whether this common fate overriding T-junctions in transparency perception when compared to moving T-junctions where the filter and overlaid layers share a common fate. Figure 5 right presents a comparison of Moving X and Dynamic T configurations and their separation into the three layers. On each frame, the overlaid surface in the Dynamic T configuration is the mirror-reversed version of the overlaid surface in the Moving X configuration, so it changes on each frame unlike the Moving T configuration. “Relative motion”: the filter moves as in the moving X-junction condition, but the overlaid background moves at one-half the speed in the same direction. This condition also creates dynamic T-junctions, but no pair of layers share a common fate. “Overlaid Motion”: the filter and surround are stationary, but the overlaid background moves, as if the disk were an aperture. In this condition, T-junctions are created at the filter’s edge but the overlaid
layer does not share a common fate with the filter or surround layers, which however do so. This study aimed to estimate a scale for the degree of perceptual transparency of the filter layer across these seven combinations of geometric and motion cues.

Figure 4 Stimuli were constructed by combining a transparent “filter” layer, an “overlaid” surface layer, and an exposed “surround” layer. A) Construction of a Static X-junctions geometric configuration. The overlaid layer is cut out from the background, thus creating a continuous surface when replaced, and
forming X-junctions on the boundary of the circular region when the filter is placed on the overlaid section. B) Construction of a Static T-junctions geometric configuration is similar to the Static X-junctions, except that the overlaid layer is mirror-reversed, so when it is placed inside the exposed background, and the filter laid on it, T-junctions form on the filter boundary. C) When the exposed surface in the Static X-junctions is replaced by an achromatic background, while the overlaid layer remains the balanced background, a color inconsistent condition is created. D) A color inconsistent condition for the Static T-junctions configuration is constructed similarly.

Physically inconsistent color configurations

In the configurations above, the ellipses in the surround and overlaid circle were chosen from the same color set, so we call these conditions “Color Consistent”. For each configuration, we also created physically “Color Inconsistent” conditions by replacing the colors of the surrounding ellipses with achromatic shades (Figure 4C & D), because no filter with transmittance constant over time (no matter how complex spatially) could turn the achromatic ellipses into the dynamically varied colors seen under the filters (Especially the Moving X-junctions and Dynamic T-junctions videos in Figure 3 bottom). It is true that the same achromatic color can be an addition of many different combinations of wavelengths, so different patches of the same achromatic color could possibly be seen as different colors when seen through one color filter, but it would be physically impossible to obtain the pairs of almost complementary colors in the balanced set by this process. The set of achromatic ellipses maintained the average luminance, but each individual color of the surround was replaced by a randomly selected luminance so that the luminance relations across the filter border were also not physically compatible with transparency.

Consistent and inconsistent color configurations were compared across all geometric configurations to test whether color inconsistency vetoes perceived transparency or whether other cues can overcome it.
Figure 5 Videos. Two example trials. Left: Moving X-junctions on the left and Moving T-junctions on the right. Right: Moving X-junctions on the left and Dynamic T-junctions on the right. The stimuli were presented on a 24 inch screen with the disks subtending 7 degrees of visual angle, so the videos should be expanded to roughly the same size to replicate observers’ percepts.
**Experimental Procedure**

On each trial, an observer was presented with one stimulus each on the left and right halves of the screen with two different configurations randomly chosen from the 7 (Geometric+Motion) × 2 (Color consistency) = 14 configurations. Thus, there were a total of (14x13)/2 = 91 distinct pairs. For each forced-preference paired comparison, one overlaid layer color set and one filter color were randomly chosen for both sides, i.e. the same filter and overlaid layer colors on both sides, so each pair was repeated 72 times for each observer (6 filter colors x 6 overlaid color sets x two left-right permutations). In the color consistent conditions, the surround colors were from the same set as the overlaid layer, whereas in the color inconsistent conditions the surround was achromatic.

The videos in the top row of Figure 5 show two example trials. The left column shows *Moving X-junctions* on the left and *Moving T-junctions* on the right, where the difference in perceived transparency is large, and the right column shows *Moving X-junctions* on the left and *Dynamic T-junctions* on the right, where the difference in perceived transparency is small despite there being T-junctions in the right stimulus and X-junctions in the left. On each trial, the observer was given these instructions, “On each trial of the experiment, a scene of oriented ellipses will be displayed on the screen. There will be two disks, moving or not, on the left half and right half of the screen. Some of the disks will be transparent and some will be not. Sometimes it will be easy to tell and sometimes not. Your task is to look at both disks and decide which has a higher probability of being a transparent layer”. Observers were instructed to use buttons to report the judgment using a 5-point Likert scale: “Left disk has much higher probability”, “Left disk has slightly higher probability”, “Left and right disks have equal probability”, “Right disk has slightly higher probability” and “Right disk has
much higher probability”.

**Observers**

Five observers participated in the experiment, all of whom had normal or corrected visual acuity and normal color vision. One of the observers is the first author of this paper and was aware of the nature and the purpose of the experiment, while other observers were briefed about the experiment after the data had been collected. Observers gave informed consent, and the procedures were approved by the SUNY Optometry IRB Committee in accordance with the Declaration of Helsinki.

**Apparatus**

Stimuli were shown on a VPixx LED monitor using MATLAB and Psychtoolbox. The observers sat at a viewing distance of 63 cm. Stimuli were displayed at 16-bits per channel, with a linear gamma. To compute screen RGB correctly for rendering light spectra, spectral distributions of the monitor primaries were measured with a SpectraScan PR650 photo-spectroradiometer.

**Thurstone scaling**

To estimate a perceptual scale for transparency we used a maximum likelihood variant of classical Thurstone scaling to analyze the paired forced-preference results. In standard Thurstone scaling, the results from paired comparisons between stimuli are stored in an $m \times m$ matrix $C$, where $C_{ij}$ is the number of times that $i$ is preferred over $j$, and $C_{ji}$ is the number of times that $j$ is preferred over $i$, so that $C_{ij} + C_{ji} = n$ the number of repeated choices. Thurstone assumed that the subjective value of each stimulus is a Gaussian random variable $S_i$ with mean $\mu_i$.
and variance $\sigma^2_j$, so the task is to estimate $\mu_i$. Forced preference between stimulus $\tilde{S}$ and $\tilde{J}$, can be modeled as judging whether $S_i > S_j$, or equivalently $S_i - S_j > 0$.

Based on the Gaussian assumption, $S_i - S_j$ is also a Gaussian with mean $\mu_i - \mu_j$ and variance $\sigma^2_i + \sigma^2_j$, giving the probability of $\tilde{S}$ being preferred over $\tilde{J}$:

$$P(S_i > S_j) = P(S_i - S_j > 0) = \Phi\left(\frac{\mu_i - \mu_j}{\sigma_i^2 + \sigma_j^2}\right),$$

where $\Phi$ is the Gaussian cumulative distribution. From the empirical results, $P(S_i > S_j)$ can be estimated by the proportion of times that $\tilde{S}$ is preferred over $\tilde{J}$:

$$P(S_i > S_j) \approx \frac{C_{ij}}{C_{ij} + C_{ji}}$$

To simplify the model, all the subjective values are assumed to have variance equal to $\frac{1}{\sqrt{2}}$, therefore $\sigma^2_i + \sigma^2_j = 1$, so $\mu_i - \mu_j$ can be estimated by:

$$\mu_i - \mu_j = \Phi^{-1}\left(\frac{C_{ij}}{C_{ij} + C_{ji}}\right),$$

where $\Phi^{-1}$ is the z-score function. If $\mu$ is the vector of all scale values $\mu = [\mu_1, \ldots, \mu_n]$, then the log-likelihood of $\mu$ given $C$:

$$L(\mu|C) = \log P(C|\mu) = \sum_{i,j} C_{ij} \log(\Phi(\mu_i - \mu_j))$$

And the scale values can be estimated as:
In pilot experiments, we realized that a two-alternative judgment was not providing sufficient nuance, so we used a 5-point Likert scale, adding strong and weak preferences and a neutral option. We used the Spicker et al. extension to Thurstone scaling. $S$ and $W$ matrices record the number of times that one stimulus is strongly or weakly preferred over another, and $N$ records the number of times that two stimuli are judged equal in value. If $\delta_0$ is the subjective boundary between “neutral” and “weakly preferred”, and $\delta_1$ be the subjective boundary between “weak preferred” and “strongly preferred”, the boundaries between adjacent options on the 5-point scale will be $[-\delta_1, -\delta_0, \delta_0, \delta_1]$. Then the log likelihood of scale values $\mu$ conditional on $S, W$ and $N$ is given by:

$$L(\mu | S, W, N) = \log P(S, W, N | \mu),$$

where

$$\log P(S, W, N | \mu) = \sum_{i,j} S_{ij} \log (1 - \Phi(\mu_i - \mu_j - \delta_1)) + \sum_{i,j} W_{ij} \log \Phi(\mu_i - \mu_j - \delta_0) - \Phi(\mu_i - \mu_j - \delta_1) + \sum_{i,j} N_{ij} \log \Phi(\mu_i - \mu_j - \delta_0).$$

The best estimate of $\mu$ is obtained by using convex optimization to solve:

$$\arg \max_{\mu} L(\mu | S, W, N), \text{ subject to } \sum_{i,j} \mu_i = 0, \delta_0 > 0, \delta_1 > 0$$

The results of the optimization form an interval scale, but not a ratio scale, so rank and differences are meaningful, but zero is arbitrary. In our case, it was set by
assuming that $\sum \mu_i = 0$ in Equation 8. The estimated mean of each configuration $\mu_i$ was taken as an estimate of the subjective scale value of transparency for each observer.
Results

In the scaling analysis, we pooled preferences from the 72 combinations (36 filter and overlaid color pairs times 2 left-right permutations) for each of the 14 configurations, thus obtaining a scale that was based on a wide range of similarities between the filter and overlaid layer colors (S, W, N matrices for all observers are presented in Appendix Figure A1). The analysis estimated the subjective scale value of transparency of the 14 configurations for each of the 5 observers. The scale values for the Combined observer were estimated by pooling all 5 observer's preferences before the analysis, thus giving 5 times the number of choices as each individual observer, hence more reliable probability estimates. As Figure 6 shows there is remarkable concordance between observers. “Moving X-junctions”, “Static X-junctions” and “Consistent Motion” values are positive, “Relative Motion” and “Static T-junctions” values are around 0.0, and “Aperture Motion”, “Moving T-junctions” values are below negative, corresponding to impressions of transparency for positive values and opacity for negative values. Since the Thurstone scale is an interval scale, we used Pearson's correlation test to examine the correlation of observers’ scale value. The pairwise Pearson’s correlations between observers range from 0.87 to 0.95 (Table 1), and the correlations with the Combined observer range for 0.96 to 0.98, so we will discuss the results of the Combined observer in detail.
Table 1 Pearson’s correlation coefficient between observers’ scale values.

<table>
<thead>
<tr>
<th></th>
<th>Obs 1</th>
<th>Obs 2</th>
<th>Obs 3</th>
<th>Obs 4</th>
<th>Obs 5</th>
<th>Combine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs 1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obs 2</td>
<td>0.9135*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obs 3</td>
<td>0.9464*</td>
<td>0.9313*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obs 4</td>
<td>0.8810*</td>
<td>0.9543*</td>
<td>0.8730*</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obs 5</td>
<td>0.9339*</td>
<td>0.9525*</td>
<td>0.9521*</td>
<td>0.8725*</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Combine</td>
<td>0.9609*</td>
<td>0.9829*</td>
<td>0.9580*</td>
<td>0.9644*</td>
<td>0.9550*</td>
<td>1</td>
</tr>
</tbody>
</table>

*p < 0.001

The results show that disk movement that continually generates X-junctions looks more transparent than its static X-junction counterpart, in fact, moving X-junctions even overcome physically impossible color inconsistency to have the third highest transparency value for the Combined observer. “Dynamic T-junctions” had
the second highest scale value after “Moving X-junctions” for the Combined observer and was rated much more transparent than “Relative Motion”, even though both configurations continuously generate new T-junctions. This result indicates that common fate could prevail over junctions in promoting a percept of transparency. “Moving T-junctions” was consistently the least transparent configuration, showing that common fate between the filter and overlaid segment enhanced the effects of T-junctions for evoking opacity. It was interesting that the motion of just the overlaid layer inside an aperture did not evoke the impression of a colored transparent layer, possibly because observers added the color of the filter to the background. All inconsistent color conditions appeared a little less transparent than their color-consistent counterparts, but geometric configurations could overcome color inconsistency in evoking transparency, despite it being physically impossible for a transparent filter to create variegated colors from all four quadrants of color space when placed on an achromatic background. Although the effects of many of these cues have been examined in isolation, the cooperation and conflict of these cues compared together reveal a hierarchy of transparency enhancers and inhibitors, with effects that are remarkably similar across observers.

**Latent factors**

The perceptual scale is a function of stimulus configurations, and this would be useful in many applications, but we wanted to take advantage of the concordance across observers to identify the latent factors that influence transparency perception. Phenomenologically, in the simplest case, transparency perception requires seeing the transparent layer as separate from the overlaid surface, and that could be made easier by seeing surround and overlaid surfaces as connected. The connection between overlaid and surround surfaces is enhanced by contour continuation in X-junctions, so the presence or absence of contour continuation is likely to influence transparency perception. Transparency layer separation and connection between overlaid and surround surfaces are both enhanced by systematic luminance and color changes from exposed to overlaid regions that simulate physical reality, as in the color consistent conditions. However, achromatic surrounds in color inconsistent
conditions simulate physical impossibility but don’t veto transparency percepts, so we wanted to find out what weight observers give to the inconsistency relative to the other factors. Since all forced choices were between pairs with the same filter and overlaid layer colors, differences between stimulus color combinations do not affect any choice, so are not reflected in the perceptual scale. Since motion-created common fate is a strong grouping enhancer, lack of relative motion between surround and overlaid surfaces in conjunction with the motion of the transparent layer with respect to the two surfaces would enhance the separation of the transparent layer. We thus took contour-continuation, color-consistency, and relative motion as the latent factors underlying the perceptual transparency choices that generate the quantitative perceptual scale for our stimuli. We used a regression model to quantify the relative weights of these factors, without committing to a particular neural or behavioral decision process.

In the latent factor stage of the model (Figure 7), the pairwise relative motion was represented by three latent factors: \( M_S = M_O \), when the overlaid surface moved with the same velocity (possibly zero) as the surround surface, \( M_F = M_S \) when the filter layer moved with the same velocity as the surround surface, and \( M_F = M_O \) when the filter layer moved with the same velocity as the overlaid surface. For each of the 14 experimental conditions, every latent factor was coded as a binary variable with +1 for True (solid arrows) and -1 for False (dashed arrows). The contour continuation factor \( K \) was +1 for X-junctions, and -1 for T-junctions, and the color consistency factor \( C \) was +1 for physically realistic consistency and -1 for physically impossible inconsistency. \( T \) represents the transparency scale in real numbers, and we fit \( T \) as an additive function of the latent factors (Equation 9) using the MATLAB
function fitlm:

\[ T = \alpha + 1 + L \cdot E + E \]

In Equation 9, \( T \) is a 14×1 array of empirical scale values, \( \alpha \) is a constant parameter to be estimated, \( L \) is a 14×1 array of 1.0s, \( E \) is a 14×1 array of errors \( \epsilon \). \( B \) is a 5×1 vector of \( \beta \) parameters to be estimated, and \( L \) is the 14×5 matrix of the relation between stimulus conditions and latent variables given by Equation 10:

\[ \hat{c} \cdot 10 \]

Figure 7 Latent factor perceptual transparency model. The top layer contains the experimental conditions in rectangles with the same labels as Error: Reference source not found. The middle layer contains the latent factors in circles, and the color-coded solid and dashed arrows mean the latent variable is True (solid) or False (dashed) for that condition. The last layer is the transparency scale in the diamond, and the black solid (positive correlation) and dashed (negative) arrows are labeled with the
The regression model fits so well with just additive binary latent factors ($R^2 = 0.976, F = 63.98, p < .001$), that making the factors continuous or adding interaction terms between them could not make the fit significantly better. The predicted transparent scale estimated from the best fitting model parameters is plotted against the combined empirical scale in Figure 8, and the points lie close to the unit-diagonal, consistent with the high correlation between the scales ($R^2 = 0.976$). Note that other sets of latent factors are unlikely to be sufficiently explanatory. For example, motion *per se* would not work because while motion enhances the transparency effect of X-junctions, it also enhances the opacity effect of T-junctions. Similarly, even though pattern similarity between surround and overlaid surfaces works for Fuchs’s transparency, in our stimuli, the *Relative Motion* and *Dynamic T-junctions* conditions have the same pattern similarity but evoke different probabilities of transparency.

![Figure 8](image.png)

**Figure 8** Perceptual scale predicted from the regression model versus the empirically derived perceptual scale for the Combined observer ($R^2 = 0.976$).
The coefficients for the latent factors for the Combined observer are shown in Figure 7. The constant term in the regression equation is equal to -0.09, so is much smaller than the other terms. The largest positive effect on transparency is from the lack of relative motion between surround and overlaid surfaces, while the next largest effects show that relative motion between the filter and surround or filter and overlaid surface enhances transparency, corresponding to the negative effect shown for lack of relative motion. Together, the relative motion latent factors promote perceptually separating the filter layer from the two surfaces. All three motion effects are larger than the effect of contour continuation, while color consistency has the smallest effect, in fact, motion-defined common fate overcomes geometrical and color improbabilities and even impossibilities to create transparency percepts. Table 2 shows that the latent factors model predicts each observer’s perceptual scale extremely well ($R^2$ ranging from 0.939 to 0.978). It shows that different observers give different relative weights to the latent factors, but the signs are the same for all observers.

<table>
<thead>
<tr>
<th>Observer</th>
<th>Combined</th>
<th>O1</th>
<th>O2</th>
<th>O3</th>
<th>O4</th>
<th>O5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-.085</td>
<td>-.008</td>
<td>-.120</td>
<td>.006</td>
<td>-.145</td>
<td>-.004</td>
</tr>
<tr>
<td>$M_s=M_o$</td>
<td>.718</td>
<td>.693</td>
<td>.703</td>
<td>.674</td>
<td>.665</td>
<td>.576</td>
</tr>
<tr>
<td>$M_f=M_s$</td>
<td>-.267</td>
<td>-.240</td>
<td>-.300</td>
<td>-.094</td>
<td>-.321</td>
<td>-.189</td>
</tr>
<tr>
<td>$M_f=M_o$</td>
<td>-.394</td>
<td>-.222</td>
<td>-.415</td>
<td>-.311</td>
<td>-.528</td>
<td>-.271</td>
</tr>
</tbody>
</table>

31
The main contribution of this study is the perceptual scale for transparency estimated for cooperating or competing cues. The values in the perceptual scale in turn allowed us to infer weights of latent factors that control transparency perception. The neural locus and mechanisms of transparency perception are open questions. To understand the brain mechanisms that extract transparency from retinal images, one possible strategy would be to measure neuronal or voxel responses to the central disk for all 14 of our stimulus conditions and correlate these responses to the combined scale. A high correlation would indicate that the cell or brain area is segmenting the transparent layer from the background surface. One caveat is that the human results are combined over all combinations of filter and background colors, whereas for each cell, the stimuli may need to be restricted to the colors to which the cell responds reliably. Note that cells or brain areas that respond only to color contrast at the edge of the filter will respond just as strongly to the Moving T-junctions configuration as to the Moving X-junctions, so would not provide strong correlations with the perceptual scale where these conditions are at the opposite extremes. For a cell that shows evidence of responding well to perceptual transparency, a fit of the latent factors model to its responses will suggest how it combines geometric, motion and color cues from earlier brain areas.
The perceptual scale shows that relative motion enhanced both transparency and opacity depending on which layers were moving relative to each other, acting more like a potentiating agent than a cue, similar to its role in distinguishing reflections from paint. One possibility is that motion could be enhancing the effects of X-junctions and T-junctions by increasing the displayed number or their salience. Relative salience versus relative validity has been studied in associative learning and navigation, but not yet in visual cue combination. Decreasing the sizes of ellipses in the displays would increase the number of X- or T-junctions, whereas increasing the sizes would increase the salience, but neither seems to have much effect on verbal ratings of transparency perception. Instead, the “Dynamic T-junctions” condition, which is a novel contribution of this study, demonstrates that the main role of relative motion is increasing the likelihood of perceiving separate layers that don’t share a common fate. In pointing out the role of certain shape changes in promoting impressions of transparency, particularly for shadows, Metzger mentions in a footnote that the law of common fate would add a contribution in cinema photography, but without details of the conditions or evidence, and it is highly unlikely that he was imagining a condition where common fate conflicts with other cues that are voting against transparency. The role we demonstrate for motion defined common fate explains motion enhancing effects in previous studies, but goes beyond them in showing that common fate can override the information provided by junctions, which are otherwise quite powerful factors.

The high perceived transparency scale values for some color inconsistent stimuli, and the lowest weight for color inconsistency in the latent factors model for the Combined observer, point to another new result of this study, that color inconsistency did not veto transparency perception despite physical impossibility and violations of perceptually derived rules for luminance and color relations. The
reasons why geometric and motion cues override color inconsistency would be interesting to explore.

Our latent factor model is extremely successful at explaining transparency-based choices with an additive regression model, but that does not mean that the decision process is restricted to a simple linear combination. Instead, as shown by Einhorn et al (1979), the signs and weights in a regression equation could reflect the ambiguities that the organism faces with regard to the substitutions and trade-offs between cues in a redundant environment, even if the choices arise from a much more complex process of cue search and attention that could include multiple hierarchical and conditional choice nodes. The regression weights could also reflect inverse reliability of the cues, if the underlying process is optimal probabilistic cue combination that treats transparency estimates as noisy, and uses a signal detection theoretic framework as in weak fusion models, but that would need to be investigated. The fact that certain latent factors can override physical impossibility in other factors is another new finding of this study. It may suggest temporal priority in processing that sometimes accumulates sufficient evidence for making a decision before the lower ranking latent factors are considered, but that too remains to be tested.

Conclusion

A perceptual scale for transparency evoked by cooperation and competition between motion, geometry, and color cues, shows that relative motion-defined common fate leads to perceptual separation of transparency layers despite conflicting geometrical and color information, and that transparency can be seen despite color and luminance inconsistency if other cues dominate.
Acknowledgments

NIH grants EY007556 and EY013312 to QZ.

Reference
Appendix

Matrices of preference counts:

Figure A1. Matrices showing the frequency that one stimulus is strongly or weakly preferred over another or that the two stimuli are judged equal in value, for each observer and the Combined observer, used in constructing the Thurstone scale. The color of the pixel represents the rate of preference for the row condition over the column condition. The sequence of the conditions is the same as the transparency scale order.
Chapter 2 Testing invariance of perceived filter color across colored backgrounds: the case of colorless filters

Introduction

When surfaces are overlaid by a transparent filter, color scission refers to the perceptual separation of the colors of the image into the colors of the underlying surface and the color of the overlaying layer. As the information from the colored transparent layer contains two chromaticities at one time: one from the background and one from the foreground, the luminance and contrast information are not enough for the perception of transparency.

Gerbino et al. first treated transparent layer perception for neutral density filters as a constancy problem. They asked observers to match the appearance of two transparent layers side-by-side, each against a background of different contrast, and found the result consistent with the prediction of episcotister model. Khang and Zaidi made a series of measurements of the perception in chromatic transparent layer. They used simulations of natural illuminants, materials, and filters in a forced-choice procedure to simultaneously measure thresholds for identifying filters and opaque patches across illuminants, and discrimination thresholds within illuminants. The result showed that geometrical and color scission can enable an observer to identify similar overlays across different illuminants on the basis of spectral properties, and they concluded that the accuracy of inferred color constancy for ensembles of objects requires color scission between material reflectances and illuminant spectra. Faul and Falkenberg used a similar configuration with a matching task, finding an incomplete constancy across multiple illuminants.

In the following experiments, filters were placed on various sets of chromatic materials and match filters on achromatic materials. Filter matching was close to
veridical in most cases, however, was not possible in cases where the transmittance of the filter was highly dissimilar in shape to the reflectance of the background materials. They thus suggest that the accuracy of color scission in the perception of transparency depends on the color composition of background materials. Faul and Ekroll continued to measure the matching results under multiple illuminants, and found a systematic deviation with different illuminants. A recent study also examined similar settings under different illuminant, and suggested chromatic induction’s role in color scission. They further measured illuminant color estimation for spectrally filtered spotlights, and the result showed that the estimation was biased when no illuminant other than the spotlight was presented, but the matching was more accurate when the surroundings were illuminated. They also proposed a heuristic model suggesting observers used different models (additive or multiplicative) based on the relative surrounding luminance.

Huang and Zaidi introduced a physically impossible color configuration of their transparency stimuli. They first simulated a color filter on a variegated colorful background, then replaced the colors of the surrounding ellipses with luminance-matched achromatic shades. Although no constant transmittance filter could turn the achromatic ellipses into varied colors, the observers still take the stimuli as transparent objects. Not many studies have been reported before. When Ekroll and Faul investigated the color conditions for the perception of transparency in neon spreading displays, one of their four stimulus’ color combination does not fit the strict additive model. The impression of transparency is still perceived but vague.

In this paper, we examine the observers’ ability to estimate filter color with transparency. We would like to see how people can scission filter color from background while perceiving transparency, and we used various filters to examine the precision the estimation. We used 3 geometric configurations from Huang and
Zaidi previous setting, and color inconsistent background stimuli will also be presented to examine if the observers are provided wrong information, how would they do to make a proper estimation. We ask observers to make a judgement of the transparency region being red or green (or, blue/yellow). By doing this we could find the neutral point of the filter that the observers think neither red, green, blue, nor yellow.
Methods

Stimuli

Materials

A 46°×26° (1920×1080 pixels) monitor screen was covered with a variegated background of randomly oriented elliptical patches (axis lengths from 0.85° to 3.12°). To simulate background surfaces, we used the 280 reflectance spectra materials chosen from measurements of natural and man-made objects that were used by Khang & Zaidi. From the MacLeod-Boynton chromaticity plot of all 280 materials under equal energy light (Figure 9 left), we selected four sets of 40 materials each from single quadrants of the color space, while the fifth set was equally balanced across the four quadrants, and the sixth set consisted of 40 achromatic materials. On each trial, reflectances from one set were randomly assigned to ellipses (Figure 9 right). The screen contained a disk-shaped region of 7° diameter. The disk was chosen from separate geometric and color transparency configurations described below, but both simulated the effect of combination of the 4 Kodak CC30 color filters, randomly chosen on each trial. On each trial, the filter will be an intermediate filter from two pairs of filters: green and magenta, cyan and orange. Green, magenta, and cyan are standard Kodak CC30 filters, while orange is a mixture of 71.4% Kodak CC30 Red filter and 28.6% Kodak CC30 Yellow filter. Filters are shown on the achromatic surface in Figure 10. The stimulus was thus constructed from three simulated layers, the transparent “filter”, the “overlaid” background surface, and the exposed “surround” surface, and the experiment will measure the degree of perceptual separation of the layers as a function of the cues. We will refer to the layers with the names inside the quotation marks.
Geometric configurations

We simulated 3 geometric configurations based on previous experiments to vary perceived transparency (Videos in Figure 11 top): “Static X-junctions”: stationary circular filter on the background. “Moving X-junctions”: the simulated filter moving back and forth horizontally. Both configurations contain X-junctions on the boundaries of the disks, as realistic cues for transparency. By asking observers to
compare the first and second configurations, we can quantify if motion enhances the perception of transparency. “Relative motion”: the filter moves as in the moving X-junction condition, but the overlaid background moves at one and a half times the speed in the same direction. The added relative motion could enhance or attenuate the impression of transparency.

Physically inconsistent color configurations
In the configurations above, the ellipses in the surround and overlaid circle were chosen from the same color set, so we call these conditions “Color Consistent”. For each configuration, we also created physically “Color Inconsistent” conditions by replacing the colors of the surrounding ellipses with luminance-matched achromatic shades, because no constant transmittance filter could turn the achromatic ellipses into varied colors, especially in the motion conditions (Videos in Figure 11 bottom). Consistent and inconsistent color configurations were compared for perceived transparency of different geometric configurations.

Figure 11 (Top) Red filter on the Balanced background set with 3 geometric configurations. (Bottom)
Experimental Procedure

On each trial, the observers will be presented one stimulus on the monitor. In the experiment, the observers will be asked to judge the color of the circular region, or the displayed disk. In half of the trials, the observers will be given red-green force choice; in the other half, they will be given blue-yellow force choice.

We used QUEST method to measure the neutral filter that that seen as neither reddish nor greenish (or neither bluish nor yellowish) to the observers.

Observers

Two observers participated in the experiment, all of whom had normal or corrected normal visual acuity and normal color vision. One of the observers is the first author of this paper and was aware of the nature and the purpose of the experiment, while other observers were briefed about the experiment after the data had been collected. Observers gave informed consent, and the procedures were approved by the SUNY Optometry IRB Committee in accordance with the Declaration of Helsinki.

Apparatus

Stimuli were shown on a VPixx LED monitor using MATLAB and Psychtoolbox. The observers sat at a viewing distance of 63 cm. Stimuli were displayed at 16-bits per channel, with a linear gamma. To compute screen RGB correctly for rendering light spectra, spectral distributions of the monitor primaries were measured with a SpectraScan PR650 photo-spectroradiometer.

Model

A material with reflectance $\theta_i(\lambda)$, filter $F_d(\lambda)$ and illuminant $I(\lambda)$, the cone absorptions will be
\[ L(\theta, \lambda, F_a, \lambda, I, \lambda) = \int \theta_i \lambda \cdot F_a \lambda \cdot I \lambda \cdot L \lambda \, d\lambda \]

\[ M(\theta, \lambda, F_a, \lambda, I, \lambda) = \int \theta_i \lambda \cdot F_a \lambda \cdot I \lambda \cdot M \lambda \, d\lambda \]

\[ S(\theta, \lambda, F_a, \lambda, I, \lambda) = \int \theta_i \lambda \cdot F_a \lambda \cdot I \lambda \cdot S \lambda \, d\lambda \]

In here, \( L(\lambda), M(\lambda) \) and \( S(\lambda) \) is the cone sensitivities by wavelength.

Without the filter, the cone absorption:

\[ L(\theta, \lambda, I, \lambda) = \int \theta_i \lambda \cdot I \lambda \cdot L \lambda \, d\lambda \]

Figure 12 L cone absorptions comparison

In Figure 12, the ratio of L cone absorptions from unfiltered to filtered condition is

44
similar to the ratio for the filters themselves. In the plot, each diamond represents a material, the filled diamond is the mean of all the materials plotted. The square represents the filter spectra, and the lines connect the filter spectra and the origin. The same hold true for M and S cones.

Hence filter trichromatic colors relative to surround colors can be estimated from cones catches of overlaid and exposed materials. This plot shows that the same hold true for all different materials:

\[
\forall i, \frac{L_i \theta_i |\lambda|, F_o |\lambda|, I(|\lambda|)}{L_i \theta_i |\lambda|, I(|\lambda|)} = \frac{L(F_o |\lambda|, I(|\lambda|))}{L(|\lambda|)}
\]

If the illuminant is equal-energy white, then:

\[
\frac{L_i \theta_i |\lambda|, F_o |\lambda|}{L_i \theta_i |\lambda|} = \frac{L(F_o |\lambda|)}{L}
\]

In here \(L = \int L |\lambda| d\lambda\), is a constant.

As we average \(N\) materials,

\[
\frac{\sum_{i=1}^{N} L_i \theta_i |\lambda|, F_o |\lambda| / N}{\sum_{i=1}^{N} L_i \theta_i |\lambda| / N} = \frac{L(F_o |\lambda|)}{L}
\]

Therefore, a good estimate of the filter will be the ratio of average filtered materials versus unfiltered materials:
This model predicts a neutral filter setting when the average filtered materials equal to the average unfiltered materials:

\[
\sum_{i=1}^{N_f} L_i \left| \theta_i \right| \lambda \bigg| F_a \lambda \bigg| = \frac{\sum_{i=1}^{N} L_i \left| \theta_i \right| \lambda}{N} = \frac{\sum_{i=1}^{N_b} L_i \left| \theta_i \right| \lambda}{N_{bf}}
\] (3)

\[
L \left| \widehat{F}_a \lambda \right| = L \cdot \frac{\sum_{i=1}^{N} L_i \left| \theta_i \right| \lambda}{N}
\] (2)
Results

In every QUEST process, the stimulus filter morphed between orange and cyan, or green and magenta, and the observer gave red vs green (or blue vs yellow) feedback. Such process ended with a neutral filter setting that the observer perceived neither green nor red (or neither blue nor yellow). We measured the red vs green and blue vs yellow neutral filter of each observer under 6 (background) × 2 (filter pair) × 3 (geometric) × 2 (color consistency) = 72 configurations. We have plotted the mean chromaticity of the overlaid region filtered by the neutral setting on each background (Figure 13 to Figure 24). The vertical line markers represent red vs green neutral settings, and the horizontal line markers represent blue vs yellow.

![Figure 13](image-url)

Figure 13 The measured neutral filter setting of Observer 1 under color consistent condition and Static X-junctions configuration, plotted in MacLeod-Boynton chromaticity diagram. Each panel represents the background materials, and the color diamonds represent the mean chromaticity of the materials. The dashed line represents the mean chromaticity filtered by the filter, one from Cyan (upper left) to Orange (lower right), the other from Green (lower left) to Magenta (upper right). The vertical line marker represents the red vs green neutral filter setting, and the horizontal line represents blue vs yellow neutral filter setting.
Figure 14 The measured neutral filter setting of Observer 1 under color consistent condition and Moving X-junctions configuration, plotted in MacLeod-Boynton chromaticity diagram.

Figure 15 The measured neutral filter setting of Observer 1 under color consistent condition and Relative Motion configuration, plotted in MacLeod-Boynton chromaticity diagram.
Figure 16 The measured neutral filter setting of Observer 1 under color inconsistent condition and Static X-junctions configuration, plotted in MacLeod-Boynton chromaticity diagram.

Figure 17 The measured neutral filter setting of Observer 1 under color inconsistent condition and Moving X-junctions configuration, plotted in MacLeod-Boynton chromaticity diagram.
Figure 18 The measured neutral filter setting of Observer 1 under color inconsistent condition and Relative Motion configuration, plotted in MacLeod-Boynton chromaticity diagram.

Figure 19 The measured neutral filter setting of Observer 2 under color consistent condition and Static X-junctions configuration, plotted in MacLeod-Boynton chromaticity diagram.
Figure 20. The measured neutral filter setting of Observer 2 under color consistent condition and Moving X-junctions configuration, plotted in MacLeod-Boynton chromaticity diagram.

Figure 21. The measured neutral filter setting of Observer 2 under color consistent condition and Relative Motion configuration, plotted in MacLeod-Boynton chromaticity diagram.
Figure 22 The measured neutral filter setting of Observer 2 under color inconsistent condition and Static X-junctions configuration, plotted in MacLeod-Boynton chromaticity diagram.

Figure 23 The measured neutral filter setting of Observer 2 under color inconsistent condition and Moving X-junctions configuration, plotted in MacLeod-Boynton chromaticity diagram.
Figure 24: The measured neutral filter setting of Observer 2 under color inconsistent condition and Relative Motion configuration, plotted in MacLeod-Boynton chromaticity diagram.
Under each configuration, if the red vs green setting coincided (showed like a cross marker on the figure) or nearly coincided the blue vs yellow setting, we will take the mean of the settings as the "neutral point", because it indicates the observer perceived neutral color of the filter that perceived as neither green nor red nor blue nor yellow. We succeeded in measuring 44 neutral points out of 72 configurations for Observer 1 (Error: Reference source not found), and 26 for Observer 2 (Figure 26).

In Error: Reference source not found and Figure 26, we plotted the chromaticity of the neutral point, or the mean chromaticity of overlaid region which the observer perceived as neutral.

As we mentioned in the Method part, the L cone absorption of a material with reflectance \( \theta_1(\lambda) \), under filter \( F_1(\lambda) \) and illuminant \( I(\lambda) \) will be

\[
L_1 \theta_1(\lambda) \cdot F_1(\lambda) \cdot I(\lambda) = \int \theta_1(\lambda) \cdot F_1(\lambda) \cdot I(\lambda) \cdot L(\lambda) \, d\lambda
\]

And the same applied to M and S cones. In our case, the filter is a linear combination of two filters:

\[
F(\lambda) = \alpha F_1(\lambda) + (1 - \alpha) F_2(\lambda)
\]

And the illuminant is equal energy white. Therefore, we have:

\[
L_1 \theta_1(\lambda) \cdot F(\lambda) \cdot I(\lambda) = \int \theta_1(\lambda) \cdot F(\lambda) \cdot I(\lambda) \cdot L(\lambda) \, d\lambda
\]

\[
\alpha \int \theta_1(\lambda) \cdot F_1(\lambda) \cdot I(\lambda) \cdot L(\lambda) \, d\lambda + (1 - \alpha) \int \theta_1(\lambda) \cdot F_2(\lambda) \cdot I(\lambda) \cdot L(\lambda) \, d\lambda
\]

So, we have shown that the cone absorption of the material under a morphed filter is equal to the morphing result of the cone absorption of the material under two filters. In Figure 25 and Figure 26, we plotted the chromaticity of the morphed filter as the measured
neutral setting.

The mean chromaticity of the overlaid region filtered by the neutral setting of Observer 1 under color consistent conditions (Figure 25 left) are presented as X and plus symbol on the figure, colored as the surrounding background while measuring. The neutral setting located close to the mean chromaticity of the corresponding background (colored diamond in the figure). To better show the relationship between the measure neutral setting and the true colorless chromaticity, we plotted the chromaticities of the neural filters (Figure 27). As the plots were divided by the horizontal and vertical dashed line as the cardinal axes of chromaticity, the measured neutral filters fell around the origin and did not change much under different geometric configurations. This result showed that the measured neutral filters are similar to the colorless (clear) filter, indicating that the observer tried to match the overlaid region chromaticity to the surrounding background. The result under color inconsistent conditions (Figure 25 right) were close to the origin, showing that the observer tried to match the overlaid region chromaticity to an achromatic or balanced background. The chromaticities of the overlaid region corresponding to the measured neutral filter shifted away from the surrounding background chromaticity (Figure 27).

The result of Observer 2 showed a systematic bias towards orange direction, indicating that the observer’s neutral point might be a little bit orangish (Figure 26). Considering the bias, the result of Observer 2 showed consistency with Observer 1, as the measured neutral filters were close to the origin under color consistency conditions, and shifted away from the background under color inconsistent conditions (Figure 26 and Figure 28).

Transparency scale and scission

In our previous paper, we have estimated the relative transparency of the geometric configurations (Static X-junctions, Moving X-junctions and Relative Motion) in a
perceptual scale. We compared the ranking of the geometric conditions and the degree of scission we measured to see if the relative higher transparency could help better scission for the observers.

We take the neutral setting on the achromatic background as the observers true neutral setting. If scission is complete in any of the three conditions, then we would expect the neutral settings on the 5 colored backgrounds to coincide with the true neutral setting. To quantify the deviation between the settings as an estimate of the degree of scission, we calculated a unit-less mean “distance” between the chromaticity of the neutral filter for each colored background and the chromaticity of the neutral filter for the achromatic background. The smaller the distance, the closer the measured neutral filter is to the true neutral point, meaning the observer has better scission. The unit-less “distance” is defined as:

\[ D = \sqrt{\left(\frac{I_L - I_W}{I_L + I_W}\right)^2 + \left(\frac{S_L - S_W}{S_L + S_W}\right)^2} \]

Where \( I = L/|L+M| \) and \( S = S/|L+M| \), \( L, M, S \) are the cone absorptions of the neutral filter \( F \) on a colored background and of the neutral filetr \( W \) on the achromatic background. As there were no scission in the color inconsistent conditions, in Table 3 we just present mean distances over the 5 colored backgrounds for the color consistent conditions and compare them to degree of perceived transparency in the different geometrical configurations.

The Moving X-junction configuration has the highest transparency scale value, and Relative Motion has the lowest (Table 3, from ). The mean distances with Moving X-junctions of both observers are the lowest among three. The distance ranking of Observer 2 is similar to the transparency scale ranking, but the case is not as clear for Observer 1. At best these results suggest that color scission measured
by estimating filter colors may be related to the level of perceived transparency for that geometric configuration.
### Table 3

<table>
<thead>
<tr>
<th>Observed Condition</th>
<th>Transparency Scale</th>
<th>Observer 1 Distance</th>
<th>Observer 2 Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static X-junction</td>
<td>.42</td>
<td>.047</td>
<td>.085</td>
</tr>
<tr>
<td>Moving X-junction</td>
<td>1.75</td>
<td>.037</td>
<td>.075</td>
</tr>
<tr>
<td>Relative Motion</td>
<td>-.10</td>
<td>.047</td>
<td>.095</td>
</tr>
</tbody>
</table>

Table 3 Comparison of the transparency scale and the mean distance of measured neutral filter under color consistent conditions.

The effect of chromatic induction

If the observer has perfect scission, we shall expect the chromaticity of the neutral filter setting is exactly the same as for the achromatic background. However, the neutral filter settings still showed a shifting away from the surrounding background (Figure 27 and Figure 28). For example, the neutral filter setting on a blue reddish (Quadrant PP) background appeared to be more yellow-greenish, and vice versa. Our previous study suggested spatial induction contributes to color scission for filters by shifting the perceived colors.
Figure 25 The measured neutral chromaticity of Observer 1, plotted in MacLeod-Boynton chromaticity diagram. Colored diamonds: the mean chromaticity of the surrounding background. Dotted line: the
morphing direction of the filter: from Cyan (upper left) to Orange (lower right), from Green (lower left) to Magenta (upper right). X: the neutral points measured in Cyan-Orange morphing conditions. Plus: the neutral points measured in Green-Magenta morphing conditions. Plus and X symbols are colored in response to the surrounding background while measuring.
Figure 26 The measured neutral chromaticity of Observer 2.
Figure 27 The measured neutral filter morph of Observer 1, plotted in MacLeod-Boynton chromaticity diagram. Dash line: two cardinal axes of chromaticity. Colored diamonds: the mean chromaticity of the surrounding background. Dotted line: the morphing direction of the filter: from Cyan (upper left) to
Orange (lower right), from Green (lower left) to Magenta (upper right). X: the neutral points measured in Cyan-Orange morphing conditions. Plus: the neutral points measured in Green-Magenta morphing conditions. Plus and X symbols are colored in response to the surrounding background while measuring.
Figure 28 The measured neutral filter morph of Observer 2, plotted in MacLeod-Boynton chromaticity diagram.
Discussion

The main goal of this study is to show whether the observer performed color scission under normal color consistent conditions or physically impossible color inconsistent conditions. In color consistent conditions, though biased by the background or individual preference, the observers' measured neutral filter settings were close to the colorless filter, showing relatively good color scission. In the color inconsistent conditions, the observers matched the overlaid region to a neutral color. Two distinctive results contrast our previous measurement of the perceived transparency, which showed the perceptual scale of transparency of the color inconsistent conditions were only a little bit smaller than their counterpart. The neutral filter settings we measured were close to the estimation we proposed in our model, as the average chromaticities of overlaid region equal to the average chromaticity of the background.

There have been numerous measurements on the color scission accuracy under transparent layer conditions. Faul and Ekroll found systematic deviations from constancy when matching transparent filters under different illumination. This result complemented Khang and Zaidi’s earlier results showing constancy under one illumination but different colored backgrounds. Later studies also indicated the importance of the measuring method: Faul and Falkenberg compared matching and identification task, Radonjić and Brainard compared four kinds of instruction to the matching task. Both papers concluded that different tasks and instructions may influence the difficulty of the task and make the observers change their strategies. To confirm our measurement of the neutral filter setting, we added another experiment under the color consistent conditions: the observer was presented with two stimuli at a time, one with the previously measured neutral filter, the other one with a grey filter (“true” neutral filter), and they had to pick which one looked more neutral to them.
The pick rate of the true neutral filter for Observer 1 is 47.2%, with no significant
difference to the rate of the measured neutral filter. This result validated our
measurement of the neutral filter. To further test this result not coming from random
guess, we have tested more filters around the measured neutral filter against the true
neutral filter. We first set two points on the morph line of the filter pair in the
experiment: the measured neutral point and the closest point to the origin (true
neutral filter). We took half of the distance between these two points and set it as a
unit distance. We then used 5 points including the measured neutral point and the
closest neutral point, and three other points which are one unit away from two points.
Each of these 5 points was presented with the true neutral filter on the corresponding
background to observers, with the question “Which one looked more neutral?”. The
result of Observer 1 was plotted in Figure 29. The result shown that the prefer rate is
not significantly different from 50% while comparing the measured neutral filter and
the true neutral filter, but such prefer rate raised up when the testing points were
further away from the measured neutral point in four out of the six cases. In the rest
of the two cases, all five points share no significant differences as the measured
neutral points were very close to the true neutral point.
Figure 29 Test results of Observer 1 comparing 5 points (description in text) and the true neutral point. Y axis represent the prefer rate of the true neutral point. Markers with plus symbol represent the measured neutral point, and markers with X symbol represent the closest point to the origin on the morph line. Red markers indicate the prefer rate is significantly higher than 50% (random guess rate).
References
Chapter 3 Spatial induction in color scission

This chapter has already published.
Short and sweet

Spatial Induction in Color Scission

Zhehao Huang and Qasim Zaidi
Graduate Center for Vision Research, State University of New York, New York, United States

Abstract
An exception to the rule that only one color is seen at every retinotopic location happens when a bounded colored transparency or spotlight is seen on a differently colored surface. Despite the spectrum of the light from each retinotopic location being an inextricable multiplication of illumination, transmission, and reflectance spectra, we seem to be able to scission the information into background and transparency/spotlight colors. Visual cues to separating overlay and overlaid layers have been enumerated, but neural mechanisms that extract veridical colors for overlays have not been identified. Here, we demonstrate that spatial induction contributes to color scission by shifting the color of the overlay toward the actual color of the filter. By alternating filter and illumination spectra, we present naturalistic simulations where isomeric disks appear to be covered by filters/spotlights of near veridical colors, depending solely on the surrounding illumination. This previously unrecognized role for spatial induction suggests that color scission employs some general purpose neural mechanisms.

Keywords
transparency, color, scission, induction

Date received: 27 July 2020; accepted: 25 January 2021

Seeing the color of a surface as separate from the color of an overlaying filter, spotlight, shadow, or fog (D’Zmura et al., 2000), is known as scission (Anderson & Khang, 2010). This ability facilitates judging the color of transparent volumes (Ennis & Doerschner, 2019), estimating illuminant color as an indicator of weather or time of day (Zaidi, 1998), and inferring surface colors (Brainard & Maloney, 2011). The disentangling problem is formally underdetermined if only the overlaid region is considered, because the spectral distribution

Corresponding author:
Qasim Zaidi, Graduate Center for Vision research, SUNY College of Optometry, 33 West 42nd St., New York, NY 10036, United States.
Email: qz@sunyopt.edu

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
coming from the overlaid image is the result of the illuminant spectrum transmitted through
the spectrum of the intervening medium, and reflected from the spectrum of the surface, with
both transmittance and reflectance leading to wavelength-by-wavelength multiplication
of spectra. Scission, however, becomes a solvable problem when information from the surround
is incorporated in the empirically established circumstance that (L, M, and S) cone absorptions
from overlaid regions are three-dimensional diagonal transforms of cone absorptions
from exposed regions, or equivalently an affine transform in cone-opponent space (Khang &
Zaidi, 2002a, 2002b; Westland & Ripamonti, 2000), opening up the possibility that neural
mechanisms could internalize this associational invariance and exploit it as a heuristic.
Khang and Zaidi (2004) showed that perceived filter colors across different colored back-
grounds were consistent with a model where observers matched the color transform across
backgrounds. We discovered that the matching is less veridical on a constant background
across different illumination spectra. To understand neural mechanisms involved in color
scission, we designed novel isomeric stimuli. To our surprise, we discovered that classical
color induction (Zaidi, 1999) is responsible in large part for setting the perceived color of the
filter/spotlight, and we demonstrate that in this article with stills and videos.

In Figure 1A (click to activate video), the circular disks in the two leftmost panels are
physically identical but appear different. The $Y_1C_F$ panel shows a variegated achromatic
background under an illuminant (script I) with the spectrum of a Kodak CC50 yellow (Y)
filter (Figure 1E), with the light then passing once through a circular Kodak CC50 cyan (C)
filter (script F). In the $C_YF$ panel, the illuminant has the cyan filter’s spectrum and
passes through a circular yellow filter. The lights coming to the eye from the two disks are
identical because the spectrum of the light in both cases is the wavelength-by-

wavelength multiplication ($C \times Y$) of the yellow and cyan spectra, reflected from the same
gray-level background. However, the filter color in $C_YF$ appears yellower than in $Y_1C_F$, an
example of partial color scission. The three left panels ($W_1C_F \times Y_F$, $W_1C_F$, and $W_1Y_F$) show
the $C_F \times Y_F$, $C_F$ and $Y_F$ filters under an equal-energy white (W) light. For convenience, we
will call these the essential colors of the filters (Zaidi, 1998). The perceived color of the filter
in $Y_1C_F$ is shifted from the essential color of the identical $C_F \times Y_F$ filter toward $C_F$ but not
completely. The perceived color of the filter in $C_YF$ is also shifted away from $C_F \times Y_F$, but
toward $Y_F$, again incompletely. These illusory shifts in filter color are the first demonstra-
tions of simultaneous color induction for simulated filters, showing that spatial induction
contributes to color scission in naturalistic displays by making filters appear closer to their
essential color. The perceived shift is in the color direction that is complementary to the
surround color with respect to the center color as described by Krauskopf et al. (1986),
consistent with color induction being mediated by higher order color mechanisms preferen-
tially tuned to a wide variety of color directions, like those in extra-striate cortex (Zaidi &
Conway, 2019).

Anderson and Khang (2010) demonstrated substantial color induction involving percepts
of moving transparent layers and suggested that scission precedes induction. Ekroll and Faul
(2013) went further and claimed that transparency underlies induction. Induction, however,
happens even when no percept of transparency is possible, for example, inside a spatially
uniform disc surrounded by drifting radial sine waves (Zaidi et al., 1992) or dynamic texture
(Spehar et al., 1996). The panels in Figure 1B have the same spatial and color distributions as
the panels above them, but when the video is activated, the initial disk is moved over the
background, replacing transparency promoting X-junctions into T-junctions evoking a
strong percept of a moving opaque patch (Khang & Zaidi, 2002a). $C_YF$ again appears
yellower than in $Y_1C_F$, showing that induction occurs even in the absence of transparency
Figure 1. A: Illuminant-filter transparency conditions on a variegated gray background, indicated by subscripts on color names. B: Opacity conditions with the same spatial and color distribution as (A). C: Illuminant-spotlight transparency conditions. D: Opacity conditions with the same spatial and color distribution as (C). E: Spectral distribution of Kodak CC50 cyan and yellow filters, and C × Y and C + Y. F: L, M, and S cone catches of materials under C × Y (black) and C + Y (gray) plotted against catches under C (diamonds) or Y (squares). Each diamond or square represents one material. Filled symbols represent catches from the filtered lights directly. Click to activate video.
or scission, so we maintain that induction has primacy, and in displays that simulate naturalistic conditions, it shifts the perceived filter color toward its essential color.

The filter displays are naturalistic in the limited sense that the colors are computed using spectra of real objects and filters, and the optical calculations are decent approximations to physical reality. Another naturalistic way to obtain identical transparent disks is to shine circular colored spotlights (subscript S) on top of illuminated scenes (Figure 1C) so that spectra of overlays are the wavelength-by-wavelength addition of spotlight and illumination spectra. The spotlight in \( C_Y S \) appears yellower than in \( Y_C S \), despite the two disks being physically identical. The perceived spotlight colors are shifted toward their essential colors from the essential color of \( C_Y S \). The induced effect thus holds for spotlights too and for opaque patches with the same color distributions (Figure 1D). Spotlights have a less saturated appearance than filters because \( C_Y S \) is a less selective spectrum than \( C_Y F \times Y_F \) (Figure 1E).

We tried many pairs of filters and found similar induced effects. As the \( C \times Y \) and \( C + Y \) filters passed bands of wavelengths, to illustrate the effect for the opposite case of notch filters that block roughly the same band, we recreated the filter and spotlight conditions for red and blue Kodak CC50 filters (click on Figure 2 to activate video). The R&B effects are similar to C&Y.

To quantify the direction and magnitude of the induced color shifts for the filters, observers were shown adjacent pairs of displays on a 48° × 27° (1,920 × 1,080 pixels) calibrated screen covered with oriented elliptical patches (axis lengths 0.85° to 1.56°) with uniform spectral reflectance. One half of the display simulated a circular 7° disk with the \( (A_F \times B_F) \) filter spectrum surrounded by \( A_I \) or \( B_I \) illuminated ellipses, and the other of a similar disk with the filter spectrum \( (A_F \times B_F) - kA_F + kB_F \) surrounded by \( W \) illumination, where the spectrum of the filter could be adjusted by \( k \) in the range \([-1,1]\). Observers were asked to match the colors of the two filters, ignoring small differences in brightness. The sign of \( k \) gave the direction of the perceived shift and \( 2k \) gave the magnitude. Interleaved in the experiment were matches to the moving opaque patches with the same color conditions. Averaged over three observers, the perceived shift in \( Y_C F \) was 0.428 and 0.056 from \( Y_F \times C_F \) toward \( C_F \) for the transparent and patch conditions, respectively. The shift in \( C_Y F \) was 0.268 and 0.026 toward \( Y_F \). The shift in \( R_C B_F \) was 0.128 and 0.072 from \( R_F \times B_F \) toward \( B_F \). The shift in \( B_C R_F \) was 0.140 and 0.104 toward \( R_F \). These results clearly show that induction moves the perceived color of the filter toward the color under neutral illumination, thus contributing to color scission, and although induction is greater under transparency than opacity percepts, there is reliable induction even with cues against transparency.

For measuring induction for simulated spotlights, one half of the display simulated a circular 7° disk with the \( (A_S + B_S) \) spotlight spectrum surrounded by \( A_I \) or \( B_I \) illuminated ellipses, and the other of a similar disk with the spotlight spectrum \( (A_S + B_S) - kA_S + kB_S \) surrounded by \( W \) illumination. The perceived shift in \( Y_C S \) was 0.428 and 0.042 from \( Y_S + C_S \) toward \( C_S \) for the transparent and patch conditions, respectively. The shift in \( C_Y S \) was 0.314 and 0.284 toward \( Y_S \). The shift in \( R_C B_S \) was 0.134 and 0.102 from \( R_S + B_S \) toward \( B_S \). The shift in \( B_C R_S \) was 0.130 and 0.078 toward \( R_S \). Measured induction for spotlights is also always in the direction toward the essential color of the spotlight over neutral illumination.

As the scission is partial, we checked to see whether there is sufficient information in the displays for a model to achieve complete scission. Figure 1F shows that the \( L, M, \) and \( S \) cone catches from the background ellipses in the disks under \( C \times Y \) and \( C + Y \) are almost perfectly correlated with catches from ellipses in the surround under \( C \) and \( Y \). The slopes are also
Figure 2. A: Illuminant-filter transparency conditions on a variegated gray background, indicated by subscripts on color names. B: Opacity conditions with the same spatial and color distribution as (A). C: Illuminant-spotlight transparency conditions. D: Opacity conditions with the same spatial and color distribution as (C). E: Spectral distribution of Kodak CC50 red and blue filters, and R × B and R + B. F: L, M, and S cone catches of materials under R × B (black) and R + B (gray) plotted against catches under R (diamonds) or B (squares). Each diamond or square represents one material. Filled symbols represent catches from the filtered lights directly. Click to activate video.
equal to the ratio of cone catches from the filter and illuminant spectra (filled symbols). Figure 2F shows similar perfect correlations for B and R. Khang and Zaidi (2004) showed that a visual system could match filter colors across backgrounds by equating ratios of spatially integrated cone catches from disks and surrounds, confirmed for volumetric transparency by Ennis and Doerschner (2019). We confirmed that the application of this model yielded essential Y, C, B, and R colors instead of the perceived colors, revealing that color scission is not perfect even when there is sufficient information.

The ability to match a filter color across backgrounds is often used to measure the degree of color scission. This article demonstrates that spatial induction contributes to color scission for filters and spotlights by shifting their perceived colors toward their essential colors. Why the color shift is seen predominantly on the overlay separated from the overlaid segment, could be modeled by simplicity or constancy assumptions about the background, but that is not the only possibility, so we hope our demonstrations will spur critical examination of this issue.

Authors' Contributions
Z. H. and Q. Z. designed the demos. Z. H. programmed the demos. Z. H. and Q. Z. modeled the results. Z. H. and Q. Z. wrote the paper.

Declaration of Conflicting Interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by National Institutes of Health Grants EY13312 and EY07556.

ORCID iD
Qasim Zaidi https://orcid.org/0000-0002-1300-2879

References


---

**How to cite this article**

Discussion

In this section, I describe the significance and implications of the results from the three studies I have done.

In Chapter 1, we have presented stimuli designed based on the cooperation and conflict of some common cues for transparency perceptions. The result was surprisingly inspiring, as some physically impossible stimuli, created by the conflict of properties, were still rated as transparent by observers. Such a result hinted that human might be more tolerant of transparency perception, which we did not find in previous studies. This could also be an implication for future studies, as more illusions are yet to be found.

We used paired comparison with modified Thurstone model in the experiment to get the perceptual scale from the observers. As previous studies usually used rating, our method prevented the bias from the individual standard difference. Ranking is also a commonly used method, but it has its own limitations: not easy to handle equal ranks. As there are many “equal” responses in our data, which were reflected as similar perceptual scales by the Thurstone model.

Our latent factor model used only binary factors and a linear model but fit the data quite successfully. From the factor weights, we concluded that motion-defined common fate led to transparency perception. Our conclusion provided a possible explanation on the effect of motion in the transparency problem, as common fate help observers to separate and group different surfaces by motion, thus identifying the transparent object. Although we only used transparent filters in the experiment, there are still many transparent objects in nature, such as water, jelly, etc. It will be interesting to see if motion-related common fate still prevails other cues in other transparent objects or not.
In Chapter 2, we measured observers’ ability to scission colors under transparency perception by adapting force-choice preference and QUEST process. This method proved to be efficient and accurate compared to the color matching task, but only limited to the colorless filter. Other colored filters are yet to be measured, especially on physically impossible stimuli.

Veridicality of scission varied little in the color consistent conditions, despite the large variation in degree of perceived transparency. It is yet early to state that veridicality of scission did not change much in every degree of transparency. Since we did not test opaque conditions, it is possible that the veridicality may change under opaque conditions. Also, we did not include conditions like “Dynamic T-junctions” from Chapter 1, which is also a physically impossible condition considered as transparent.

In Chapter 3, we designed isomeric stimuli which are physically identical but perceived differently. Such demonstration showed the effect of induction on perceptual scission, and our measurement also confirmed that. Further tests could be done on the induction effect. For example, about the shift direction of the induction. Does the perceived color shift away from the surround color, or shift towards the circular region, or both?

As all experiments in this thesis are psychophysics, we also set a possible plan in the future to further explore the neuron mechanisms in transparency perception. We proposed two key questions which are yet to be answered: 1. How does transparency perception express in neuron signals; 2. What’s the difference between transparent colors (derived from scission) and normal colors in neuron signals, especially when both (background color and filtered color) are perceived by the observer. If the physiology results show that the set of cells narrowly tuned to the filter color respond invariantly to the background color, and simultaneously cells
tuned to the color of the background, respond invariantly to the filter color, then this will be easy to see in the population response to the “filter” stimuli, and could be quantified by fitting a mixture-of-Gaussians or cosines model. However, if the results are more complicated, we have to propose alternative models to decode the filter and background signals from the population responses.
Conclusion

We found that motion-generated common fate promotes the inference that the overlaid region belongs with the exposed surround, thus enhances the perception of transparency. Such enhancement is strong enough to override the inconsistency in geometrical structure or color.

In color consistent conditions, though biased by the background or individual preference, the observers' measured neutral filter settings were close to the colorless filter, showing relatively good color scission. In the color inconsistent conditions, the observers matched the overlaid region to a neutral color. The measurement was close to the estimation proposed in the model, but the difference in color consistency contrast the transparency scale results.

Spatial induction contributes to color scission for filters and spotlights by shifting their perceived colors toward their essential colors. Why the color shift is seen predominantly on the overlay separated from the overlaid segment, could be modeled by simplicity or constancy assumptions about the background, but that is not the only possibility, so we hope our demonstrations will spur critical examination of this issue.