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Figure 1: Equiluminant teapots.

Abstract

The phenomenon of warmer colors appearing nearer in depth to viewers than cooler colors has been studied extensively by psychologists and other vision researchers. The vast majority of these studies have asked human observers to view physically equidistant, colored stimuli and compare them for relative depth. However, in most cases, the stimuli presented were rather simple: straight colored lines, uniform color patches, point light sources, or symmetrical objects with uniform shading. Additionally, the colors used were typically highly saturated. Although such stimuli are useful in isolating and studying depth cues in certain contexts, they leave open the question of whether the human visual system operates similarly for realistic objects. This paper presents the results of an experiment designed to explore the color-depth relationship for realistic, colored objects with varying shading and contours.

CR Categories: I.4.8 [Image Processing and Computer Vision]: Scene Analysis—Depth Cues

Keywords: depth perception, depth cues, warm-cool colors

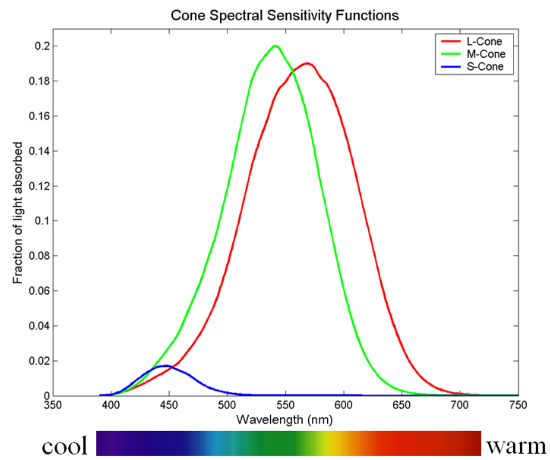

Figure 2: Response of the long, medium, and short wavelength (L, M, and S) sensitive cones to different wavelengths of light. Data based on experiments conducted on human observers [Stockman et al. 1999] [Stockman and Sharp 2000].

1 Introduction

Colors that appear closer to the red end of the visible spectrum are said to be warm while the colors that appear closer to the blue end are said to be cool. In general, the color of an object affects our judgment of its apparent depth in a scene. This phenomenon has been exploited by many traditional artists and has been studied extensively by psychologists, and other vision researchers. Early references to the color-depth relationship in literature refer to reds and oranges as *advancing colors* and blues as *receding colors* or *retiring colors* [Goethe 1982] [Luckiesh 1918]. The actual experimental study of the effect of color on perceived depth began in latter half of the 19^{th} century (see [Payne 1964] and [Sundet 1978] for summaries). In most of these studies, different colored stimuli was presented to human observers and their depth preferences were recorded. It was generally observed that warmer colors tend to appear closer to the viewer than cooler colors. In a few experiments, however, the opposite effect was observed where the cooler colors appeared closer than the warmer colors [Sundet 1978].

In order to account for these observed depth differences, several theories that are based on the physiology of the human visual system have been proposed. For example, it has been observed that the color sensitive cones in the retina exhibit a slight bias (higher responses) to colors toward the warm end of the visible spectrum (see Figure 2). Some physiologists have suggested that this bias may be strong enough to result in perceived depth differences between colors [Livingstone 2002].

Another (more accepted) theory states that the difference in perceived depth is due to fact that shorter wavelengths of visible light are refracted more than longer wavelengths [Sundet 1978]. As a result, equidistant sources of differing wavelengths cannot be simultaneously focused onto the retina by the eye's optical system. This is referred to as *chromatic aberration* and is illustrated in Figure 3.

A review of the research literature on color-depth experiments (and in fact most depth-cue experiments) reveals that in most cases the stimuli presented was very simple. They generally consisted of

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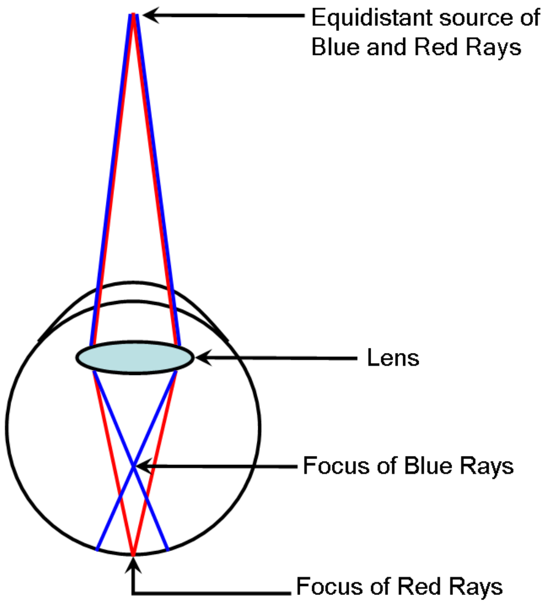

Figure 3: Chromatic aberration. Assumes eye is red accommodated. Adapted from [Sundet 1978].

straight colored lines, uniform color patches, point light sources, or symmetrical objects with uniform shading. Additionally, the colors used were typically highly saturated [Sundet 1978].

There are two main reasons for the use of such simple stimuli. First, many early researchers use the *weak observer theory* [Landy et al. 1995] as a basis for their experiments. This theory suggests that the various depth cues are processed by the visual system independently of each other and our final overall depth perception is simply a weighted combination of the contribution of the individual depth cues. Additionally, while most modern researchers quickly dismiss this theory, it is difficult to design effective experiments for the alternative *strong observer theory* [Landy et al. 1995]. The strong observer theory suggests that there are complex interactions between the various depth cues. The presence of one or more depth cues may either enhance or suppress the effect of other cues. Secondly, the use of simple stimuli by early researchers can be attributed to the lack the computing power, display technology, and accurate measuring devices.

While simple stimuli are useful in isolating and studying depth cues in certain contexts, they leave open the question of whether the human visual system operates similarly for realistic objects. This paper presents the results of a psychophysical experiment designed to explore the color-depth relationship for realistic, colored objects with varying shading and contours. The stimuli chosen for this experiment is an object (teapot) that appears natural regardless of its color. We begin with a photograph of the object and use a simple color replacement technique to create additional stimuli that have the same luminance as the original teapot (see Figure 1). The experiment takes the form of a *paired comparison test*. Participants were asked to observe all possible pairs of differently colored teapots on a computer screen and select the teapot in each pair that appears closest to them. This approach is more effective than ranking or rating studies, which require a large number of trials and often suffer from distorted results [Siegel and Castellan 1988].

Previous work is discussed in section 2. In section 3, we describe our experiment in more detail. In section 4 we present a detailed analysis and discussion of the results. We conclude in section 5 and discuss future directions for our research.

2 Previous Work

Various sources of information in a scene contribute to our perception of depth. These sources are referred to as depth cues and are typically grouped into three categories: pictorial, occulomotor and stereo cues [Gillam 1995]. The pictorial depth cues are ones that we obtain from two-dimensional images. These include information such as relative size, distance to horizon, focus, occlusion, shadows, shading, color, relative brightness, and atmospheric effects [Pfautz 2000]. Perspective cues such as relative size, occlusion, and distance to the horizon are generally more effective at conveying depth than shading, luminance, and color [Wanger et al. 1992] [Hone and Davis 1993] [Surdick et al. 1994].

Sundet provides an excellent summary of the early studies of the role of color as a depth cue [Sundet 1978]. Typically, in these early studies, researchers used very simple stimuli in an attempt to eliminate or minimize other depth cues. The trend in more recent studies is the exploration of the complex interactions between various depth cues [Doorschot et al. 2001] [Guibal and Dresp 2004] [Landy et al. 1995].

The knowledge gained from the study of human depth perception has been used by computer graphics researchers to develop techniques for manipulating the apparent depth of objects in a scene. These techniques typically rely on three-dimensional representations of the scene where depth information is readily available. Examples include the introduction of atmospheric effects like haze or fog [Rogers 2000] [Ope 2002], perspective changes such as the shape, size, or position of objects (or camera) [Foley et al. 1996], and level of detail (LOD) changes [Heckbert and Garland 1994]. In the case of images, where a 3D representation of the scene is not available, Gooch and Gooch have shown that the perceived depth can be enhanced by adding an artistic matting [Gooch and Gooch 2004]. More recently, Bailey and Grimm have shown how subtle apparent depth changes can be introduced by manipulating either the luminance or color of the object and/or background [Bailey and Grimm 2006].

Nevertheless, there is an absence of research pertaining to perceived depth from colored, realistic objects, which inspired the present study. The primary stimulus used was an image of a teapot that appeared realistic regardless of its color. Participants were presented with all possible pairs from a set of differently colored teapots and were asked to select the teapot in each pair that appears closest to them. This approach is called a paired comparison test. Ledda et al. present a strong case for the use of this type of testing [Ledda et al. 2005]. Although the number of test pairs (and hence experiment time) grows quickly as the number of objects in the test set increases, they point out that the results of a paired comparison test do not suffer from the distortion that is common in ranking or rating approaches. The teapots were presented against 4 different backgrounds of varying intensity levels. This allows us to analyze the impact of luminance contrast on the depth preferences recorded. Additionally, participants also performed the test on the uniform color patches that we used to color the teapots. This allows us to evaluate the impact of shading on the depth preferences.

3 Experiment Design

The stimuli used in this experiment consists of 7 colored teapots (and 7 colored patches). This choice of stimuli was motivated by

Figure 4: Original photograph of teapot. Courtesy of Jack Tumblin and Ankit Mohan.

(a)

(b)

Figure 5: (a) Perceptually distinct colors. (b) Adjusted equiluminant colors.

the fact that this particular teapot appeared natural regardless of its color. We begin with a photograph of the teapot (see Figure 4) and perform segmentation using an interactive min-cut max-flow segmentation algorithm proposed by Boykov and Jolly [Boykov and Jolly 2001]. Seven perceptually distinct colors were manually selected from the color spectrum (see Figure 5(a)). The luminance of these colors was adjusted to match average luminance of the original teapot. The resulting equiluminant colors are shown in Figure 5(b). Each of these target colors was then applied to the teapot. The target colors were scaled by the pixel luminance values of the original teapot to create the stimuli used in this study. This approach preserves the shading and specular highlights of the original teapot (see Figure 1).

Fifteen subjects (4 females, 11 males), between the ages of 18 and 40 volunteered to participate in this study. They all reported normal or corrected-to-normal vision with no color vision abnormalities. Participants were seated in front of a computer screen in a dimly lit room. Stimuli were presented on a 17 inch monitor, operating at 60 Hz with a resolution of 1280 x 1024. Two objects of the same type (teapot or color patch) were presented for each trial. Each teapot was 1.6 inches high and 1.8 inches wide. Each color patch was 1.6 inches high and 1.6 inches wide. The objects were displayed 1 inch apart on either side of an imaginary central point on the screen. The background could be one of four different uniform levels of gray, ranging from black to white. Participants were instructed to decide which object appeared nearer and responded by moving the mouse over their choice and clicking on it. If participants were unsure, they were instructed to choose based on their initial impulse. Between each trial, a blank screen was displayed for a 2 seconds. This was done because, it has been shown that our perception of depth diminishes with viewing time. A 2 second interval prevents total adaptation, thereby ensuring that depth perception remains stable [Troscianko et al. 1991]. Each participant

	x	0	0	0	0	1	1
	1	x	1	0	0	0	1
	1	0	x	0	0	0	0
	1	1	1	x	0	1	0
	1	1	1	1	x	1	1
	0	1	1	0	0	x	0
	0	0	1	1	0	1	x

Figure 6: Preference matrix. A 1 in row i column j signifies that stimulus i appeared closer than stimulus j.

								Score
	x	7	11	13	12	11	8	62
	8	x	6	7	10	8	10	49
	4	9	x	9	8	7	6	43
	2	8	6	x	11	7	4	38
	3	5	7	4	x	6	6	31
	4	7	8	8	9	x	9	45
	7	5	9	11	9	6	x	47

Figure 7: Cumulative matrix for teapot data set against black background.

experienced every possible comparison against every background for both the color patch and teapot data sets. A object was never compared against itself. Participants were given breaks after every 7 minutes of testing.

The presentation order of the stimuli was randomized for each participant. The color patch pairs, and teapot pairs were also randomly interleaved. Participant responses were stored in 7 x 7 preference matrices (see Figure 6). This approach (patterned after [Ledda et al. 2005]) allows for easy analysis of the results. Eight preference matrices were generated for each participant: four for the teapot data set presented against each of the 4 possible backgrounds and likewise four for the color patch data set. A preference matrix is best interpreted in a row-wise fashion. For example in Figure 6 the 1's in the first row specify that the purple teapot appears closer than the orange and red teapots. Corresponding preference matrices of all participants are summed together to form eight cumulative preference matrices.

4 Results and Discussion

Figure 7 shows the cumulative matrix for the 15 participants for the teapot data set presented against the black background. If we sum across each row we obtain a score for each colored teapot (shown in last column). This score tells how many times a given teapot is chosen relative to all other teapots. The interesting thing to note

Background Intensity

Stimuli

	62	57	44	53
	49	54	43	41
	43	38	43	41
	38	39	49	51
	31	21	32	40
	45	42	49	45
	47	64	55	44

Figure 8: Scores for the teapot data set.

Background Intensity

Stimuli

	56	61	36	39
	52	41	57	47
	31	35	34	39
	32	40	37	55
	19	17	44	48
	57	46	51	50
	68	75	56	37

Figure 9: Scores for the patch data set.

about this particular matrix is the clear cyclic trend in scores as you move from top to bottom (cool to warm). The high score for the purple teapot compared to the red teapot could be explained in terms of the the cyclic nature of the color spectrum[1]. Purple can be considered to be a warm or cool color depending on the amount of red content. This particular purple that resulted from the luminance equalization process has a high red content.

Figure 8 shows the scores for the teapot data set for each background and Figure 9 shows the scores for the patch data set for each background. These two figures give us valuable insight into the impact of luminance contrast on our depth perception. The two dark patches that are used for the background are darker than the average luminance of the stimuli while the two light patches that are are lighter than the average luminance of the stimuli. Notice that for both the teapot and patch data sets that the cyclic relationship between warm-cool color ordering and perceived depth gets stronger as the background gets darker. On the other hand, as the background gets brighter the relationship is lost.

Figure 10 and Figure 11 show the average probability or responding "near" for each of the teapots and color patches over the 4 possible background luminance. The trends for the color patches reveal less variability, as evidenced by the smooth functions for each color patch. This suggests that the more complex an image is, the more an observer may try to gather other depth cues from that image. When complex images are viewed, such as the teapots, color is not necessarily the overriding depth cue. This is evidenced by a comparison between the pattern of results for the color patches and teapots. Note that in the color patches, red, which has been established in the literature as appearing nearer, does indeed show this pattern: the red comparison was chosen reliably more than the purple, cyan, green, yellow, and orange patches. In the teapots, however, the red comparison was chosen reliably more than the cyan, green, and yellow teapots only. Additionally, the warm orange color which received a high probability of being reported as "near" for the color patches received was less effective when applied to the teapot.

[1]The color spectrum is often presented as a continuous color wheel with red blending into purple.

5 Conclusion

This paper presents the results of an experiment designed to explore the color-depth relationship for realistic, colored objects with varying shading and contours. This study was motivated by the fact that previous studies used very simple unnatural stimuli. Our tests consisted of two types of stimuli: Uniform equiluminant color patches and equiluminant colored teapots. Although the colors of the stimuli were less saturated than those of previous studies, we still observed that there was a relationship between warm-cool color ordering and perceived depth for the color patches. The warmer colored patches (most specifically the red) tended to appear closer than the cooler patches.

When complex images such as the teapot are viewed, however, we observe that color is not necessarily the overriding depth cue. This motivates the need for more research in the field of depth cue interaction.

In this particular study, we also recorded participant response time for each of the trials. Guibal and Dresp [Guibal and Dresp 2004] have observed that there is a correlation between the probability of a "near" response and the response time (the higher the probability the shorter the response time) for simple, highly saturated stimuli. As part of our future work we will be further evaluating this study to see if the same relationship holds for the realistic, stimuli that was used.

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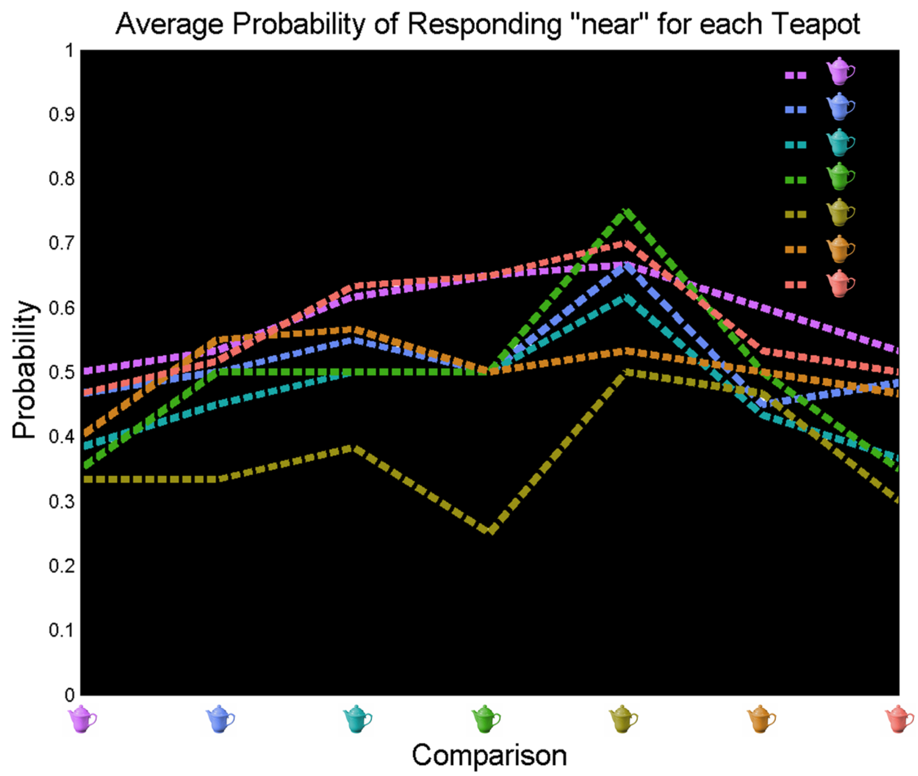

Figure 10:

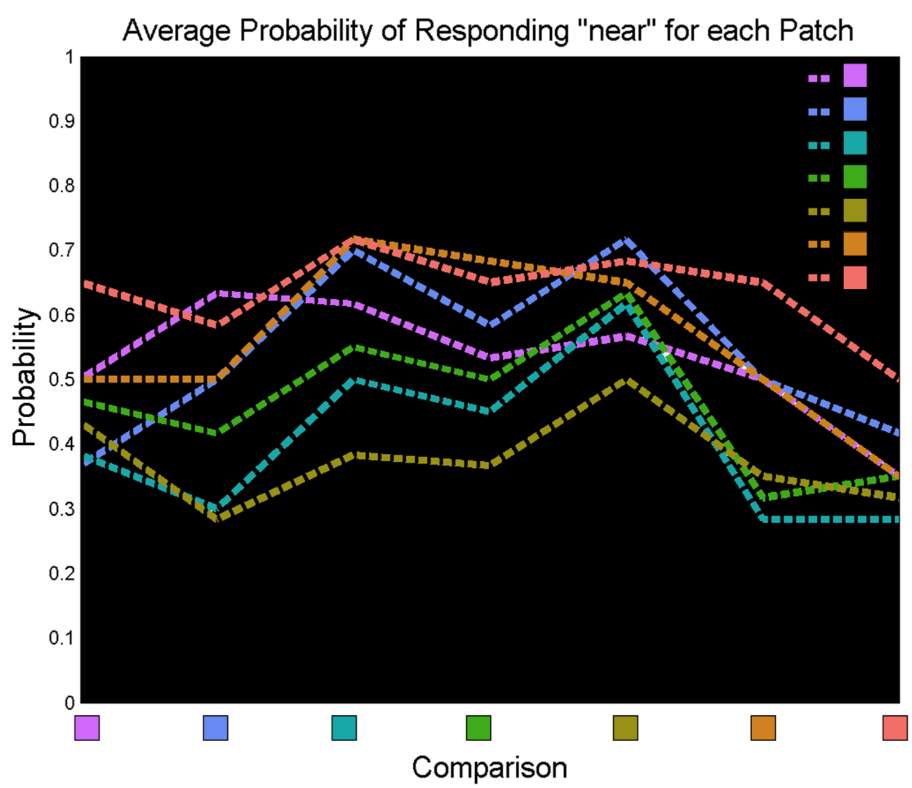

Figure 11:

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