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Depth and Orientation through Surface Transparency

In the research described in this article we have tested the idea that the recovery of depth and orientation of two-dimensional patterns is aided by constraints in the physical world. We presented a variant on a bistable Necker cube. The surfaces of the cube were constructed from transparent planes. We examined which color compositions lead to the highest number of correct identifications of orientation. The results can be explained on the assumption that people use constraints present in additive color mixture. When this type of mixture is used, it leads to significantly better responses. The luminance of the mixed color is the largest contributor. © 1995 John Wiley & Sons, Inc.

Key words: machine vision, chromatic transparency, surface transparency, depth and orientation.

INTRODUCTION

A two-dimensional (2-D) pattern can be the result of an infinite number of three-dimensional (3-D) scenes. The human brain has to solve ambiguities to rebuild the one unique 3-D scene that caused the 2-D pattern; this is called the recovery problem. In modern computer vision one tries to find algorithms between the input image (2-D) and object perception (3-D) by using natural constraints.¹ We investigated whether people make use of the constraints that are present in additive color mixture, and if this use of knowledge has a modular character.

Light that is reflected from physical surfaces forms an array of light intensity values. This two-dimensional image representation has to undergo several different computations to get to a three-dimensional representation of

the world. Marr² saw vision as a process with an information-processing task, a mapping from one representation to another. He stated that a computational theory is an investigative analysis of the nature of a task that, if successful, puts a set of constraints on the problem. Constraints are situated in the real world and applied to the representation to decide what is possible for a scene and what can be occluded. According to Marr any device that has an information-processing task has three levels that one must look at. He called the first level the **computational theory**. One of its important features is that "the resulting operation is defined uniquely by the constraints it has to satisfy" (p. 23). The second level of analysis of a process involves choosing a representation for input and for the output of the process and an **algorithm** to make the transformation between these two. The last level describes how the processes (representation and algorithm) are **physically realized**. An object has different characteristics that can be viewed independently but also belong together (e.g., color and shape). The visual process can be separated in different subprocesses, called modules, for these characteristics. These modules can be investigated independently, like the different characteristics of an object, because there is no influence from other modules. The information that comes from these different modules is joined later to get to object perception.

Marr distinguished three phases between the image and shape information (3-D): the Primal sketch that has information about intensity changes, the 2.5-D sketch that has information about the orientation and rough depth of the visible surfaces, and the 3-D model representation. The first step is that simple computations are performed on the array with intensity values. The difference in intensity values is computed and changes are represented in the Primal sketch. The methods to come

FIG. 1. The two possible orientations of the cube.

from Primal sketch to 2.5-D sketch are called "shape-from" methods;³ these methods (or algorithms) are applied to different modules. There are several "shape-from" methods; each make use of different constraints that the physical world places on objects. There is a "shape from shading" method, where constraints that are known about shading (i.e., constraints about intensity changes due to illumination properties assuming some material properties) are used to recover form. Other "shape-from" methods are motion, texture, stereo, contour, etc.

We investigated if there is something like a "shape from surface color" module; whether humans can compute the basic parts of a mixed color and use the knowledge of constraints that belong to color mixing to get depth perception. An aspect of an object is color; when surfaces are placed over each other there is information about which surface lies in front of the other. This gives depth information and can lead to a unique 3-D structure. Following Marr's ideas, we looked at the constraints that are present in the particular case of chromatic transparency (without looking at the physical implementation), and investigated if people have incorporated knowledge about these constraints.

As an ambiguous 2-D pattern, we chose a variant on the Necker cube, not with white surfaces divided by black lines but with colored surfaces. Other investigations on the Necker cube showed that orientation is biased by coloration.⁴ There are two possible orientations that can be seen in the cube, although not at the same time (see Fig. 1); or, one can see a 2-D, flat patchwork of colored triangles and quadrangles.

In this variant of the Necker cube, the cube is an open box with five colored sides. These colored surfaces are transparent and are placed over each other. Before we discuss the experiment we first consider different views concerning transparency perception.

TRANSPARENCY

When two colored surfaces are placed over one another, such that the surface in the back is seen through the surface in the front and the surface in the front is also seen, transparency can be perceived. The two colors are mixed on the place of overlap. In the classical literature there are two forms of color mixture: additive and subtractive color mixture. Brill⁵ added a new form, partitive mix-

ture, which is a mixture of these two. The question is on which kind of mixture the perception of transparency is based.

In a subtractive mixture, one type of spectral transmission function is multiplied with another. The optic stimulus is altered before it reaches the eye; this kind of mixture can be obtained when paints are put together (e.g., blue and yellow together become green). The exact color depends on the type of filters that are used and on the spectral composition of the light sources. The transparency-perception model that is partly based on this sort of mixture is Beck's Filter model.^{6,7} Beck further states that transparency perception depends on lightness values and lightness relations that determine organizational processes. Lightness is the dimension of sensory experience, going from white through grey to black, and is a psychological dimension. Transparency is determined both by relations in image intensities and by cues given by the figural organization. In Beck's transparency model, the retinal stimulus is the result of the light that is reflected by the object, transmitted by the filter, and partly reflected by the surface of the filter [see Fig. 2(b)]. In this model, the values that transmittance and reflectance can have are restricted by what is possible in the physical world. This leads to formulae that express relations between different surface reflectancies.

In an additive mixture, different bands of wavelengths stimulate the same retinal region simultaneously. This kind of mixture is used in real life, for example, in color television where light outputs of three different sets of phosphors are mixed; such mixtures can p.e. "be perceived through clouds of dust" (Beck et al.,⁸ p. 415). The corresponding transparency model is Metelli's episcotister.^{9,10} In this model, transparency can be perceived when an episcotister (a device with open and closed sectors) is placed in front of another perceptually nonhomogeneous surface and is spun around very fast (see Fig. 3). Transparency varies with the proportion that goes to the opaque layer. Physical restrictions lead to four constraints. The two constraints to be dealt with here are derived from the restriction that the open angle^a can have a value between 0 and 1 only. When a is equal to 1, the transparent disk is seen as completely transparent and, thus, when a is 0, an opaque disk is seen. Violations of

FIG. 2. The Filter model. Figure 2(a) is the physical situation where A and B are the surfaces and F is the filter. There are four areas that differ in reflectance: a , b , c , and d . Figure 2(b) shows the reflectance pattern, where a is the reflectance of surface A , t is the transmittance of filter F , and f is the reflectance of the filter F .

FIG. 3. The episcotister model. Figure 3(a) shows the episcotister when it is not turning round, with an open part with angle a . Figure 3(b) shows the retinal stimulus that is the result when the episcotister is turning in front of the surfaces with different reflectances.

these two constraints lead to an alteration in transparency perception. Metelli¹⁰ distinguishes two forms for transparency perception: one in which the perceptual transparency corresponds to a physical situation, and one in which the latter is not the case. These two forms can occur separately. The perceptual transparency depends on spatial and intensity relations of the light that is reflected by a relatively large field. Metelli¹¹ states that physical realization is not necessary for transparency perception. Transparency perception depends on figural conditions (unification, continuation, and stratification) and chromatic (or intensity) conditions (i.e., the darker the color of the transparent layer, the greater the perceived transparency).

Both models are essentially formulated for achromatic colors. Although the constraints on reflectance differ in terms of solution sets,¹² some constraints of both models are related to one another, because they have a simple interpretation in terms of lightness. Achromatic colors vary only in "lightness," measured in the percentage of reflected light. In the case of achromatic colors, the constraints placed on subtractive mixtures can mathematically be replaced by those of the additive mixtures.

Until 1985, Metelli used reflectance value as a determinant for transparency; after an article by Beck et al.,⁸ he transposed his model to lightness values. This was done because of the criticism from Beck et al. that reflectance values (physical values) could not be seen in a mathematical relation with lightness values; this will be clarified later. Beck et al.⁸ stated that the difference between the two models in terms of their values (physical vs. psychological) makes the episcotister model invalid. This model is expressed in terms of physical reflectance values, and not in terms of lightness values. According to Beck et al., perceived transparency is a function of relative similarity of the lightness of the overlapping surface to the lightness of the underlying region and to the lightness of the overlying region. Transparency is indicated by an alteration in image intensities produced by figural configuration, depth, and motion. In an experiment, they found that transparency perception is based on lightness values and cannot be the result of splitting the luminance of a stimulus (color scission); this happens in the episcotister model (see also Metelli et al.¹³). The system looks at lightness relations if figural cues suggest the

perception of transparency and does not look at reflectances. As mentioned above, Metelli¹¹ adjusted his model for lightness values and stated a relation between lightness and reflectance values.

In a later article Beck⁸ stated again that although order and magnitude constraints are shared, the episcotister model is not ecologically valid. The constraints of the episcotister model that are compatible with the filter model are preferred, because they are relatively more simple, but Beck states that it is unnatural psychologically to look at the sum or product of lightness values (as is done in additive mixture). He states that it seems nonsense to determine the sum or product of a medium grey and a light grey; it is not intuitively interpretable. According to Beck, it is ecologically necessary to code transparency judgments in terms of lightness values, their differences, and relative sizes of lightness differences. Brill¹⁴ compared Metelli's model to a "translucent" sheet. Brill argues that Metelli does not use a transparent sheet "because a transparent sheet can not reflect light, the sheet must seem darker than the background that is immediately behind it—a constraint that does not appear in Metelli's paradigm" (p. 357). Brill showed that Metelli's model can be used by the eye, because most constraints present in the model are scale-invariant. This means that it does not matter if reflectances are multiplied or not. He showed that Metelli's model shares scale-invariant constraints with models of translucency. The visual system can use these scale-invariant rules when it has no access to illuminant intensity.

Da Pos¹⁵ compared the two models for a chromatic setting; the result of his experiment favors additive mixture. His conclusion is that additive mixture is a better predictor for transparency perception; but the additively mixed color he used is not exactly the same mixed color that would be obtained from the episcotister model. First there is the difference between the chromatic colors in Da Pos' experiment and the achromatic colors in Metelli's experiment. Secondly, Da Pos does not take the sum of the luminances but a weighted average. He mentions that chromatic dimensions of a color (saturation, hue) are less important for the impression of transparency than luminance.

The relation between transparency and depth modules was investigated by Nakayama et al.¹⁶ There is a relation between depth and transparency perception; transparency mechanisms influence depth perception. The results showed that a sequential activation of modules, for example, a depth module followed by a transparency module, could not be applied to their data. They suggested that the occurrence of transparency follows Metelli's luminance conditions; the specifics of chromatic signals are mostly ignored by the visual system. There is only limited information necessary to perceive transparency.

In summary we can expect that the contribution of hue and saturation are less important but still have an

TABLE 1. The five conditions of the main experiment.

Hue Luminance		
	Additive	"Subtractive"
Additive	Condition 1 (LaHa)	Condition 3 (LaHs)
"Subtractive"	Condition 2 (LsHa)	Condition 4 (LsHs)
	Condition 5 (Ls ₂ Ha)	

influence in solving a possible transparency situation. The additive mixture is easily solvable for color surfaces, because luminances are added and the coordinates of the mixed color are placed on the line between the two constituent colors. It is relatively easy to determine how the mixed color was composed and how surfaces overlap each other. The subtractive mixture is mathematically more difficult to analyze. In a study by de Weert,¹⁷ the assumption that people have some intuitive notion about additive color mixing is confirmed. We, therefore, expect that when people are offered ambiguous 2-D images where surfaces are (partly) covered by other surfaces, the images where colors, especially luminances, are additively mixed are correctly solved.

We investigated the following question: If we give subjects an ambiguous 2-D pattern, will they use knowledge about additive mixture to find one unique 3-D image? The experiments are based on previous research that is reported by Wagemans and de Weert¹⁸ and by Wagemans.¹⁹ For reasons of readability, the main experiment will be described first.

EXPERIMENT

This experiment was designed to investigate if people incorporate physical constraints of color mixing and if they make use of this "knowledge" for the recovery of a 3-D structure from ambiguous 2-D patterns.

Method

Design

The luminance and hue of the mixed color was determined in two different ways (see Table I). We used a between-subjects design.

Stimuli

We made the distinction between hue and luminance because luminance is known to be more important than hue. The additive mixture is the position of the mixture in the chromaticity diagram; in the "hue additive" (Ha) method this corresponds to the position that would be attained with additive color mixture. The formulas are:

$$x_m = (L_1x_1y_2 + L_2x_2y_1)/(L_1y_2 + L_2y_1) \quad (1)$$

$$y_m = y_1y_2/(L_1 + L_2)/(L_1y_2 + L_2y_1). \quad (2)$$

Given the position in the chromaticity diagram, the total luminance can be varied independently. The coordinates of the subtractive mixture were determined by placing a line perpendicular to the coordinates of the additive mixture. The new color was subjectively determined with the criterion that this color had to be different from the original additively mixed color and was found by varying across the perpendicular line (see Fig. 4). The values of the luminances were chosen to be lower than the lowest value of the two colors that were mixed, but never so low that the mixture had zero-luminance. We made this choice because the hue of a subtractive mixture depends on the type of filters used; the coordinates of the mixture vary accordingly, and this is the same for luminances. With subtractive mixtures, luminances can be lower than the lowest value of the mixed colors.

In conditions 2 (LsHa) and 4 (LsHs), we chose the luminance value of the subtractive mixture lower than the lowest luminance value of the two constituent colors. When we look at Beck's filter model and the reflectance values, one can see that the luminance value is not necessarily lower than the lowest value. In a subtractive mixture, a beam of light is reduced by a filter; the size of the reduction is determined by the type of filter. The only condition is that it is lower than the sum of the luminances of the constituent colors. In condition 5 we determined the luminance value of the "subtractive" mixture as the mean of the luminances of the two constituent colors. For the hue coordinates of the mixture, the same coordinates as in an additive mixture were chosen. This was done because condition 2 showed no significant difference in performance between mixtures when the coordinates of the hue were determined by the rules of additive mixing and when the coordinates were determined as subtractive mixture. This condition is notated as Ls₂Ha.

A stimulus trial consisted of two briefly presented colored displays. The first display was presented for 1500 ms and consisted of two squares beside each other. The

FIG. 4. The way the hue of a subtractive mixture was determined. The hue of the additive mixture (M) of the two colors (C1 and C2) was determined and we chose a point on the perpendicular line 1.

FIG. 5. The different colors in the cube. Figure 5(b) is the second display. Figure 5(c) shows the way the colors were mixed.

square on the right side was filled with color 2 (see Fig. 5) and the square on the left side contained either color number I (because this color was not present in pure form in the cube with orientation 1) or number 3, when the cube was presented in orientation 2 for the same reason [see Fig. 5(c)]. So, color II was shown with the color that it was mixed with in the colored cube. The second display, the colored cube, was presented for 1500 ms with an ISI of 500 ms. It subtended a visual angle of 3.2° horizontal and 3.0° vertical.

The color set from which colors were chosen consisted of seven basic colors (for value specifics see Table II) and twelve possible mixtures (for value specifics of the different conditions see Tables III–VII). Only mixtures of neighboring colors were used (e.g., yellow-red, red-violet, violet-white, etc.). Colors whose coordinates were far apart in the CIE-diagram (e.g., red-green, green-blue, blue-yellow, etc.) were not used; this was done because mixtures were determined by the laws of additive color mixing (i.e., luminances were added and CIE-coordinates located on a straight line connecting the coordinates of the two constituent basic colors). When two colors are too far apart, it might be less easy for an observer to determine the particular basic colors from which the mixture is composed. The luminance values of the basic colors varied between 5 and 20 cd/m²; these were chosen to avoid isoluminous borders, which are known to lead to reduced form and depth perception.²⁰ The background had zero-luminance. The following basic colors were combined:

- 1) white-red-yellow;
- 2) white-red-violet;
- 3) white-green-yellow;
- 4) white-green-cyan;
- 5) white-blue-violet;
- 6) white-blue-cyan.

Each combination in itself is six combinations, e.g., white-red-yellow; white-yellow-red; red-white-yellow, etc. for color numbers I, II, and III, respectively. This gives 36 combinations that can have either orientation 1 or 2. Combining the basic colors with one another in this way led to 72 trials. There were 18 stimuli that occurred twice in the experiment; this led to a total of 90 stimuli.

Subjects

There were 15 subjects for each condition.* They were psychology and cognitive science students who voluntarily participated. All subjects were naive with respect to the goals of the experiment and its theoretical background. They all had normal or corrected-to-normal eyesight.

Apparatus and Material

S. Ishihara's "tests for colourblindness" (1964) was used to make sure that subjects were not color-blind. A color-television monitor, type BARCO CVS, with separate red (R), green (G), and blue (B) inputs was used for presentation of the colored patterns. A PDP 11/23 generated these patterns; 256 colors can be presented simultaneously, and each of the R, G, and B guns can have 1024 values. The luminance values of the three primaries, measured with a Spectra Pritchard Photometer, are stored in a database. These values can be used to generate any of the 1024*1024*1024 possible positions in the color space. The x , y primaries were factory given.

* There were more subjects for each condition because we wanted to have the data of 15 different subjects for each condition. Because some subjects were unable to see anything else than orientation 2, there were 17 subjects for condition 1, 16 for condition 2, 17 for condition 3, and 16 for condition 4.

TABLE II. The seven basic stimuli colors.

Color number and name	CIE- coordinates		Lum. cd/m ²	Luminance per channel		
	x	y		Lr	Lg	Lb
1 White	0.333	0.333	12	3.00	8.15	0.85
2 Red	0.592	0.339	10	8.81	1.09	0.10
3 Green	0.298	0.533	20	0.08	19.71	0.21
4 Blue	0.161	0.072	5	0.46	0.13	4.41
5 Yellow	0.465	0.427	15	5.95	8.91	0.14
6 Violet	0.425	0.243	16	12.09	2.21	1.70
7 Cyan	0.273	0.388	15	0.72	13.41	0.87

TABLE III. The stimuli with additive hue and luminance.

Color number and name	CIE-coordinates		Lum. cd/m ²	Luminance per channel		
	x	y		Lr	Lg	Lb
8 White-red (1-2)	0.450	0.336	22	11.81	9.24	0.95
9 White-green (1-3)	0.315	0.435	32	3.08	27.86	1.06
10 White-blue (1-4)	0.220	0.161	17	3.46	8.28	5.26
11 White-yellow (1-5)	0.398	0.379	27	8.95	17.06	0.99
12 White-violet (1-6)	0.392	0.275	28	15.09	10.36	2.55
13 White-cyan (1-7)	0.302	0.361	27	3.72	21.56	1.72
14 Red-yellow (2-5)	0.522	0.387	25	14.76	10.00	0.24
15 Red-violet (2-6)	0.477	0.273	26	20.90	3.30	1.80
16 Green-yellow (3-5)	0.379	0.482	35	6.03	28.62	0.35
17 Green-cyan (3-7)	0.285	0.459	35	0.80	33.12	1.08
18 Blue-violet (4-6)	0.289	0.155	21	12.55	2.34	6.11
19 Blue-cyan (4-7)	0.201	0.185	20	1.18	13.54	5.28

Procedure

After subjects were tested for color blindness, they got written instructions that showed the two orientations of the cube; the text explained that subjects had to push a button, corresponding to the orientation they had seen, as fast as they could after the image had disappeared from the screen. Subjects were told that they could control the speed of the experiment by pressing a third button for getting the next trial. Then the room was completely darkened and subjects were given two practice sessions, one with 12 nontransparent cubes and one with 12 trials (for stimuli specification, see Appendix A); the latter randomly selected from the 72 possible stimuli. Both sessions had six stimuli with orientation 1 and orientation 2. The first practice session was done in order to see if subjects remembered the buttons corresponding with the two orientations. The second practice session was done to avoid that subjects who saw only one orientation or a patchwork of colors would have to perform the entire experiment of 90 trials. Subsequently, the experimenter asked if the subject had any questions. Subjects were told to imagine that the two squares preceding

the cube were transparent and were placed over one another in the following cube. They were also told that the color of the square on the right was identical with the back side of the cube, and that the color of the left square was not present in pure form in our cube. Subjects were then given the experiment with 90 trials.

Subjects who were not able to see both orientations in the second practice session were excluded from the experimental session. Responses of the subjects were directly registered by computer and stored in a database.

Results and Conclusion

Table VIII presents the results of this experiment. As one can see, there is a significant difference from chance for the conditions LaHa and LaHs. There was no significant difference between these two conditions; $t = 1.21$ and $p < 0.10$. This means that luminance is the greatest contributing factor in determining the orientation. When the hues are additively mixed, this leads to a better performance although this improvement in performance is not significant.

TABLE IV. The stimuli with additive hue and "subtractive" luminance (LsHa).

Color number and name	CIE-coordinates		Lum. cd/m ²	Luminance per channel		
	x	y		Lr	Lg	Lb
8 White-red (1-2)	0.450	0.336	8	4.30	3.36	0.34
9 White-green (1-3)	0.315	0.435	9	0.86	7.84	0.30
10 White-blue (1-4)	0.220	0.161	4	0.82	1.94	1.24
11 White-yellow (1-5)	0.398	0.379	10	3.32	6.31	0.37
12 White-violet (1-6)	0.392	0.275	9	4.84	3.34	0.82
13 White-cyan (1-7)	0.302	0.361	10	1.38	7.98	0.64
14 Red-yellow (2-5)	0.522	0.387	5	2.94	2.01	0.05
15 Red-violet (2-6)	0.477	0.273	6	4.82	0.77	0.41
16 Green-yellow (3-5)	0.379	0.482	10	1.73	8.17	0.10
17 Green-cyan (3-7)	0.285	0.459	10	0.22	9.47	0.31
18 Blue-violet (4-6)	0.289	0.155	4	2.38	0.45	1.17
19 Blue-cyan (4-7)	0.201	0.185	4	0.23	2.72	1.05

TABLE V. Stimuli with "subtractive" hue and additive luminance.

Color number and name	CIE-coordinates		Lum. cd/m ²	Luminance per channel		
	x	y		Lr	Lg	Lb
8 White-red (1-2)	0.451	0.293	22	14.45	6.14	1.41
9 White-green (1-3)	0.400	0.450	32	7.76	23.78	0.46
10 White-blue (1-4)	0.190	0.181	17	0.25	12.04	4.71
11 White-yellow (1-5)	0.429	0.379	27	13.16	12.55	1.29
12 White-violet (1-6)	0.287	0.168	28	14.56	6.10	7.34
13 White-cyan (1-7)	0.224	0.276	27	0.64	22.66	3.70
14 Red-yellow (2-5)	0.421	0.241	25	18.75	3.52	2.73
15 Red-violet (2-6)	0.442	0.334	26	13.57	11.25	1.18
16 Green-yellow (3-5)	0.312	0.376	35	5.07	28.00	1.93
17 Green-cyan (3-7)	0.347	0.448	35	5.09	29.07	0.84
18 Blue-violet (4-6)	0.264	0.194	21	6.64	9.69	4.67
19 Blue-cyan (4-7)	0.251	0.167	20	6.88	7.50	5.62

We determined the number of inconsistencies on the 18 trials that occurred twice in the experiment session. As mentioned in the introduction, it is very unlikely that people use knowledge about the constraints perfectly. The use of constraints will never be 100%²¹ and previous research^{18,19} shows that the percentage of correct scores lies at around 70%. If we assume that a good use of the constraints would lead to 70% correct answers, the number of inconsistencies is not significant. When the subjects are not lucky guessers, the correlation between scores (percentage of correct answers) and number of inconsistencies will be negative; a high percentage of correct answers is given with a great security (low number of inconsistencies).

The correlation (r) is zero for condition LsHa. This means that although some subjects may have high scores, this is based on guessing; otherwise, people would have scored few inconsistencies. The correlation of conditions LaHa and LaHs can be explained accordingly. Surprisingly, the correlation for condition LsHs is also negative; this would mean that the higher the scores the lower the inconsistencies (guessing). But when you look at the high number of inconsistencies (and low devia-

tion) and the low mean, the importance of the correlation is not very high. The number of inconsistencies is relatively high for condition Ls₂Ha, but the certainty of responses ($r = -0.70$) is higher than in the other conditions. This seems to indicate that the mixture of colors is easier to solve for the subjects because they seem to be more certain of their choice. The number of inconsistencies decreases when the percentage of correct scores increases.

The question is if there is a significant difference between these conditions. An ANOVA was computed to see if there were any significant differences between the five conditions. Because this was indeed the case, we used the Tukey method to determine where these differences occurred (see Table IX). In this table one can see that there is a significant difference between conditions LaHa and LsHs, conditions LaHa and LsHa, and conditions LaHa and Ls₂Ha. Condition LaHa has the highest mean, and, although this mean is not significantly higher than the mean of condition LaHs, this does indicate that people have more knowledge about the constraints concerning the additive mixtures for the present set of stimuli. Luminance seems to be the factor with the greatest in-

TABLE VI. Stimuli with "subtractive" hue and luminance.

Color number and name	CIE-coordinates		Lum. cd/m ²	Luminance per channel		
	x	y		Lr	Lg	Lb
8 White-red (1-2)	0.451	0.293	8	5.26	2.23	0.51
9 White-green (1-3)	0.400	0.450	9	2.18	6.69	0.13
10 White-blue (1-4)	0.190	0.181	4	0.06	2.83	1.11
11 White-yellow (1-5)	0.429	0.379	10	4.87	4.65	0.48
12 White-violet (1-6)	0.287	0.168	9	4.68	1.96	2.36
13 White-cyan (1-7)	0.224	0.276	10	0.24	8.39	1.37
14 Red-yellow (2-5)	0.421	0.241	5	3.75	0.70	0.55
15 Red-violet (2-6)	0.442	0.334	6	3.13	2.60	0.27
16 Green-yellow (3-5)	0.312	0.376	10	1.45	8.00	0.55
17 Green-cyan (3-7)	0.347	0.448	10	1.45	8.31	0.24
18 Blue-violet (4-6)	0.264	0.194	4	1.27	1.84	0.89
19 Blue-cyan (4-7)	0.251	0.167	4	1.38	1.50	1.12

TABLE VII. Stimuli with "subtractive" luminance and additive hue (Ls₂Ha).

Color number and name	CIE-coordinates		Lum. cd/m ²	Luminance per channel		
	x	y		Lr	Lg	Lb
8 White-red (1-2)	0.450	0.336	11	5.91	4.62	0.47
9 White-green (1-3)	0.315	0.435	16	1.54	13.93	0.53
10 White-blue (1-4)	0.220	0.161	8	1.64	3.88	2.48
11 White-yellow (1-5)	0.398	0.379	13	4.31	8.21	0.48
12 White-violet (1-6)	0.392	0.275	14	7.52	5.21	1.27
13 White-cyan (1-7)	0.302	0.361	13	1.80	10.37	0.83
14 Red-yellow (2-5)	0.522	0.387	12	7.06	4.83	0.11
15 Red-violet (2-6)	0.447	0.273	13	10.45	1.66	0.89
16 Green-yellow (3-5)	0.379	0.482	17	2.93	13.90	0.17
17 Green-cyan (3-7)	0.285	0.459	17	0.38	16.09	0.53
18 Blue-violet (4-6)	0.289	0.155	10	5.96	1.12	2.92
19 Blue-cyan (4-7)	0.201	0.185	10	0.59	6.77	2.64

fluence, as can also be seen in condition LaHs, which differs significantly from chance.

For all the conditions, the responses were given very fast and did not show any sudden decrease in errors that would indicate that subjects had learned something.

Based on the results it can be stated that luminance is the most important factor in determining depth and orientation for the present set of stimuli. When the mixed color follows the rules of additive color mixing, resulting in the highest luminance value, this leads to the highest number of correct responses. Although the hue of the mixture can be changed without significantly altered result, the consistency of the response decreases.

Before we performed the main experiment, we wanted to make sure that there were no other factors involved that could influence the results when we used our variant of the Necker cube. First there is the possibility that people will choose an orientation by looking at the luminance contrast in the corners. It is known that an object with a greater luminance contrast, with respect to the background, than another object is perceived as the nearer.²² Schwartz and Sperling²³ propose that proximity-luminance covariance (PLC, i.e., line-intensity covaries with position in depth) is a powerful cue for disambiguating depth. In our investigation all this would mean that if the luminance contrast in corner EFB is greater than in corner HDC, a subject is likely to choose orientation 2 and vice versa (see Fig. 6).

Secondly, there exists a possibility that a greater familiarity with orientation 2 can influence the outcome of the experiment. Research done by Girgus, Rock, and Egatz²⁴ showed that half of the people who did not know there were two possible orientations of the Necker cube did not report any alterations in what they saw. Girgus et al. acknowledged the possibility that subjects saw two orientations but did not report this. This was possible because subjects had to tell what they saw and the cube stays a box no matter what orientation. The absence of seeing multiple possibilities has also been reported for other ambiguous figures. We wanted to make sure that

the familiarity with orientation 2 would not lead toward a bias for this orientation.

Two control experiments were designed, one for each possible factor that is mentioned above.

CONTROL EXPERIMENT 1

This experiment was designed to investigate whether subjects use the difference between luminance contrast in the corners of our cube to decide which orientation is "right."

Method

Subjects

There were 21 subjects, all cognitive science students at the university of Nijmegen who voluntarily participated. All subjects were naive with respect to the goals of the experiment and its theoretical background. They all had normal or corrected-to-normal eyesight.

TABLE VIII. The data of the experiment. *M*: percentage of correct answers; *t*: test statistic; *p*: probability values; inconsistencies: number of different answers to equal stimuli; *r*: correlation between *M* and inconsistencies.

	Conditions				
	LaHa	LsHa	LaHs	LsHs	Ls ₂ Ha
<i>M</i>	73.41	57.04	66.73	56.52	58.74
<i>t</i>	7.43	1.67	3.80	2.25	2.83
<i>p</i>	0.001	0.10	0.005	0.025	0.005
Inconsistencies	4.53	6.27	6.67	7.47	6.53
<i>r</i>	-0.57	0.00	-0.56	-0.65	-0.70

TABLE IX. Calculation of Q using the Tukey Method with $\alpha = 0.05$. The asterisk (*) indicates where there is a significant difference.

	LsHs	LsHa	Ls ₂ Ha	LaHs
Condition 4	56.52			($\bar{X}_i - \bar{X}_k$)
Condition 2	57.04	0.52		
Condition 5	58.74	2.22	1.70	
Condition 3	66.73	10.21	9.69	7.99
Condition 1	73.41	16.89	16.37	14.67
				6.68
Condition LsHs				Qcv
Condition LsHa	0.14			
Condition Ls ₂ Ha	0.62	0.47		
Condition LaHs	2.83	2.69	2.22	
Condition LaHa	4.68*	4.54*	4.07*	1.85

Apparatus and Material

See main experiment.

Stimuli

A stimulus trial consisted of two shortly presented colored displays. The first display was shown on the left side of the screen for 1000 ms and contained three rectangles that were placed below one another. Each rectangle contained one of the three original colors that constituted the cube [see Fig. 5(a)]; the order of the colors in the rectangles was the same for every stimulus; I, II, and III below each other. The size of a rectangle was 11.7 cm by 2.9 cm, corresponding to a visual angle of 4.2° horizontal and 1° vertical. The second display was the same transparent colored cube as in the main experiment, presented for 1500 ms with an ISI of 500 ms.

Of the 72 possible trials, only ten of them had such a luminance contrast in the corners that this would lead to a false answer, e.g., the luminance contrast in corner EFB was higher than that in corner HDC (see Fig. 6) while the programmed orientation belonging to that trial was orientation 1. We computed the difference in luminance contrast between the two corners and found ten matching stimuli with approximately the same difference but with a luminance contrast that would lead to the right answer (predicting contrast). This gave us 20 trials, 10 with orientation 1 and 10 with orientation 2; both orientations were equally present in the subgroups.

Procedure

See main experiment. Instead of the two squares there were three rectangles, so it was explained that the three rectangles were the colors of the cube when this was taken apart. There was only one practice session with 12 stimuli, the same as the second practice session in the main experiment (see Appendix A).

Results and Conclusions

Of the 21 subjects, 3 were unable to see orientation 1; therefore, we used the data of 18 subjects. As already suspected, the number of correct answers when there was predicting contrast ($M = 5.28$ correct answers) was not significantly higher than when the luminance in the corners was not predicting ($M = 5.22$ correct answers), $t(17) = 0.105$, $p < .10$. Also there is evidence from Egusa,²⁵ who found that, when dealing with only chromatic colors, it is not the luminance contrast that puts something in the foreground but the specifics of a color (decreasing frequencies) that determine whether a color is seen in front of another color or not. We used only neighboring colors, so this did not occur in our research. Now it was possible to determine whether orientation is of influence.

CONTROL EXPERIMENT 2

This experiment was designed to investigate whether our assumption that subjects were more familiar with orientation 2 than with orientation 1 would lead to significantly more responses with orientation 2.

Method

Subjects

There were 10 subjects who were from the same student population as the experiment above.

Apparatus and Material

See main experiment.

Stimuli

The set was enlarged to 48 trials that were chosen from the 72 possible. Of these 48 trials, we took 12 trials that were used twice in the experiment trial to check if the answers to stimuli were consistent or chosen by chance (for the stimuli specifications, see Appendix B); giving a total of 60 trials. These repeated trials can be an indication of how sure people are of an orientation. We took the same 12 trials for practice session as in the main experiment (see Appendix A). There were 32 stimuli with orientation 2 and 28 stimuli with orientation 1.

FIG. 6. The corners EFB and HDC where the luminance contrast is computed.

Procedure

Nothing was changed.

Results and Conclusions

None of the 10 subjects had any difficulty with seeing two orientations. There was no sign of any preference for a specific orientation; ($M = 30$ correct answers), $t = 0.98$ and $p < 0.10$, in their responses. The hypothesis that there is no response bias toward one of the two orientations is not rejected.

We determined the number of inconsistencies on the 12 trials that occurred twice in the experiment session; this number was rather large ($M = 4.9$). But as mentioned earlier, it is very unlikely that people use knowledge about the constraints perfectly. If we assume that a good use of the constraints would lead to 70% correct answers, the number of inconsistencies is not significant. When the subjects are sure of their response, the correlation between scores (percentage of correct answers) and number of inconsistencies will be negative; a high percentage of correct answers is given with a great security (low number of inconsistencies). This was indeed the case, $r = -0.38$.

Because three subjects were unable to see anything except orientation 2 in control experiment 1, and because one subject forgot which button corresponded with which orientation, we decided to give subjects an extra practice session with 12 nontransparent cubes (six with orientation 1 and six with orientation 2) in the main experiment to check if they remembered which button corresponded with which orientation.

Although neither of the control experiments showed any sudden improvement of percentage of correct answers in the second half of the session, we wanted to make certain that the subjects could not get any geometrical cues from the colors preceding the cube. This was possible with the three rectangles; because the mixed color would be either in the upper or the lower half of the cube. Subjects only had to look at the upper (or lower) rectangle and check if this color was also in the cube to decide which orientation was correct. If they looked at the upper rectangle and this color was not in the Necker cube (or not the same as the color at the top of the cube) they would choose orientation 2.

There were colors given in advance (pure color cues) because one color (number I or III, depending on the orientation) was not present in pure form, but only mixed with color number II [see Fig. 5(c)]. When subjects determined the orientation by using the original basic colors, it was easier to solve than when all the basic colors of the cube were not known.

GENERAL DISCUSSION

The results show that, for the present set of stimuli, people use the constraints that are present in additive color

mixture; conditions LaHa and LaHs differ significantly from chance. As expected, luminance is the most important factor in this mixture, but hue is also important. This can be seen in the lower number of inconsistencies and the higher percentage of correct answers for condition LaHa. Condition Ls₂Ha has a relatively low percentage of correct answers. Based on this condition and on condition LsHa, one can suspect a strong negative influence of "subtractive" luminance. Now we can answer our question; do people make use of the constraints that are imposed by the rules of additive color mixture. Based on the results of conditions LaHa and LaHs, there seems to be some use of the rules; but the limited number of subjects per condition and the relatively large variation of scores within each condition make strong statements not yet possible.

Can we conclude that there is a "shape-from-color" module? Our data show that subjects performed significantly better when these additively mixed colors are used. What needs to be investigated is if our conclusions are also true when the colors that are mixed are further apart. We already explained the difficulties that could arise for people when this takes place. There will probably also be poorer performance around the white point. Up to this point, we can only conclude that people have knowledge of the constraints that are present in additive color mixture with the stimuli that are used in these experiments; if there is a "shape-from-color" module, this needs to be investigated. One could think of a "visual search" task as described by Treisman,²⁶ to see if there's a "pop-out" effect; in this way, one can determine how basic (pre-attentive) the underlying mechanism is.

If the constraints that are present in additive color mixture are part of an algorithm that the human information processing system uses to get useful representations, then the constraints must also be used in organism-environment interaction. The human information processing system has been shaped over the course of phylogenesis. The question then is whether subtractive or additive mixture is used in real life. As we mentioned earlier, according to Beck,¹⁰ additive color mixing is not ecologically valid. The reasons he gives for this point seem to be based on hardware arguments. He states that Metelli's episcotister model is not valid because it requires multiplication and addition. This would be in conflict with the way the visual system codes information. In Marr's theory, looking at the neurological basis is the final step and can be done only after an adequate representation and algorithm are found. But there are also problems that occur when the mixture is subtractive. There is the problem that the appearance of the subtractively mixed color depends on the type of filters that are used and on the spectral composition of the light sources; so, when two colors are mixed under different lighting circumstances, the mixed color can look changed. And there is a problem that lies in the stimulus. How can humans "solve" the information in a subtractive mixture (for additive mixture, see Table III)? How can one know

the spectral composition of the source or the object? And why do people perform as well as they do (73.41%) when presented with an additive mixture? However, the visual system is capable of seeing transparency when this is physically not possible. The visual system is especially robust against violations of color transparency. This implies that transparency perception is not totally ecological valid.¹⁶ They do have knowledge about the constraints that are present in additive color mixture, and it seems unlikely that this was the first time they used this knowledge.

The fact that people have "knowledge" of the constraints that are present in additive color mixing (and the importance of adding luminances) can be used in designing interfaces. There can be different layers of information that are partly covered by one another. Mixing the ($a-$) chromatic colors in an additive way would lead to better recognition. This same application was described by de Weert,²⁷ who also concluded that additive color mixture is recognized by humans and leads to a good performance.

APPENDIX A

TABLE A-I. The stimuli for the practice session with transparent cubes; the numbers are the color codes that correspond to the numbers in Tables III, IV, V, VI, and VII.

I	II	III	IV	V	VI	Orientation
1	2	6	8	12	6	2
1	3	7	1	13	17	1
1	7	4	13	10	4	2
2	1	5	2	14	11	1
2	5	1	14	8	1	2
2	6	1	2	8	12	1
3	1	7	9	17	7	2
3	5	1	3	9	11	1
3	7	1	17	9	1	2
4	1	7	4	19	13	1
4	1	7	10	19	7	2
4	6	1	4	10	12	1

TABLE A-II. The stimuli for the practice session with nontransparent cubes.

I	II	III	IV	V	VI	Orientation
1	2	3	1	1	3	2
1	2	6	1	6	6	1
1	3	7	1	7	7	1
2	5	1	2	1	1	1
2	6	1	2	1	1	1
3	7	5	3	3	5	2
4	1	7	4	7	7	1
5	2	1	5	1	1	1
5	2	1	5	5	1	2
5	3	1	5	5	1	2
6	4	1	6	6	4	2
7	1	4	7	7	4	2

APPENDIX B

TABLE B-I. The stimuli for the second control experiment; the numbers are the color codes that correspond to the numbers in Tables III, IV, V, VI, and VII. Asterisks (*) indicate stimuli that are repeated.

I	II	III	IV	V	VI	Orientation
1	2	5	1	11	14	1*
1	2	5	8	11	5	2
1	2	6	1	12	15	1
1	2	6	8	12	6	2
1	3	5	1	11	16	1
1	3	5	9	11	5	2
1	4	6	1	12	18	1
1	4	6	10	12	6	2*
1	5	3	1	9	16	1
1	5	3	11	9	3	2
1	6	4	1	10	18	1*
1	6	4	12	10	4	2*
1	7	3	1	9	17	1
1	7	3	13	9	3	2*
1	7	4	1	10	19	1
1	7	4	13	10	4	2
2	1	5	2	14	11	1
2	1	5	8	14	5	2
2	1	6	2	15	12	1*
2	1	6	8	15	6	2
3	1	5	3	16	11	1*
3	1	5	9	16	5	2
3	7	1	3	9	13	1*
3	7	1	17	9	1	2
4	1	6	4	18	12	1
4	1	6	10	18	6	2
4	1	7	4	19	13	1
4	1	7	10	19	7	2
4	6	1	4	10	12	1*
4	6	1	18	10	1	2
4	7	1	4	10	13	1
4	7	1	18	10	1	2
5	1	3	5	16	9	1
5	1	3	11	16	3	2*
5	3	1	5	11	9	1
5	3	1	14	11	1	2
6	1	2	6	15	8	1*
6	1	2	12	15	2	2
6	1	4	6	18	10	1
6	1	4	12	18	4	2
6	2	1	6	12	18	1*
6	2	1	15	12	1	2
6	4	1	6	12	10	1
6	4	1	18	12	1	2
7	1	4	7	19	10	1
7	1	4	13	19	4	2
7	3	1	7	13	9	1
7	3	1	17	13	1	2

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