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STRENGTH EVALUATION OF FILLING-IN COLOR ILLUSION

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The strength of chromatic after-effect was studied using the filling-in after-effect image illusion (Van Lier *et al.*). In our experiments, two stimuli, each consisting of round and sharp-edged overlapping chromatic shapes, were presented to the subjects for 1.2 s on both sides of the fixation point. After that the empty shapes of the stimuli appeared for 0.6 s, and in the next 0.6 s changed the orientation on both sides of the fixation point thus changing the after-effect color from side to side. The subjects made judgments about the strength of the perceived after-effect on a ten-grade scale for different color pairs. The color of one stimulus was kept constant, while the color of the other was changed; as a result of color changes of both stimuli 192 color pairs in total were formed. Some of them were found to arouse a powerful sensation of the after-effect with a color not directly arranged on the opposite axis of chromaticity diagram. Blue and yellow colors were valued as creating the most pronounced after-effect.

1. INTRODUCTION

The light in the retina is absorbed by long-, medium-, and short-wavelength–sensitive (L, M, S) cone receptors. These physical and physiological aspects led to the trichromatic theory of color perception (Helmholtz). The results of the theory provide evidence that any color sensation in additive sense can be produced with a mixture of three basic colors: red, green and blue. However, after the retinal transformation of light into an electric pulse the signal is transformed in the post-receptoral pathways into three opponent-type channels, processing luminance, red-green, and blue-yellow information separately (E. Hering, see in [1, 2]). Jameson & Hurvich [3] later developed Hering`s theory, and in the late 1960s physiological recordings from a primate lateral geniculate nucleus (LGN) emerged to support this opponent model of color processing [4].

'Unique hues' were first mentioned by E. Hering (1964) and relate to the basic perceptual colors known as blue, green, yellow and red – main colors that have been studied in the psychological and adjustment research [5]. However, until these days the unique hues have remained the mystery, because there is no cortical mechanism explaining transformation of the opponent signal to the perceptual hues. Neurons tuned to directions other than the cone-opponent axes have been found in striate (V1) and extra-striate (V2, V4) visual cortex [6, 7].

It has long been observed that after an observer fixates on the colored patch for a long period, he sees an illusory complementary color [8]. Several biological principles have been distilled from the careful study of illusions, and these will continue to guide the neuroscience research. Many illusions remain unresolved, providing ground for the next generation of experimenters and techniques [4, 5, 8].

Receptive field concept is the basic theoretical issue from the times of Hubel and Wiesel [9, 10]. It has been shown that different parts of the visual cortex resemble particular receptive field properties [11, 12]. Receptive fields become more complex with the distance of visual pathways leading to the hierarchical organization of the visual cortex. Color signals are processed through LGN to V1 and then to area V4, which is said to be the main (and most studied in this regard) color centre of the visual system [8, 11, 12].

We suppose that complementary colors identified in the adjustment experiments should lay close to the perceptual 'unique hue' directions, similar as in the case of hue scaling study [13]. In relation to our proposed experimental method, the color pairs of the 'unique hues' would produce the most pronounced color sensation.

2. EXPERIMENTAL

The filling-in illusion proposed by Van Lier *et al* [14] is used to produce the sensation of after-effect. The experimental approach is based on the judgment of the subjects about the strength of the perceived color after-effect between two chromatic pairs.

The colors of the stimuli were chosen based on the spectral irradiation of a computer display. To provide similar distances between the colors and differences in saturation, appropriate color space for stimuli color generation should be chosen. First, the test colors were chosen in the CIE L*a*b* color space, with L value being equal to 60 units, and *a, b* values forming a circular shape with radius of 40 units. The lightness values chosen corresponded to luminance of 35 cd/m^2 (measured by a Konica Minolta CS 100A colorimeter). We chose a set of fifteen colors for our stimulus, which changed only in hue, keeping the brightness, saturation and color differences constant. A look-up table technique [15] was used to obtain the digital values of the used colors. Figure 1 shows the coordinates of our stimuli in the CIE *x,y* chromaticity diagram, with the number near the color spots indicating the coding of the sample.

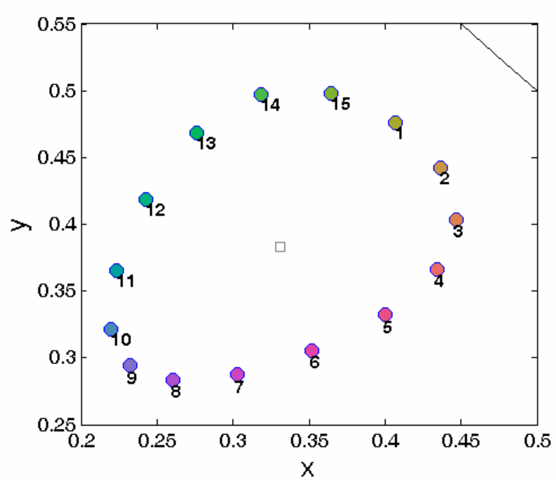

Fig. 1. Stimulus coordinates in CIE *x,y* chromaticity diagram (truncated to the data).

A stimulus consists of two overlapping color shapes opposed to each other in 45 degrees (Fig. 2). Colors of the shapes overlap in additive way. Shapes are arranged on both sides of the fixation cross in 2.5 degrees of visual angle. The colors of all overlappping stimuli can be adjusted with the keyboard buttons. Both stimuli are presented for 1200 ms, after which black contours of the stimuli appear for 600ms, and, in the next 600 ms change their orientation by 45 degrees. As we have to change the colored figures in our stimuli, two variables representing the color of each figure were introduced. We will call these variables X1 (for zero-rotated stimuli) and X2 (for diagonally rotated stimuli).

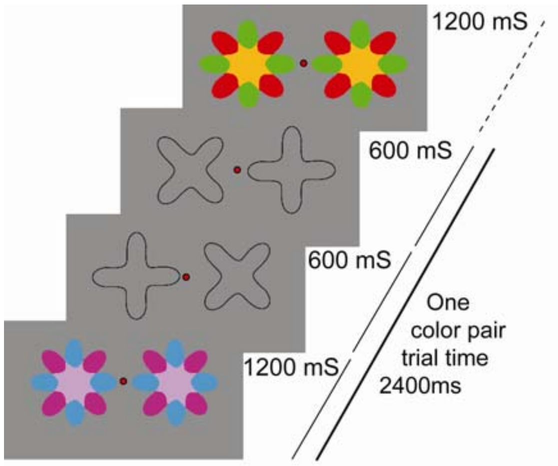

Fig. 2. Sequence setup of experimental stimuli. Colored shapes are presented for 1200 ms and replaced with empty shapes changing the directions by 45 degrees after 600 ms. This direction change produces switching of the after-effect from side to side. On the right, two types of stimuli with the same color pairs are shown.

The subjects were instructed to make judgment of the chromatic pair depending on the perceived strength of the after-effect. Before measurements, each of the participants spent some time manipulating with the stimuli to understand the purpose of the experiment and the after-effect evaluation procedure. The strength of a color pair was evaluated on the ten-grade scale by pressing button, from 1 to 0, (0 corresponds to 10 points). The lowest marks belong to the stimuli of the same colors. Four subjects (two males and two females, age from 27 to 30) with normal color vision participated in the study. Two of the participants are the authors of the research and two naïve subjects. Each of them underwent the experiment five times.

3. RESULTS

Average responses of all subjects were calculated for each pair of the stimuli. The responses could be represented in 15x15 cells matrix with the *x*-axis showing first stimulus colors (X1) and *y*-axis representing second stimulus colors (X2). Such a response surface has a diagonally oriented valley of the lowest marks, as the similarly colored shapes give a relatively low magnitude after-effect. For this reason another surface was introduced, which, in our opinion, shows the data in a more appropriate way (Fig.3). The abscissa axis in Fig. 3 shows X1 (first stimulus color), and the ordinate axis shows the sequence of the other fifteen stimuli from X1, where *i* changes from 0 to 14. In such a way the horizontal line at the eighth position represents the truly opponent position and the shifts from this point are to be analyzed. The lightness of the squares represents the strength judgment of the perceived after-effect.

The most powerful responses have been obtained for the 1^{st} color (yellow) paired with the 11^{th} from it (cyanic blue), and for the 10^{th} color (blue) paired with the 12^{th} from it (pink), which is the 6^{th}. Two diagonally oriented peaks were identified through the surface in Fig. 3. This indicates that a powerful after-effect is formed not on the opposite side in the CIE *x,y* diagram but rather at the places with colors creating with others a powerful after-effects. If the rated after-effect peak is decreasing from X1+ i = 11 to X1+ i = 9 at X1 = 1 to 5, this means that these colors have narrower peaks (X1 = 11 to 13) arranged on the opposite side of the diagram (see Fig. 1).

If we analyze the peaks of the obtained surface and plot the sample numbers (X2 in this case) on the peaks, two pronounced areas with X2 repetitions will be identified. These two areas belong to green (X2 = 14) and pink (X2 = 7) colors.

Overall, the responses cover quite a broad range, and for some stimuli two peaks can be observed. For example, the 10^{th} (blue) stimulus is producing the sought-for effect with the 6^{th} (lime, X2 = 15), the 10^{th} (red, X2 = 4) and the 12^{th} (pink, X2 = 6) positions from it. Also, interesting is the first color (yellow), which has two peaks with the 7^{th} (violet, X2=7) and the 11^{th} (cyan) from it.

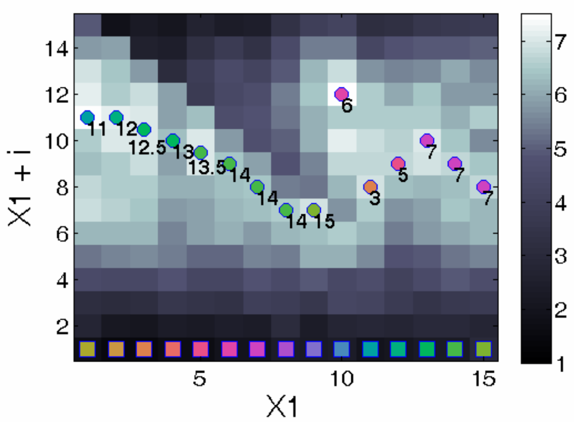

Fig. 3. Surface representing the adjusted strength of the after-effect for the pair of X1 and X2 (average of all subjects). The abscissa shows the first stimulus color (X1) and the ordinate – the sequence of the other fifteen stimuli from X1, where *i* changes from 0 to 14. The squares in the lower part show X1 colors. The circles on the peaks of the surface represent X2 and the number of a color sample.

To compare our findings with the theoretical opponent lines and 'unique hues', the total sum of the marks in all trials was calculated. This analysis is based on the proposition that there are color pairs which were judged low in most of the cases (going through X1), and also that strong pairs were usually judged with high marks. If we sum up all the responses, there will be positions judged higher or lower. In such a way we tried to identify the colors marked as strong in all trials. The average of all answers was summed together, after which the lowest value was set to zero and the result was normalized to the peak value. Figure 4 shows the stimulus chromaticity coordinates in CIE *x,y* diagram, with the size of spot showing the occurrence of a particular color being judged with a high value.

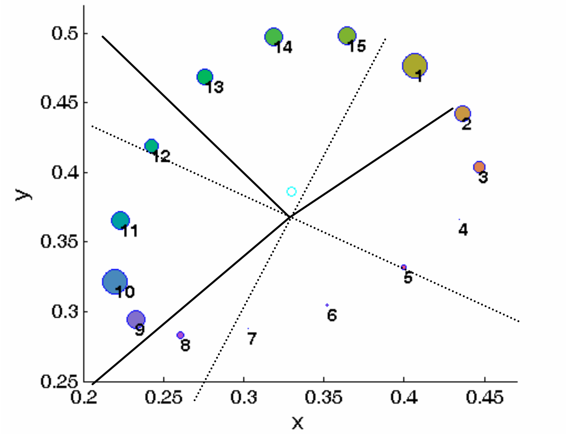

Fig. 4. Stimulus coordinates in CIE *x–y* chromaticity diagram. Spot size represents the occurrence of a particular color rated as forming a strong after-effect. Dashed lines represent cardinal directions of the opponent color space [16]. Solid lines are showing 'unique hues' directions [17].

The results of our analysis show that the yellow (1st) and the blue (10th) are the colors that form the most powerful after-effect in the case of our stimuli (Figs. 3, 4). These stimuli are placed close to the unique blue (478 nm) and unique yellow (578 nm) lines. After-effects produced by green and cyan colors also are rated quite high. On the other side the magenta colors are marked with the lowest value in this analysis.

According to our results, the opponent cardinal directions seem to play a role in the formation of the after-effect judgment process. For example, the 12th sample is forming the most pronounced after-effect with the 5th sample (see Fig. 3), where groups of colors on the *x* axis (X1 = 13, 14, and 15) are found producing the most powerful after-effect with one color (X2 = 7).

4. DISCUSSION

In our previous research we used round stimuli for producing the color after-effect. The results of that study have shown a bending of the complementary colors close to the 'unique hues' directions [18]. In the present study, we have used more complex stimuli for studying the mentioned effect. These types of illusory color stimuli are produced with active cortical processing and are less related to the retinal pigment bleaching, which takes time more than 1200 ms. Two stimuli of different colors are presented to the subjects simultaneously, which produces the interaction of colored figures and, probably, influences the signal processing. Earlier, it was shown how different color spaces represent the physiological levels of visual cortex [17]. The physiological level representing the color opponency is processed in late retinal and LGN networks. The 'unique hue' directions were identified in the hue scaling experiments and provided the ground for the multi-stage model of color vision (De Valois *et al.*, 1997 [13]), which proposes some transformation of opponent signals into sensitivities of the primary cortex to color.

Some recent works (e.g.[19]) show that the glob cells found behind area V2 and in area V4 of the ventral pathway could be a basis for the 'unique hue' representation. However, this particular study by Stoughton *et al.* was criticized by other color vision experts regarding the right choice of stimuli and data interpretation [20]. Our choice of the stimuli was based on the area V4 receptive field properties, and theoretically we expected the results to be more corresponding to the 'unique hues'. Two of the colors valued as producing the most powerful after-effect are really close to blue and yellow 'unique hue' directions. As previously noted, we used two overlapping stimuli producing the contextual induction, which could be the reason for our results not to correspond to the 'unique hue' lines.

5. CONCLUSION

It was found that the colors forming the most pronounced after-effect do not correspond to the 'unique hue' directions. Color samples of some area of the chromaticity diagram tend to produce the powerful after-effect with some particular colors. This allows for the conclusion that green and magenta colors play an important role in the formation of the after-effect.

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KRĀSU PIEPILDĪJUMA ILŪZIJAS STIPRUMA NOVĒRTĒJUMS

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K o p s a v i l k u m s

Tika pētīts krāsu pēcefekta stiprums, balstoties uz krāsu piepildījuma ilūziju [Van Lier *et al*, 2009, Current Biology, 19 (8), 323–324]. Izmantototais stimuls sastāv no divām krustam līdzīgām krāsainām formām, kas pārklājās 45 grādu leņķī. Divi tādi stimuli ir izvietoti uz abām pusēm no fiksācijas punkta. Krāsaini stimuli, kuriem ir iespējams mainīt krāsu, parādās uz 1200 ms, pēc kā seko šo stimulu ahromatisko formu parādīšanās uz 600 ms. Katrā pusē parādās tikai vienas formas ahromatiskas kontūras, kuras pēs 600 ms maina savu virzienu par 45 grādiem un pārtop par citu formu. Pateicoties šiem pagriezienam, rodas pēcefekta krāsu maiņas efekts no vienas uz otru pusi. Eksperimenta uzdevums ir novērtēt rādītā pēcefekta stiprumu dažādām krāsu kombinācijām pēc desmit punktu sistēmas. Stimulu krāsas tika izvēlētas CIELAB krāsu telpā un veikts pārrēķins uz CIE XYZ un digitālo RGB krāsu telpu. Rezultāti rāda, kā stiprākais pēcefekts veidojas, pamatā piedaloties zilajai un dzeltenai krāsai. Ar nedaudz mazākam vērtībām tika vērtētas zaļas un zaļi-zilas krāsas. Bet visrētāk stipra pēcefekta veidošanā piedalās rozā krāsa. Noteikts, ka spēcīgs pēcefekts zilajai un dzeltenai krāsai var veidoties ar vairāk nekā vienu krāsu, kas var neatrasties uz kādas no oponento krāsu asīm vai 'unikālo tonu' virzieniem.