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Dynamic phenomenology of grapheme-color synesthesia

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Abstract. In grapheme-color synesthesia, observers perceive colors that are associated with letters and numbers. We tested the dynamic limits of this phenomenon by exposing two synesthetes to characters that rotate smoothly, that morph into other characters, that disappear abruptly, or that have colors either consistent or inconsistent with the corresponding synesthetic color. Rotating letters changed their synesthetic colors abruptly as letter identification changed or failed. Morphing letters also changed color together with a change in letter identification. Abrupt disappearance of a black character on a white background yielded a negative afterimage, but maintenance of the same synesthetic color. Our synesthetes could maintain both physical and synesthetic color in the same character, without conflict. Neon color spreading in one observer occurred for physical but not synesthetic color. These and other results show close linking of synesthetic color with character identity rather than image properties, in contrast to physical color.

1 Introduction

Though synesthesia has been known by anecdote for centuries, recent applications of modern psychophysical techniques (Cytowic 1989/2002) have revived interest in the phenomenon and have yielded a greater understanding of it. Grapheme-color synesthetic observers report distinct colors associated with numbers and letters, a different color for each letter or number.

It is now clear that synesthesia is not the result of an overactive imagination or a vivid sense of imagery, but is a real perceptual phenomenon (Ramachandran and Hubbard 2003). Objective psychophysical tests in which synesthetes use information not available to non-synesthetes demonstrate this. For example, grapheme-color synesthetes can be shown an array of the numbers 2 and 5 that are difficult to differentiate without attending to each digit, so that a pattern made of 2s embedded in an array of 5s is difficult to identify. Synesthetes, however, experience a 'popout' of the pattern because it is in a different synesthetic color than the background, and it is perceived immediately and effortlessly, much as a real color difference would lead to the same result in normal observers (Ramachandran and Hubbard 2001a), though this interpretation has been disputed (Edquist et al 2006).

The time-honored strategy of psychophysics is to make perception more difficult along a selected dimension until the perception breaks down. It is in where and how the breakdown occurs that the mechanisms of perception are revealed. We propose to apply this method to grapheme-color synesthesia. We already know that some properties of synesthetic perception differ from conventional perception, for example a lower flicker fusion rate for synesthetic colors than for forms or for physical colors, that could not be easily predicted a priori (Ramachandran and Hubbard 2001a).

Most previous studies of synesthesia have used static targets, so that it is not clear to what degree synesthetic colors are assigned to meanings rather than geometric forms. Our goal in this paper is to press dynamic perception of alphanumeric characters along four dimensions: character rotation, morphing of one letter into another, afterimages upon abrupt character removal, and color consistent or inconsistent with synesthetic color. The latter condition is not physically dynamic, but might be expected to yield unstable dynamic perceptions analogous to binocular rivalry. We examined the perceptions of two observers with grapheme-color synesthesia, the most common type. Because grapheme-color synesthesia is stronger at high contrast (Hubbard et al 2006), and our goal was to explore cognitive rather than physical aspects of the phenomenon, we used high-contrast stimuli throughout.

2 Method

Two female grapheme-color synesthetes were recruited from the undergraduate student body at the University of California, Santa Cruz. Both volunteered their time. One of them happened to be a research assistant in the senior author's laboratory; she recruited the second observer from the pool of undergraduate psychology majors.

2.1 *Stimuli and procedure*

Each observer was tested separately, in the absence of the other observer. In a preliminary screening, our observers were shown all the letters of the alphabet, in alphabetical order, and asked for their color perception of each letter. These were followed by the numbers 0 through 12 in numerical order, and again the observers were asked for their color perceptions. Roman numeral combinations were also tested. The complete procedure was repeated on a second non-consecutive day of testing.

In the static experiments, for negative afterimage trials the observers were asked to fixate a location on one of the letters used in the initial synesthesia scan for 10 s, and to report color perceptions upon abrupt replacement of the letter by a blank white screen of the same brightness as the letter background. Color conflict trials were given with the number 8, which elicited synesthetic color in both observers, in the physical colors blue, red, and black, and they were asked to describe their physical and synesthetic color impressions. In this experiment, the number was present throughout the trial and there was no time limit on verbal reports of perceptions.

In the first dynamic experiment, isolated capital letters 10 cm in height were presented on a flat-panel screen at a distance of 60 cm and rotated clockwise at a rate of $30^\circ\ s^{-1}$, controlled by a flash program, while the observer reported the perceived colors, and reported change in color as soon as it occurred. Letters were black on a white background in a sans-serif font with constant line width, because serif or line-width cues might interfere with the re-identification of letters rotated from their canonical orientations. The letters presented in the rotating format were chosen for having different axes of symmetry and different transformations into the forms of other letters as they rotated. The following letters and numbers were tested, along with their transformations at the specified amounts of clockwise rotation from the 0° upright position:

N rotates to Z at 90°, N again at 180°, Z at 270°;
M rotates to E at 90°, W at 180°, no letter at 270°;
T no letter transformation;
A no letter transformation;
H rotates to H at 180°;
S rotates to S at 180°;
K no letter transformation;
X rotates to X at 90°, 180°, and 270°;
9 rotates to 6 at 180°.

Observers were asked to name the color they saw, and to name a new color when they saw a change. After each rotation trial, they also reported the remembered letter orientations at the times of color changes, if any.

On the same screen, the observers saw letters morphed into other letters over a 10 s interval by gradually changing the lengths of components that differentiated one letter from another. Physical parameters were the same as in the rotation trials. The transformations were E – F, P – R, and I – J.

After all trials the observers were again asked about the nature of their synesthetic perceptions, their personal histories of synesthetic experience, and any other observations they could add.

3 Results

3.1 *Characterization of synesthesia*

In this section we review tests performed on both observers to define and verify their synesthesia, with techniques that have been used by others in the past.

When tested on the complete set of alphanumeric characters, both observers gave color associations that were 100% consistent between their original tests and their repeat tests (table 1). This result confirms that our observers were true synesthetes, as this degree of consistency would not be expected in the absence of synesthetic color perceptions (Baron-Cohen et al 1996). For both of our observers, the letter O and the number 0 had the same synesthetic color, reflecting their similar geometries, as did the letter I and the number 1. They reported that they had experienced consistent color associations as long as they could remember, and both had initially assumed that everyone experienced associations like theirs.

Table 1. Perceptions of synesthetes CA and SN. Dashes indicate lack of synesthetic color.

Letter	Synesthetic color		Number	Synesthetic color	
	CA	SN		CA	SN
A	yellow	red	1	white	white
B	blue	light blue	2	red	yellow
C	light blue	orange	3	blue	red
D	yellow	dark blue	4	yellow	green
E	blue	–	5	purple	blue
F	green	–	6	brown-purple	pink
G	purple	brown	7	yellow	light purple
H	orange	yellow	8	blue	turquoise
I	white	white	9	pink	purple
J	teal	grey	10	both white	[combination]
K	pink	purple	11	white	[combination]
L	yellow	brown	12	white – red	[combination]
M	red	dark green	0	white	dark
N	red	light green			
O	white	dark			
P	light yellow	blue			
Q	orange	–			
R	orange	–			
S	red	–			
T	blue	–			
U	yellow	–			
V	white	light yellow			
W	purple	orange-brown			
X	teal	–			
Y	yellow	–			
Z	purple	mid-grey			

CA reported synthesthetic colors for all letters and all numbers. Three letters (I, O, V) and two numbers (1, 0) were reported as white, a color that was reported to have little or no synesthetic content.

Observer SN did not perceive synesthetic colors for all letters; 17 letters had synesthetic accompanying colors. All numbers had synesthetic colors. Though fluent in

English, SN is a native speaker of German; two of the ten letters without synesthetic components are letters that are not used in German (X and Y), though they occur occasionally in German usage as parts of identifiably foreign loan words, and Y appears in obsolete spellings of some words. The other non-synesthetic letters were a mix of relatively frequent and infrequent letters in both English and German. Colors were described as 'vague', except for A, B, C, M, and N, even though all letters and numbers upon retest received the same color assignments as in the original test.

The numbers 10, 11, and 12 were tested because they have unitary names rather than component names, and might be perceived as units with their own colors. All were perceived with the synesthetic colors of the component digits, however, with a color attached to each component digit.

Both observers were familiar with Roman numerals, and knew the number values of the numerals presented, but had much more experience with the symbols as alphabetical letters. Even though the figures were described by the experimenters as Roman numerals at the time of testing, they were always perceived with the colors of each component letter, I, V, and X, replicating a finding of Ramachandran and Hubbard (2001b).

4 Experiment 1. Static forms

When presented with the number 8, seen synesthetically as blue or turquoise, in the physical colors black, blue, and red, both observers could easily identify both the physical and the synesthetic colors, and could differentiate the two. Synesthetic color did not interfere with physical color naming—the observers made no errors in identifying the physical colors. Observer SN also noticed a neon color spread of the physical color, but not the synesthetic color, into the inner loops of the colored versions of the 8. *RGB* distances between stimulus color and synesthetic perception could not be determined because the synesthetic color descriptions were qualitative.

Abrupt offset of a high-contrast pattern normally results in a brief negative afterimage. The negative afterimage of a colored stimulus appears in the complementary color. Abrupt offsets of black letters S, F, and E always had white afterimages along with the original synesthetic color. The color complementary to the synesthetic color was never perceived. For observer CA the letter S, for example, seen with synesthetic red, was seen in the afterimage as "white, but still red". Neither observer was surprised by the lack of negative complementary synesthetic afterimage color, but considered it perfectly natural, as though the synesthetic color belonged to the letter, not to its physical instantiation.

5 Experiment 2. Dynamic forms

For the letter rotations, CA saw N as red, and Z as teal. As the N rotated, she saw red followed by purple, no color, and red. Purple might be interpreted as a combination of the red N and the teal Z. Other rotations always resulted in distinct letter-related colors rather than combinations. Color change always coincided with the change in the perceived identity of the letter; if there was any hysteresis in letter identification, the synesthetic color followed it precisely. M started with its red synesthetic color, then transformed to blue from the number 3, purple W, blue again this time from the letter E, and back to red as the rotation completed. Each time, letter identification and synesthetic color changed simultaneously. The remaining rotations showed the following patterns, starting with the upright synesthetic color:

T blue → no color → blue about 10° before vertical
A orange-peach → no color → white [V] → no color → peach
H orange → white → orange → white → orange
S red → left side blue from C, right white → red
K pink → no color → pink

X teal-white same all around
9 pink → blue → white[0?] → purple[6] → pink
6 purple → no color → pink → blue-white → purple

Figure 1 shows examples of the synesthetic color transitions for M, T, A H, and X, each showing a different pattern of transitions due to differences in patterns of axes of symmetry in the respective letters.

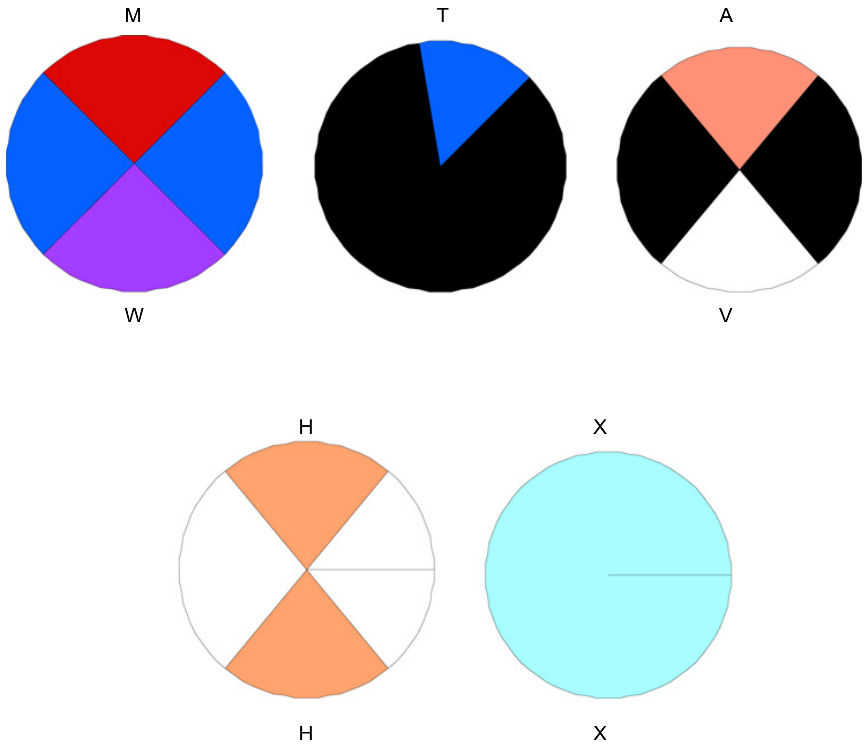

Figure 1. [In color online, see http://dx.doi.org/10.1068/p6321] Polar representations of synesthetic color perceptions in observer CA for letters as they rotate through 360°. In each trial, letters begin at the canonical orientation given above each polar plot. The inverted letter identification, if any, is given below the corresponding plot. Shading represents the perceived synesthetic color at the corresponding orientation. Black indicates no synesthetic color. Thin black radius line is a horizontal reference for calibration. CA accepted the inverted A as a V despite the presence of the horizontal cross-bar. Changes in perceived color correspond closely to the changes in perceived letter identity during the rotation.

The morphed letters elicited perceptions consistent with the perceptions of rotated letters. For CA, E's blue synesthetic color changed to F's green when about half of the bottom line had disappeared and the letter was identified as an F. Precise values of stem length at the transition cannot be determined with our method because of response latency. Critical, though, is the existence of a change and its simultaneity with letter identification, rather than the precise locations of the transitions in each observer. The change was abrupt, as was the change in letter identification, reflecting a qualitative cognitive decision superimposed on the continuous smooth change of the stimulus. P's light-yellow became R's orange when about half of the growing diagonal stem was present. I's white became J's teal when the growing curve reached a horizontal tangent and the letter was perceived as a J.

Observer SN saw no color in the letter morphing experiment for the ambiguous intermediate forms, only for perfect or nearly perfect letters, possibly reflecting her higher criterion for letter identification than CA's and a corresponding lacuna in synesthesia for the intermediate morphed forms. Again, changes in letter identification and synesthetic color were simultaneous.

Observer SN also noted that synesthetic color made it easier to remember telephone numbers by their color combinations. German telephone numbers often have more digits than North-American numbers, making them more challenging to encode and remember. Thus synesthesia can have advantages in everyday life, and potentially be selected for. It can be seen as an adaptation, not a handicap.

6 Discussion

Grapheme-color synesthesia is the most common form of the phenomenon, though estimates of its frequency vary greatly; from 1/20 000 (Cytowic 1989/2002) to as many as 1/20 (Galton 1880). Our finding of two grapheme-color synesthetes in a population of about 1000 is too small a sample to fix a frequency, but would suggest a number between these extremes. It is possible that other synesthetes existed in our source population, but did not come forward to volunteer for the experiments.

The close match between synesthetic color and character identification in the rotation and morphing experiments shows that the synesthetic color is attached to a perception of identity of a character, rather than the physical form of the pattern making it up. Real color of a character of course does not change as the character rotates and changes its identity. If the synesthetic color were attached to the geometry of the figure features, such as line components, intersections, etc, rather than its lexical/numeric meaning, the synesthetic color in our rotation experiment would have remained constant as the figure morphed into another or rotated through 360°. Our results here are consistent with recent studies suggesting that attention, or overt recognition, is crucial in eliciting synesthetic color experience (Edquist et al 2006; Nijboer and Van der Stigchel 2009).

Perception of a negative color afterimage along with a simultaneous positive synesthetic afterimage shows that synesthetic color in our observers is not influenced by negative aftereffects, which arise at the retinal level. At the same time, the brightness afterimage shows that the stimuli were adequate to elicit normal afterimages. Neon color spread of the physical but not the synesthetic color in observer SN is consistent with this observation. These phenomena are further indications that synesthetic colors are aroused by the cognitive identities of alphanumeric characters and, at least in our two cases, are not dependent upon their physical shapes. It is the meanings of the letters and numbers that elicit synesthetic perceptions.

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