SYNESTHETIC COLORS DETERMINED BY HAVING COLORED REFRIGERATOR MAGNETS IN CHILDHOOD

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ABSTRACT

Synesthesia is a condition in which percepts in one modality reliably elicit secondary perceptions in the same or a different modality that are not in the stimulus. In a common manifestation, synesthetes see colors in response to spoken or written letters, words and numbers. In this paper we demonstrate that the particular colors seen by a grapheme-color synesthete AED were learned from a set of refrigerator magnets and that the synesthesia later transferred to Cyrillic in a systematic way, with the colors induced by the Cyrillic letters determined by their visual or phonetic similarity to English letters. Closer examination of the data reveals that letters of either language that are more visually similar to the English capitals in the magnet set are also more saturated. In order to differentiate AED's synesthesia from ordinary memory, we use a novel psychophysical method to show that AED's synesthetic colors are subject to ordinary lightness constancy mechanisms. This suggests that the level of representation at which her synesthesia arises is early in the stream of visual processing.

Key words: synesthesia, perception, lightness constancy, learning

INTRODUCTION

The origin of the relation between what are sometimes termed the inducer and concurrent (Grossenbacher and Lovelace, 2001), meaning the stimulus that produces synesthesia and the synesthesia itself, has provoked much debate. One general line of argument is that the relation between inducer and concurrent results from pre-existing mappings between sensory areas that are overactive or fail to be pruned during development (Ramachandran and Hubbard, 2001a). To bolster this view, researchers have pointed to what seem to be innate alignments between sensory dimensions. For example, normal subjects will rate higher pitched sounds as brighter than lower pitched sounds, a trend which seems to hold true for pitch-color synesthetes (Marks, 1975). It has also been suggested that infants may be innately synesthetic, with sensory differentiation coming only with development and the gradual pruning of connections (or at least development of inhibition) between sensory areas (Maurer, 1997).

Another theory is that learning can influence the development of particular inducer-concurrent pairings. This idea has a long history, beginning over 100 years ago with Galton's (1880, 1907) pioneering account of a synesthete who perceived dates as colored and claimed that the colors were derived from a history book used for childhood instruction (Galton, 1880, 1907). Despite the intuitive plausibility of a learning account, this view has largely fallen out of favor due to the inability of researchers to produce even a single case where learning could be traced to a particular environmental source (Marks, 1975; Ramachandran and Hubbard, 2003b).

However, recent findings suggest a need to acknowledge a role for environmental influences. Mills et al. (2002) report a color-grapheme synesthete, MLS, who perceives colors in response to both English and Cyrillic letters (Mills et al., 2002). While the origin of MLS's letter-color mappings are unknown, MLS surprisingly developed new concurrents for English letters following brief laboratory exposures to letters displayed in colors that did not match any of the colors normally elicited by English letters. These new and inadvertently acquired photisms matched those colors given in the lab but were weak and transient, disappearing within a few weeks. A different kind of environmental influence is at work in a recently reported case of a word-taste synesthete, for whom a number of factors, including semantics and phonology, seem to have influenced the link between inducer and concurrent (Ward and Simner, 2003). For example, words containing the phoneme "k" tended to elicit the taste of foods with the same phoneme, such as "cake". The authors argue that the mappings between inducer and concurrent can be conceptually mediated rather than simply reflecting hardwired connections between sensory modules.

This paper presents a series of results from an investigation of a color grapheme synesthete, AED. She has had synesthesia for as long as she can remember and reports all achromatic text as having colors overlaid on the surfaces of the letters or numbers. She is highly educated and has received a

Ph.D. in a scientific field. She has no history of neurological or psychiatric disorder and has normal color vision as assessed using the "16 Plate Pseudoisochroamatic Color Vision Test" from Goodlite. None of the other members of her immediate family reports having synesthesia of any kind. What sets AED apart from previously reported synesthetes of this type is evidence suggesting that the inducer-concurrent relationship was learned from a refrigerator magnet set and subsequently transferred to the Cyrillic alphabet. Further experiments shed light on the representations of the inducer and concurrent and where in the respective streams of processing they might arise.

CONSISTENCY OVER TIME

Like other synesthetes, AED reports that her particular set of inducer-concurrent pairings has always been the same. Consistency over time is ordinarily considered a prerequisite for establishing the genuineness of synesthesia (Baron-Cohen et al., 1987; Grossenbacher and Lovelace, 2001; Rich and Mattingley, 2002). We quantified the consistency of AED's photisms by correlating the hue, saturation, and brightness of her matches generated on a computer during two tests 3 weeks apart.

Methods

Stimuli were presented using a Macintosh G4 computer with a 17-inch LCD flat panel monitor using Vision Shell stimulus generating software. Testing was done on two separate occasions, 21 days apart, in a quiet darkened room with the same computer and monitor used for both sessions. The graphemes appeared in gray and AED adjusted the hue, brightness and saturation of the grapheme using controls also on the screen. Moving the pointer on the surface of a color wheel or brightness slider simultaneously adjusted the color of the letter or number. There were 360 possible hues, 100 levels of saturation and 128 levels of brightness, encompassing the full range afforded by the monitor. AED had unlimited time to make the matches but could not go back once a match was made. During each matching session AED was presented in random order with the digits 0 to 9 and all letters of the alphabet both uppercase and lowercase (n = 62). The consistency of AED's synesthetic pairings was assessed by separately

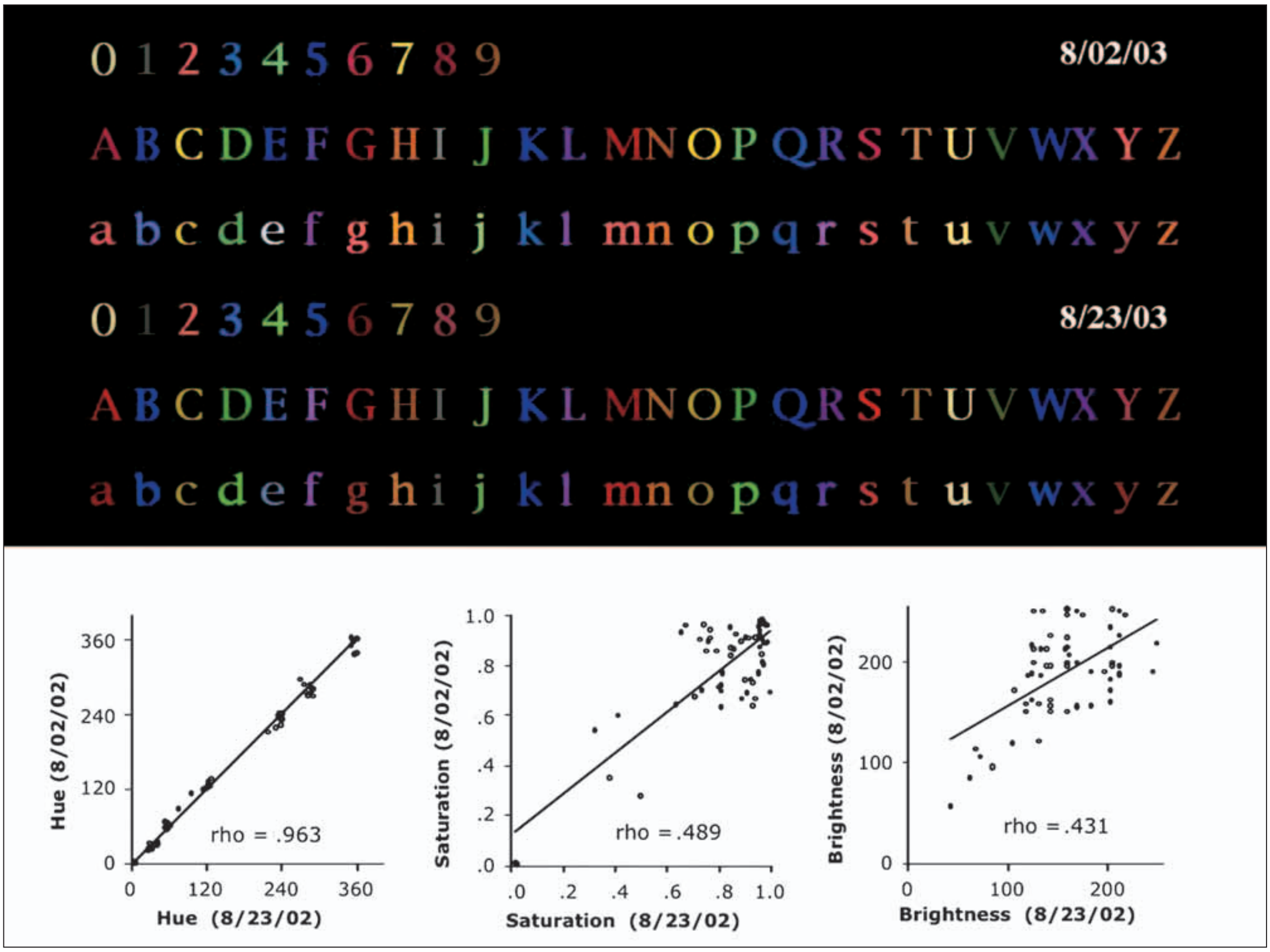

Fig. 1 – *Consistency over time. Top: AED's synesthetic colors as produced in a matching task on two different test sessions. Bottom: Correlations between the two test dates on the dimensions of hue, saturation and brightness. While all three are highly significant, the hue shows almost no variation between the two dates. Lines represent least square regression.*

Fig. 2 – *Patterns in AED's synesthetic alphabet. Aligning AED's matches from Experiment 1 so that every 6th letter falls in the same column reveals a striking pattern. With the exception of the letter 'B' and possibly 'I', every 6th letter has a similar hue.*

correlating the hue, brightness and saturation from one test with the same measures from the next. Since the data were not normally distributed on some dimensions, the non-parametric correlation coefficient Spearman's rho is used to assess the strength of the correlations.

Results

The hues of the individual letters taken from the two tests were highly correlated (rho = .963, $p < 0.001$), while the saturation and brightness were more variable (saturation: rho = .489, $p < .001$; brightness: rho = .431, $p < .001$, Figure 1). AED clearly satisfies the criteria for this measure of synesthesia. While all of these correlations are highly significant, it is notable that AED is more specific about the hue dimension than either saturation or brightness. AED did this task very quickly, doing all the trials in 15 minutes or less on each test.

REFRIGERATOR MAGNETS

Reorganizing AED's alphabet (Figure 2) reveals that with the exception of the B, every sixth letter has a similar hue. When asked about the pattern AED recalled having a toy as a child with similarly colored letters. A photograph of the toy, obtained from her parents, appears in Figure 3. The relationship between AED's synesthetic colors and the refrigerator magnets is obvious and we conclude that AED learned her colors from this toy. As far as we have been able to determine, this represents the first and only documented case of experience determined color-grapheme synesthesia. It also presumably extends the consistency of her inducer-concurrent mappings across nearly 30 years.

An outstanding question remains regarding the origin of AED's synesthesia for numbers. AED believes that the numbers were also learned from an accompanying set of refrigerator magnets that included numbers and basic mathematical operators ('+', '–', '/', '=') for which AED also experiences synesthesia. However, AED is no longer in possession of the set and we have been unable to locate one and are therefore unable to say anything definitive about the origins of these colors.

TRANSFER TO CYRILLIC

AED's experience dependent mapping of inducer to synesthetic color extends beyond the English alphabet. AED moved to Russia at age 3

Fig. 3 – *Experience-dependent synesthesia. Top: AED's synesthetic colors, as adjusted by her in random order using a color wheel and a brightness bar. Bottom: AED's childhood refrigerator magnet set, recovered from her parent's attic. Note that the "B" was apparently missing in her childhood and recently found, and the "G" and "H" were present during childhood and recently lost.*

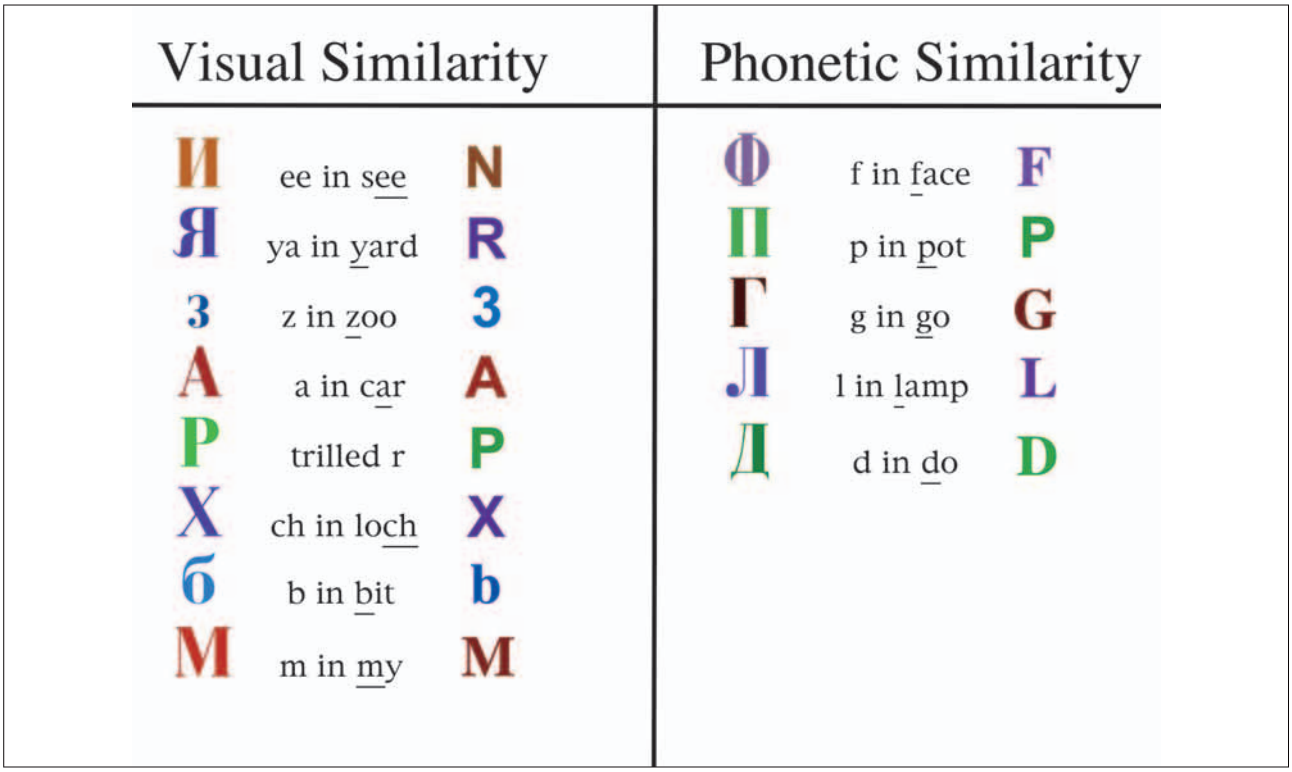

Fig. 4 – *Transfer of synesthesia to Cyrillic. In the right column are some examples of Cyrillic letters that have the same basic form or are mirror-reversed versions of English letters. There were 40 such examples total (20 upper and 20 lower case). There were 10 letters with phonetic but not visual analogs to English letters (5 upper and 5 lower case), shown on the right.*

and developed concurrents for Cyrillic letters. Many of the letters in the Cyrillic alphabet visually resemble those used in English, even while standing for different sounds or concepts. For example, the symbol “3” in English is a number, but in Russian, a very similar symbol is “3” is read “z” as in *z*oo. However, there are also letters in the Cyrillic alphabet that are not visually similar to any letters in the English alphabet but represent phonemes that also occur in English. We investigated whether or not there were any correspondences between the colors elicited by the two alphabets and whether visual or phonetic or even conceptual similarity might prove to be a determining factor.

Methods

Colors for Cyrillic letters were obtained using exactly the same environment, software, computer and monitor as the matches for English letters. A total of 62 stimuli (31 upper case and 31 lower case) were presented. Twenty of the 31 pairs of Cyrillic letters have the same basic form as English letters or are mirror reversals of English letters and were considered visually similar to English letters. There was no ambiguity about whether the letters were English or Cyrillic both because AED knew that all letters on this test date were Cyrillic, and because there are subtle differences between even the English and Cyrillic letters classified as visually similar. Of the remaining 22 letters, 10 (5 upper case letters and their 5 lower case counterparts) had the same sound as single English letters. The last 12 did not clearly resemble any particular English letter and represented sounds that are not used in English or that required more than one English letter to represent (for example, sh) and are not included in the analysis.

Results

Generally, the concurrents for Cyrillic letters depend on their visual similarity to English letters (Figure 4). Correlating the hue, value and saturation of the 40 visually similar letters with the average of their counterparts generated in the two matching experiments with the English alphabet gave significant correlations for hue and saturation but not brightness (hue, rho = .960; saturation, rho = .611, both p < .001). The correlation among the hues is nearly perfect despite the fact that many of the Cyrillic letters stand for different sounds or concepts. This suggests that visual similarity to English letters (or the original letter set) is a dominant factor in determining the synesthetic color generated by Cyrillic and has implications for the representation which induces AED’s synesthesia.

Comparing the Cyrillic letters that have only a phonetic similarity to English letters also revealed a near perfect correlation with respect to hue (rho = .973, p < .001) but no significant correlations for either saturation or brightness (Figure 5). These

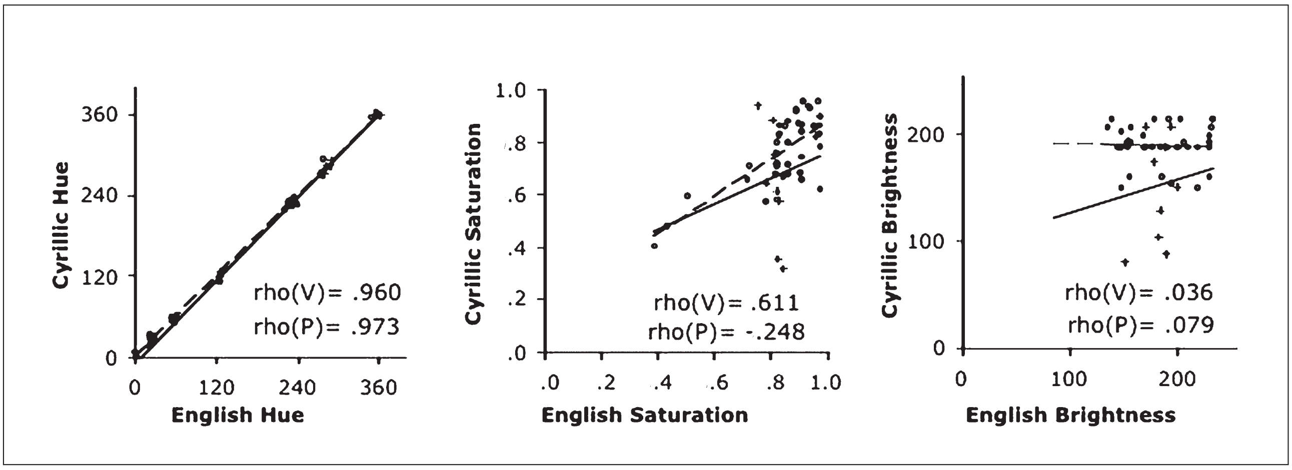

Fig. 5 – *Synesthesia for Cyrillic letters. Pictured above are the correlations for hue, saturation and brightness between the Cyrillic letters and the average values on these same dimensions taken from English letters. Visually similar letters (dashed lines) and phonetically similar (solid lines) are least square regression lines. The hue for the Cyrillic letters correlates strongly with those from English even when the relationship is only phonetic. The saturation shows significant correlation only when the Cyrillic letters are visually similar to English letters.*

results are nicely consonant with a previous report of an English speaking synesthete, MLS, who developed photisms for Cyrillic letters after learning Russian in high school (Mills et al., 2002). Like AED, MLS also showed similar colors for most visually similar letters in the two languages, and colors based on phonetic similarities for the majority of the rest.

WHAT IS THE LEVEL OF REPRESENTATION OF THE INDUCER?

At first it might seem strange that phonetic similarity in the absence of visual similarity can have an effect. But the relationship between Cyrillic letters that have no visual counterpart in English is no different than the relationship between many lowercase letters in English and their uppercase partners. For example, the relation between “a” and “A” is analogous to the relation between “**A**” and “F”, in that the only relation they have is they stand for the same sound.

It has been reported that for some color-grapheme synesthetes the case of the letter or even the font may have some effect on synesthesia, with more prototypical fonts yielding more vivid synesthesia (Ramachandran and Hubbard, 2003a, 2003b). Others have suggested that for most synesthetes font and case have no impact on the color (Grossenbacher and Lovelace, 2001). This question is of interest because noting what type of changes in the stimulus produce changes in the concurrent provides insight into the specificity of the representation of the inducer. For example, if synesthesia were only produced by one particular font, then it could be argued that the inducer is a representation that contains very specific shape information. If variations in font or case have no effect on the concurrent than it is likely that the representation that produces the concurrent is more abstract, concerned with the category to which the letter belongs. The method of obtaining synesthetic colors used here is useful to this end. Previously, most researchers have used color names to verify consistency over time, but this approach may mask significant differences in the concurrent since changes in case may result in subtle but detectable changes in the concurrent that are lost when mapped onto the coarser code of language.

Since hue was clearly unaffected by changes in case or shape, we investigated whether case or font had any systematic effect on the saturation or brightness of AED’s synesthesia. In the English alphabet some lower-case letters are visually similar to upper-case letters, distinguished from them largely by their relative size or position (‘W’ *vs.* ‘w’) while other letters can have the case determined by shape alone (‘A’ *vs.* ‘a’). To see if visual identity was an important factor with English letters, we looked at the importance of visual similarity of upper to lowercase letters on both saturation and brightness. For the Cyrillic alphabet, we separated the letters both by case and by similarity to the English capital letters and examined the impact on saturation and brightness.

Methods

Brightness and saturation data from the English letters were taken from the consistency experiment (in Times font) and from an additional testing session using the Sand font (a cursive font). The data were analyzed in a 2 × 2 × 2 ANOVA, with case (upper *vs.* lower) and font (Times *vs.* Sand) as repeated measures over 25 letters and similarity between the cases as a between groups factor. The letter “I” was excluded because it was mistaken for the number “1” in one session. The matching results for the Times font were averaged from the two test sessions, while the Sand results came from

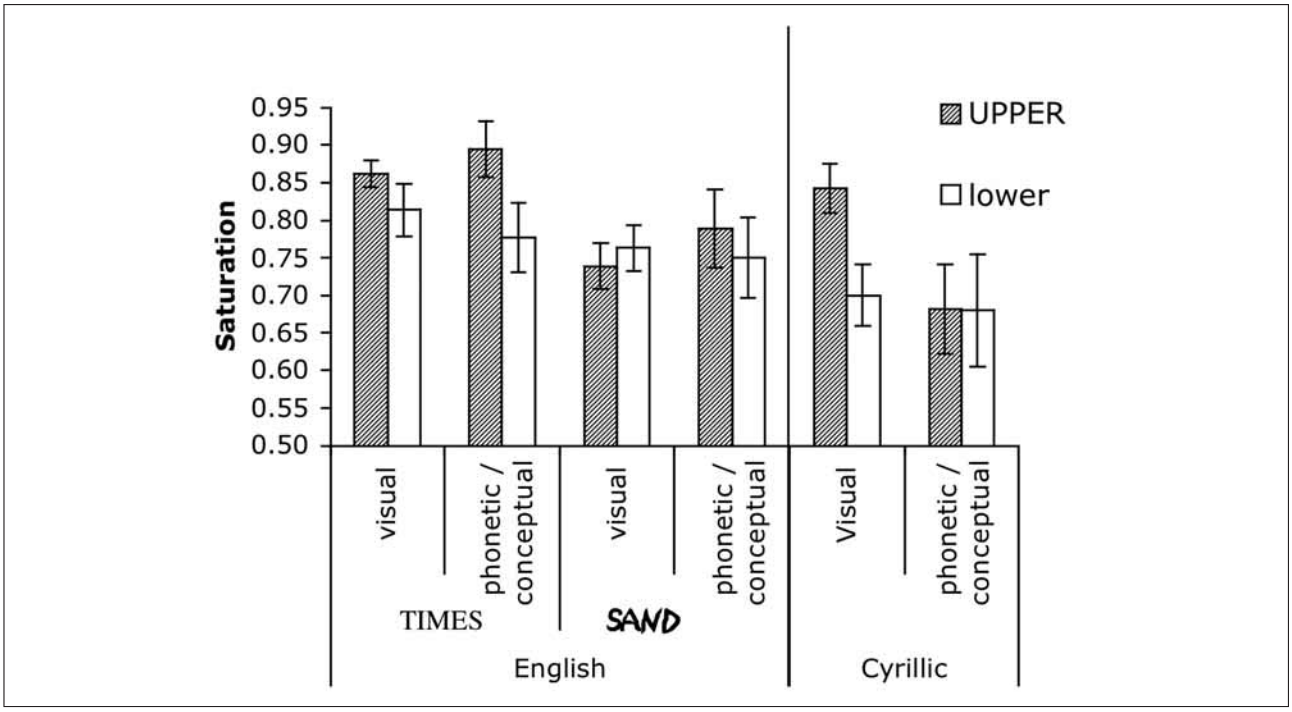

Fig. 6 – *Saturation for AED' s synesthesia. Left and Center panels: English letters. Upper case letters are more saturated than lower case letters in the standard TIMES font (left), but not in the more unusual SAND font (center). Generally, the letters in Sand have a saturation similar to that of the lower case Times letters. Moreover, the reduction in saturation with lower case compared to upper case is more evident in those letter pairs for which the upper and lower case are not visually similar to each other. These findings all support the notion that letters which are less similar to a prototype are also less saturated. The letters C, K, O, P, S, U, V, W, X, Y, Z were designated as being visually similar in upper and lower case, whereas the letters A, B, D, E, F, G, H, J, L, M, N, Q, R, T were designated as being visually dissimilar between upper and lower case. Right panel: Effects of similarity to English capital on the saturation of AED's concurrents for Cyrillic letters. Visually similar upper case letters are highly saturated, like the upper case Times letters in English. Their lower case counterparts, as well as letters that are only phonetically or conceptually similar to English letters (whether upper case or lower case), all show a reduction in saturation. As with English letters, the more the letters differ from an upper case English prototype, the less saturated they appear.*

a single session. Eleven letter pairs were considered visually similar between cases and 15 pairs were considered dissimilar.

Responses from the Cyrillic matches were analyzed in a 2 × 2 ANOVA with case as a within subject factor and similarity to the English capitals (visual *vs*. phonetic), as a between subject factor. Several of the capital Cyrillic letters are visually similar to lowercase English letters resembling either "b" or and upside down "h". Since it was unclear how to treat these letters they were excluded from the analysis. This left 17 pairs of letters that were visually similar to English and 5 pairs that were phonetically similar.

Results

No significant effects for brightness were found in any contrast using either the Cyrillic or English letters. Saturation of the letters showed a number of effects. For the English letters there was a main effect of case with AED rating the uppercase letters as significantly more saturated than the lowercase (mean saturation of uppercase = .824, SE = .019, mean lowercase 0.775, SE = .020, F (1, 23) = 11.983, p < .01). There was also a main effect of font, with Times more saturated than Sand (mean Times = .837, SE = .018, mean Sand = .762, SE = .020, F (1, 23) = 18.580, p < .001). These factors also interacted, such that the effect of case was bigger for Times than for Sand [F (1, 23) = 7.131, p < .05], with all the saturation values in Sand resembling the lowercase values in Times (Figure 6). There was no main effect of similarity, but there was an interaction between similarity and case, such that the uppercase was more saturated than lowercase for pairs that were visually dissimilar, but not for pairs that were similar [F (1, 23) = 6.123, p < .05]. There were no other significant interactions for the English letters.

For the matches generated to Cyrillic letters there was also a main effect of case on saturation [F (1, 20) = 6.211, p = .022] with the uppercase letters showing significantly greater saturation than their lowercase counterparts. There was also an interaction between the case and similarity of the letters to English [F (1, 20) = 5.94, p = .024]. This was entirely due to a reduction of saturation for the lowercase Cyrillic letters visually similar to English. The remaining Cyrillic letters, those that are not visually similar to English letters, showed no effect of case on perceived saturation and in fact overall had a similar saturation to the lowercase English letters (Figure 6, right panel). The fact that both upper and lowercase letters in these Cyrillic letters were reduced in saturation

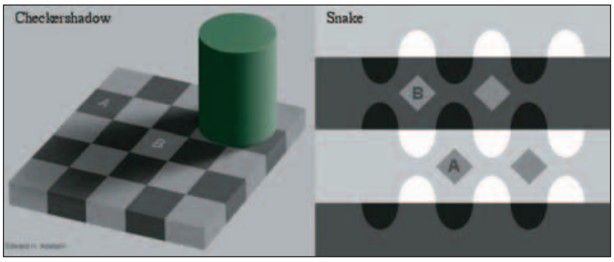

Fig. 7 – *Lightness constancy illusions. In the Checkershadow illusion (left) and the Snakes illusion (right) the regions marked A and B are of identical lightness. However, lightness constancy mechanisms "correct" the apparent brightness such that the two regions marked B appear brighter either because they are in apparent shadow (left) or behind a dark transparent surface (right). For the lightness experiments, AED was presented with gray letters, one per trial, either in region A or B, either in the Checkershadow or the Snakes illusion. AED adjusted the color and brightness of a small rectangular patch outside the illusion until it matched the apparent color and brightness of the synesthetic color. The two illusions were used on separate test dates. Both illusions are creations of Ted Adelson.*

relative to their English counterparts further supports the relevance of visual information to the inducer representation.

Overall, the pattern seems to be that greater visual similarity either to the original refrigerator magnet set or possibly to a prototypical font representation causes AED's synesthesia to appear more highly saturated. Thus the more standard font (Times) led to more saturation than the non-standard font (Sand) and uppercase more saturation than lowercase. Moreover, the loss of saturation for lowercase letters was greater for those that are not scale or position transformations of their uppercase counterparts. One interesting and compelling possibility is that visually dissimilar letters activate synesthesia only indirectly. For example, looking at a lowercase letter may activate neural regions that sufficiently overlap or spread activation to those that would be activated by the uppercase letter. This overlap in pattern of activation is similar enough to evoke synesthesia, but the difference results in weaker saturation. Letters in Cyrillic standing for sounds that also occur in English would also weakly activate their counterparts either through spreading activation or neural overlap and subsequently generate the synesthetic concurrent. On the other hand, it could be that multiple levels of representation of the inducer are each capable of activating the concurrent directly on their own. How they do so differs as the representation changes from visual to phonetic or conceptual.

WHAT IS THE LEVEL OF REPRESENTATION OF THE CONCURRENT?

The specificity with which AED selects hue, and the subtle changes in saturation with changes in case or visual similarity suggest that AED's concurrents arise early in the stream of visual processing. Certainly the hue seems to arise at a level earlier than linguistic categorization. Nonetheless, skeptics might argue that AED may just have an extraordinary memory for particular color-letter pairings as could be learned by any person willing to put in the time.

Not all color-grapheme synesthetes claim to see colors as part of the visual scene; some report seeing the colors only in their mind's eye and some others say only that they have very specific ideas about what colors letters are (Grossenbacher and Lovelace, 2001). Synesthetes like AED, who report seeing colors on the surfaces of letters (sometimes referred to as projectors; Smilek et al., 2001) are of particular interest because the ways in which their concurrents interact or fail to interact with normal visual processing can point to where in the stream the percepts arise (Ramachandran and Hubbard, 2001b; Palmeri et al., 2002). While AED's subjective experience is ultimately impenetrable, and therefore we cannot talk conclusively about what AED 'sees', it is possible to infer whether the concurrent is processed by very early visual mechanisms, mechanisms that would ordinarily be considered insulated from information in associative memory.

To this end we tested whether AED's synesthesia was affected by lightness constancy illusions. Working with lightness constancy can reveal whether synesthetic colors are integrated into early stages of perceptual processing and treated as part of the visual scene. In the Checkershadow illusion (Adelson, 2000; http://web.mit.edu/persci/people/adelson/checkershadow_illusion.html), two identical squares marked A and B appear to be very different shades of grey (Figure 7, left). The illusion is created because the visual system takes into account illumination conditions when computing the reflectance properties of a surface. Identical amounts of light are reflected by the two squares, but for something apparently in shadow to reflect as much light as something that is directly lit, the surface in shadow must have greater reflectance than the lit surface. The visual system thus 'discounts the illuminant' and interprets surface B as brighter than surface A (Adelson, 2000). The same process is at work in the Snakes illusion (Adelson, 2000) except that the illusion results from B appearing to lie beneath a dark transparent surface instead of beneath a shadow (Figure 7, right).

We reasoned that if AED's photisms were incorporated into the normal stream of visual processing at an earlier stage than lightness constancy is computed, synesthetic colors produced by achromatic letters embedded in the illusion should also be adjusted by the same constancy mechanisms. That is, given that the visual system detects two colors of identical luminance, but one seeming to be in a shadow, lightness constancy mechanisms should determine that the one in the shadow must actually be brighter. It does not matter that those colors are not in the physical stimulus, only that the brain treats them as real, incorporates them into its representation of the visual scene and processes them. In short, if AED generates matches for letters appearing to be in a shadow or beneath a transparent surface that are brighter than the same letters when perceived to be directly lit, her concurrents arise before lightness constancy has been fully computed.

Methods

The software from the previous color matching tasks was modified so that achromatic letters now appeared embedded in one of the two lightness illusions. On two test dates, AED did the task using letters embedded in the Checkershadow illusion, and on a third occasion did the matching on the Snakes illusion. Each capital letter appeared in two trials, once on the square in the light and once on a square in the shadow or beneath the transparency (marked ‘A’ and ‘B’, respectively, in Figure 7). AED adjusted the color of a patch located above the illusion using a color wheel and brightness slider until the test patch matched the color of her synesthesia. All other conditions were identical to those in the color matching tasks.

To quantify the effect of the lightness illusion on real colors, 3 non-synesthetic control subjects with self-reported normal color vision also did the Checkershadow task, except that the letters appearing in the illusion had colors. The control subjects matched the test patch outside the illusion to the color presented on screen. AED did a similar control task to make sure her lightness constancy was normal, except that instead of letters she was presented with ovals embedded in the illusion. The colors for the ovals (for AED) and the letters (for non-synesthetic control subjects) were generated from AED’s previous matching results.

For both AED and controls each experiment using letters had 50 trials with each letter or oval appearing twice (once in each location for 25 pairs). Only capital letters were presented and the letter ‘I’ was excluded. For the experiment using colored ovals, AED was given 30 trials (15 pairs of colors). Data were analyzed by doing a one-sided paired t-test on the brightness values of each of the letters (or ovals) taken from the two different locations in the illusion. By hypothesis, it was expected that stimuli appearing in the shadow would be rated as brighter than those appearing in the directly lit square. Brightness values are units of pixel intensity from 0 to 255.

Results

AED showed a highly significant effect of the Checkershadow illusion on the perceived brightness of her photisms ($n = 25$, mean difference 17, $SE = 3.4$, $p < .001$), demonstrating that her concurrents are available to the early stages of visual processing. A similar result was found with the Snakes illusion; AED’s photisms were systematically brighter when perceived to be beneath a dark transparent surface than directly lit ($n = 25$, mean difference 14, $SE = 5.4$, $p < .01$). As expected, normal controls and AED showed similarly large and systematic effects in the predicted direction when matching real colors (AED: $n = 15$, mean difference 37.3, $SE = 6.7$, $p < .001$; controls: $n = 25$, mean difference 40, $SE = 4.5$, $p < .001$). Thus in all cases, the brightness of the colors, whether real or synesthetic was modulated by the apparent illumination.

Analysis of a control experiment in which the brightness of achromatic letters was systematically varied with no change in the apparent illumination showed no correlation between the brightness of the achromatic letter and AED’s matches. This suggests that the effects described above are due to lightness constancy mechanisms operating directly on AED’s synesthetic colors, and not due to the apparent difference in brightness of the inducing letter in the different regions of the illusions. That is, the cues to shadow (or transparency) surrounding the letter affect the apparent brightness of the synesthesia, but the brightness of the inducer itself does not matter.

An obvious question is why the effect on AED’s synesthetic colors is smaller than for real colors. One possibility is that lightness constancy is the result of several mechanisms and only a subset of these processes has access to the synesthetic colors. We presume based on these experiments that the synesthetic color is added to the visual scene via feedback from letter recognition areas to early stages of visual processing involving color. Since simultaneous contrast has been shown to influence neural activity as early as V1 (MacEvoy and Paradiso, 2001) and given that there is a simultaneous contrast component to the illusions, it is likely that the synesthetic color is not available to some of the earliest constancy mechanisms.

Discussion

Together these findings document the first clear case of experience-dependent color-grapheme synesthesia. For AED, exposure to colored refrigerator magnets in childhood led to a lifelong pairing between graphemes and synesthetic colors. However, we do not claim that the refrigerator magnets caused AED’s synesthesia, only that they shaped its manifestation. There are many reasons to think that synesthesia does not require refrigerator magnets or the like. For example, studies of synesthetes and their relatives have suggested that synesthesia is heritable with women much more likely to be synesthetic than men (Baron-Cohen et al., 1996). Thus while it may not be the case that all synesthetes, or even the subset with the same type of synesthesia as AED have learned their particular inducer-concurrent pairings, it may be that for those who will become synesthetes, there exists a sensitivity to certain kinds of input (in this case colored letters) that can result in this kind of learning. This adds to a growing body of evidence that experience can play a role in determining inducer-concurrent pairings (Ward and Simner, 2003; Mills et al., 2002).

The fact that AED's synesthesia was learned from a magnet set does not mean that one can dismiss it as an ordinary high level memory association. In fact, the lightness constancy experiments make a strong case that AED's synesthesia is available to early visual processes which are considered encapsulated with respect to associative memory. In short, this study highlights the fact that a learning account of synesthesia can be consistent with an early processing account. These results are quite surprising because they imply that synesthetic color is not added to the end-product of visual form recognition. Rather the color seems to be added to the processing stream such that it becomes part of the stimulus subject to further visual processing. Whether this finding generalizes to other synesthetes is of course an important question. Our results suggest that careful case studies can point to surprisingly tight connections among synesthetes. For example, the fact that AED's synesthesia generalized to Cyrillic through visual similarity where possible and phonetic similarity secondarily is in perfect agreement with the case reported by Mills et al. (2002), and the reduction in saturation with lowercase letters and non-prototypical fonts is in agreement with the claims of Ramachandran and Hubbard (2003b).

One way to interpret AED's inducer-concurrent relation is using the model for color-grapheme synesthesia put forward by Rich and Mattingley (2002). It proposes based on work in neuroscience, separate processing hierarchies for form and color. Synesthesia happens because functional connections are formed between different levels of representation in the two pathways. The lightness constancy results, the specificity of the hue, the subtle effects on saturation and AED's report that the colors appear on surfaces in the world, all suggest that functional connections are made from the form pathway to somewhere early in the color processing stream, prior to abstract categorical representations. The level and content of the representation of the inducer is less clear, though we have enumerated several possibilities in our discussion of the results. However, the usefulness of precise color matching should be clear. Future studies using these methods may provide a way of generating a useful taxonomy of color grapheme synesthetes, based on information about the inducer and concurrent gleaned from careful analysis of the matching data.

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