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Is “Σ” purple or green? Bistable grapheme-color synesthesia induced by ambiguous characters

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ABSTRACT

People with grapheme-color synesthesia perceive specific colors when viewing different letters or numbers. Previous studies have suggested that synesthetic color experience can be bistable when induced by an ambiguous character. However, the exact relationship between processes underlying the identity of an alphanumeric character and the experience of the induced synesthetic color has not been examined. In the present study, we explored this by focusing on the temporal relation of inducer identification and color emergence using inducers whose identity could be rendered ambiguous upon rotation of the characters. Specifically, achromatic alphabetic letters (W/M) and digits (6/9) were presented at varying angles to 9 grapheme-color synesthetes. Results showed that grapheme identification and synesthetically perceived grapheme color covary with the orientation of the test stimulus and that synesthetes were slower naming the experienced color than identifying the character, particularly at intermediate angles where ambiguity was greatest.

1. Introduction

Synesthesia is the condition where a stimulus in one sensory modality induces perceptual experience not only in the relevant sensory modality but also in another, usually irrelevant modality (Cytowic & Eagleman, 2009). Synesthesia can involve cross-modal associations such as vision-induced auditory experiences and taste-induced tactile experiences (Cytowic, 1989). Other cases of synesthesia involve intra-modal associations such as grapheme-color synesthesia, one of the most prevalent forms of synesthesia (Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2006). It is this type of synesthesia that we focus on in this paper.

People with grapheme-color synesthesia describe seeing achromatic letters and/or numerals as colored. Some people (dubbed associators) report that these illusory colors appear in their mind’s eye, whereas others (dubbed projectors) actually see the colors on the inducing characters themselves (Dixon, Smilek, & Merikle, 2004). Regardless of which type of grapheme-color synesthesia we’re dealing with, the associations of character and color are highly specific and enduring. Much remains to be learned about this fascinating propensity, but one thing can be said with certainty: a given color cannot be evoked without the identity of the character being established. The direction of the causal arrow is unequivocal. Note, by the way, that this conclusion does not necessarily mean that a character must be *consciously* perceived before color can emerge. Indeed, there is conflicting evidence concerning the role of awareness in grapheme-color synesthesia, with some results pointing to color induction without conscious character identification (e.g., Ramachandran & Hubbard, 2001; Smilek,

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Dixon, Cudahy, & Merikle, 2001; Smilek, Dixon, & Merikle, 2005; Wagar, Dixon, Smilek, & Cudahy, 2002; but see also Hubbard, Arman, Ramachandran, & Boynton, 2005) and other results implying that synesthetic color is available *after* the inducing stimulus is consciously identified (Mattingley, Rich, Yelland, & Bradshaw, 2001; Rich & Mattingley, 2010). In the study described in this paper we have not attempted to resolve this issue but, instead, have sought to answer a related question about the emergence of synesthetic color under conditions where the identity of the inducing character is ambiguous and, therefore, requires additional time to be identified. Stimulus ambiguity, in general, provides a useful tool for studying fluctuations in perception despite unchanging physical stimulation (Kim & Blake, 2005).

There are situations where a given inducing character can take on one of several different identities. Consider, for example, the two character sequences in Fig. 1A, where the middle character in both sequences is physically identical but semantically different owing to the context in which it appears. When synesthetes view character sequences like this, the reported color of the ambiguous character corresponds to the type of character – letter vs numeral – implied by the sequence (Dixon, Smilek, Duffy, Zanna, & Merikle, 2006). Likewise, when a large character is produced by appropriate arrangement of small characters different from the global shape they form (Fig. 1B), synesthetes experience either of two colors dependent on whether their attention is focused at the local or the global level of representation (Palmeri, Blake, Marois, Flanery, & Whetsell, 2002). Recently, Bridgeman, Winter, and Tseng (2010) described another instance where synesthetic color experience evoked by ambiguous inducing characters is ambiguous. They had synesthetic observers view alphabetic letters that continuously rotated in a clockwise direction, and the observers were instructed to verbalize the color they were experiencing throughout the presentation, being sure to report if one color replaced another. At the end of each rotation presentation, the synesthetes were required to remember and report the orientation of the letter at the time the color switched, if it did. Bridgeman et al. found that synesthetic colors tended to change.

The results of Bridgeman et al. fit nicely with the earlier studies using ambiguous inducing characters, but they do not tell us anything about the time course of this change in character and color identification with orientation, information that could be potentially revealing with respect to processes underlying grapheme-color synesthesia. Accordingly, we performed a different version of the letter rotation experiment that allowed us to assess psychometric performance together with reaction time performance. In our study, we took advantage of particular pairs of synesthesia-inducing characters that could be

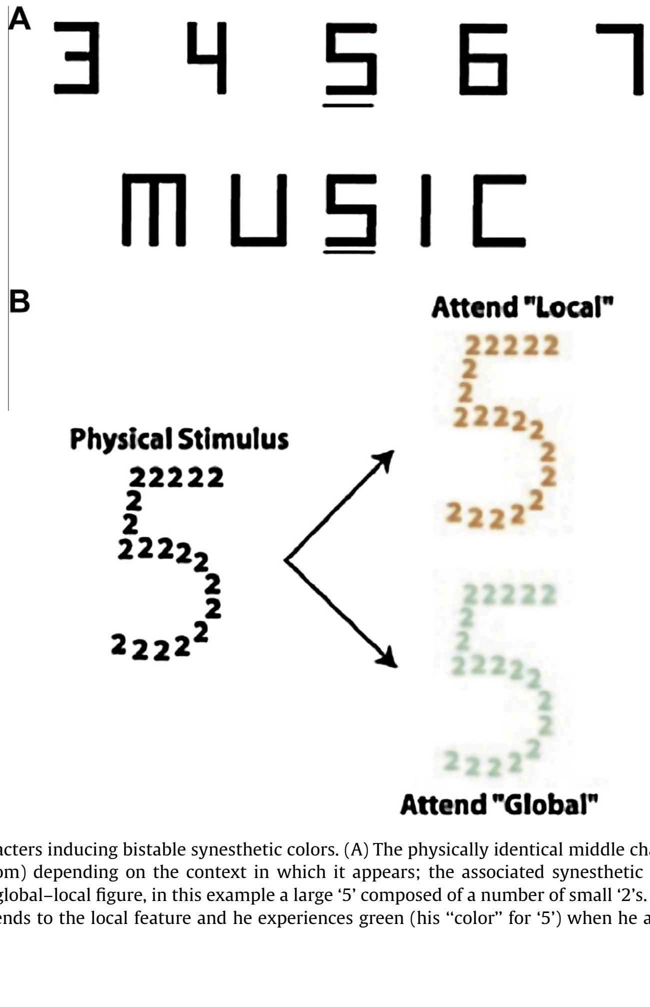

Fig. 1. Examples of ambiguous characters inducing bistable synesthetic colors. (A) The physically identical middle character can be identified either as the digit '5' (top) or the letter 'S' (bottom) depending on the context in which it appears; the associated synesthetic color varies depending on the letter perceived (Myles et al., 2003). (B) A global–local figure, in this example a large '5' composed of a number of small '2's. Synesthete WO experiences orangish red (his "color" for '2') when he attends to the local feature and he experiences green (his "color" for '5') when he attends to the global shape.

recognized as either of two letters or two numbers when rotated through 180 degrees. For example, the Roman alphabetic letter "M" becomes "W" when turned upside down and, similarly, the digit 9 becomes 6. When those particular characters assume intermediate degrees of rotation, their identities become ambiguous; befitting their ambiguous status, people report sometimes seeing a given, rotated character as M (or 6) and other times as W (or 9). Using such character pairs in a speeded judgment task, we measured response times (RTs) for identifying a character and for identifying its (synesthetic) color. We tested a group of four grapheme-color synesthetes whose native language is English (the "US group") and a group of five bilingual grapheme-color synesthetes who learned English as young children (the "Korean group"). We reasoned that both groups would have had equivalent years of experience with digits (the Korean number system being identical to the US) but somewhat different total experience with Roman alphabetic characters (since English was their second language, and the vast majority of their reading throughout their lives was in Korean). The Korean synesthetes, not surprisingly, also experience grapheme-color synesthesia when viewing Korean characters. But we wish to stress that they characterize their synesthetic photisms for Roman alphabetic characters as being as vivid and unchanging as the photisms experienced when viewing Korean characters.

2. Material and methods

2.1. Participants

Nine grapheme-color synesthetes participated in the Experiment. Four of them (2 females; mean age = 32.75 years, range: 20–65) were native English speakers and they were recruited and tested at Vanderbilt University. All four were 'projectors', meaning that they "see" their synesthetic colors located in visual space on the alphanumeric characters themselves (Dixon et al., 2004). The other five (all female; mean age = 23.2 years, range: 20–28) were native Korean speakers having about 10 years of experience learning English and they were recruited and tested at Korea University. All five of them reported their synesthetic colors to appear in their mind's eye and, therefore, were classified as associators (Dixon et al., 2004). All nine participants had normal or corrected-to-normal visual acuity. Prior to the experiment, they gave written informed consent approved by Vanderbilt University Institutional Review Board (4 US synesthetes) or by Korea University Institutional Review Board (5 Korean synesthetes).

2.2. Apparatus

For both the Korea University and Vanderbilt University experiments, stimuli were presented on a 17-inch CRT monitor (1024×768 resolution, 60-Hz frame rate) under the control of an Intel PC using Matlab 7.0.4 (MathWorks, Co.) and Psychophysics Toolbox 2.54 (Brainard, 1997; Pelli, 1997). Testing was done in a quiet, dark room in which the video monitor provided the only source of illumination.

2.3. Stimulus and task conditions

Two pairs of graphemes – W/M and 6/9 – were used as stimuli. Printed in Skia font, the upside down and right-side up versions of the members of a pair were identical, and when shown at intermediate orientations at and around 90 deg the character was ambiguous (Fig. 2A and B). Participants confirmed that both members of both stimulus pairs induced comparably vivid synesthetic colors (Fig. 2C). For all observers except two, the synesthetic colors of the two members of a pair were distinctly different; L.R. (a member of the US group) experiences 6 and 9 as subtly different shades of purple and S.Y. (a member of the Korean group) experiences W and M as subtly different shades of blue.

On each trial, a member of a given stimulus pair was presented in one of seven orientations (0, 30, 60, 90, 120, 150 or 180 angular degrees, where 0 refers to the upright position for a given character); when appearing in its non-canonical orientation, the direction of its rotated orientation could be in either the clockwise (CW) or the counterclockwise (CCW) direction. Each stimulus subtended 5.13×5.35 degree of visual angle and was shown in white against a dark background, yielding a contrast close to 100%.

The two stimulus conditions – alphabetic letters (W/M) and digits (6/9) – were presented in separate blocks. For both the digit condition and the letter condition, the two task conditions were administered in separate blocks of trials, one devoted to character identification and the other to perceived synethetic color. In the character identification task, participants indicated the perceived identity of the stimulus (e.g., "W or M") by pressing one of two pre-designated keyboard keys, and in the synesthetic color task they indicated the perceived "color" of the stimulus (e.g., "purple or green") again by pressing one of two keys.

The experiment included a total of 6 blocks (3 stimulus conditions $\times$ 2 task conditions), and each block contained 280 trials (7 orientation values $\times$ 2 directions $\times$ 20 repetitions). Four US synesthetes were tested with the alphabetic letters, but only three were tested on the digit task and one of those participants (L.R.) had to be dropped from that condition because she perceived the 6 and the 9 as highly similar in color. All five Korean synesthetes were tested with the digits, but only four were tested on the letter task and one of those participants (S.Y.) had to be dropped from that condition because she

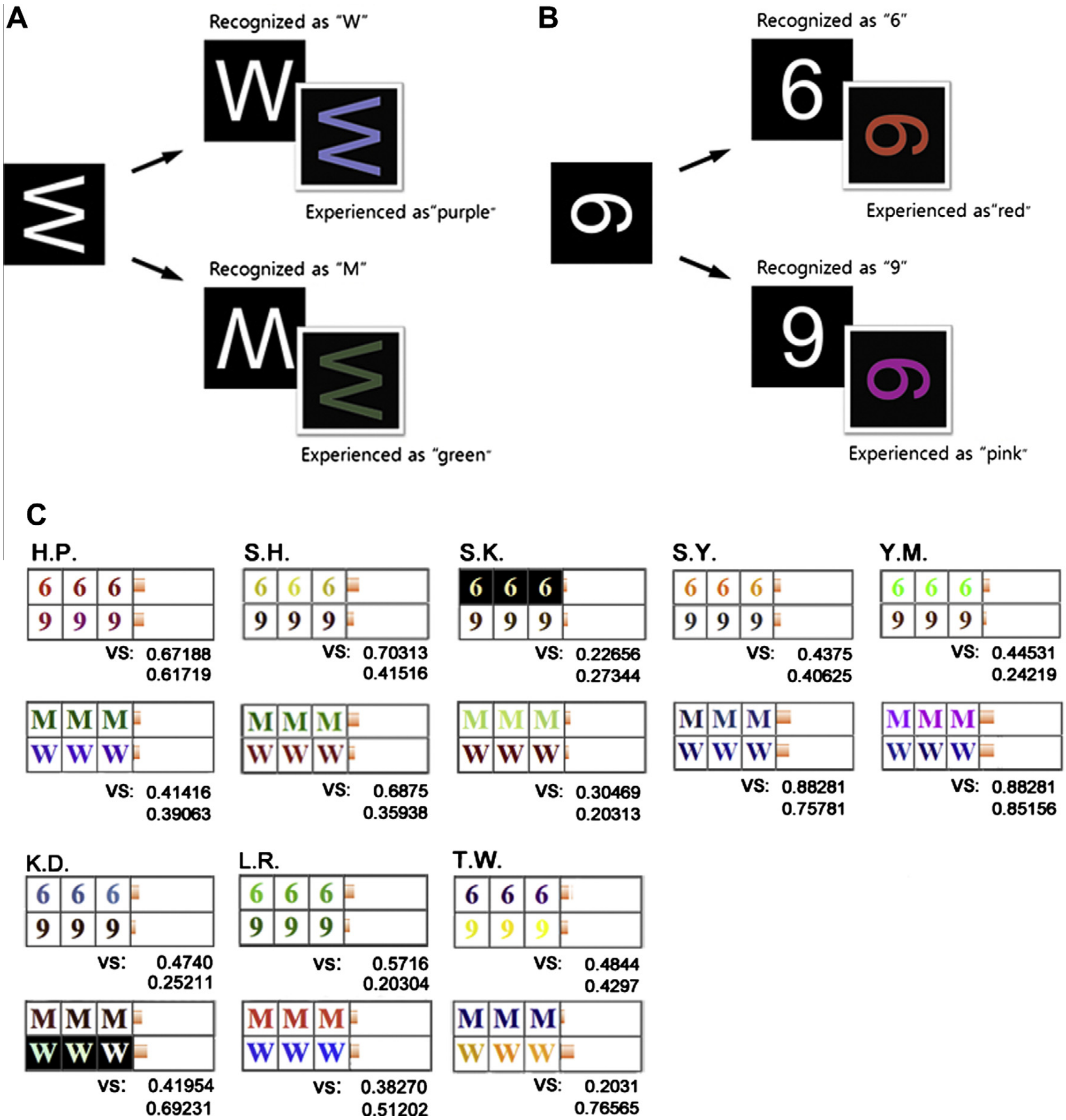

Fig. 2. Examples from the two stimulus conditions and the color matching results from the synesthetes tested. (A) An alphabet letter can be recognized either as "W" or as "M" when shown at intermediate orientations at and around 90 deg. Synesthetic color experience will change accordingly; the letter can be experienced either as "purple" or as "green" (Based on HP's color matching results, see figure C). (B) A digit can be recognized either as "6" or as "9" when shown at intermediate orientations at and around 90 deg. Synesthetic color experience will change accordingly; the digit can be experienced either as "red" or as "pink". (Based on HP's color matching results, see figure C). (C) Color matching results for W, M, 6, and 9 from eight of nine synesthetes in our two groups; one synesthete - WO - was not tested with this color-matching procedure. Matched colors from three repeated trials for each of the four chracters are shown. The variability of those three color matches for each character is expressed numerically by the VS index values and by the small, orange horizontal bars appearing at the right-hand side of each row of character color matches; those values were obtained using a standardized, web-based synesthesia test (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007).

perceived the W and the M as highly similar in color. The order of the blocks was counterbalanced among participants, and the order of the trials within a block was unpredictable within the limits of the MATLAB randomization routine.

2.4. Procedure

Fig. 3 shows the sequence of an example trial. A trial began with a white stimulus presented on the exact center of the black background for 100 msec. A white square-shaped border (6.89 $\times$ 6.89 degrees in visual angle) was presented to indicate the location of the stimulus. In each trial, the target was presented at one of the seven orientations in either of the two possible directions. A pattern mask appeared immediately following the stimulus and remained present until the observer responded. Observers were urged to respond as quickly as possible.

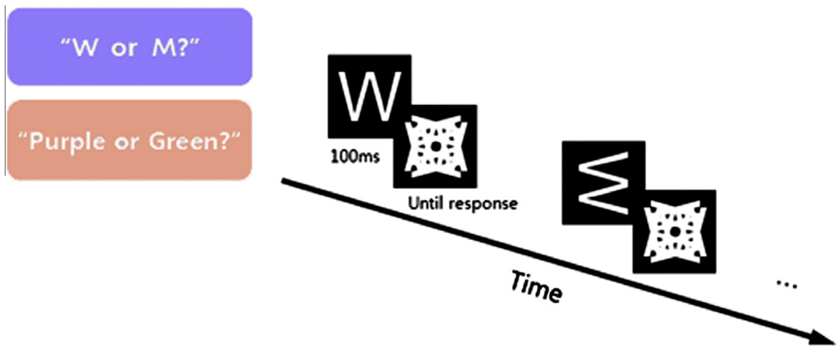

Fig. 3. Experimental Procedure. Stimuli were presented for 100 msec and then masked until a response was made by the observer. The angular orientation of the inducer characters varied randomly over trials, with orientation ranging from 0 to 180 degrees in 30 degree steps. In separate blocks of trials observers performed a character identification task and synesthetic color identification task.

2.5. Data analysis

To examine the difference between task (character and synesthetic color) conditions, we performed psychometric curve fitting and RT analyses. Accuracy could only be assessed on trials where the characters were at or very near their cardinal orientations; when characters appeared at intermediate orientations, there was no explicitly correct answer because the character's identity and, by inference, its perceived "color" were ambiguous. Both character and synesthetic color psychometric curves in the digit and letter conditions were generated by psignifit toolbox version 2.5.6 with Matlab (http://bootstrap-software.org/psignifit/), implementing the maximum-likelihood method (Wichmann & Hill, 2001a). Each curve was fitted by a general psychometric function: $\Psi(x;\alpha,\beta,\gamma,\lambda) = \gamma + (1 - \gamma - \lambda) F(x; \alpha,\beta)$ where F was Cumulative Gaussian function. Four parameters (α, β, γ,λ) were estimated from the simulations. Confidence intervals spanned .05 to .95 based on 4999 simulations (Wichmann & Hill, 2001b).

Mean RTs were also computed to compare the perceptual latency between the character and color task conditions. Outliers were eliminated based on ±3 standard deviation cutoff.

3. Results

Fig. 4 shows the proportion of trials on which given character identification and synesthetic color responses were made to digits (Fig. 4A) and to letters (Fig. 4B) whose orientations varied over trials. Combined results (the panel labeled Total) are shown together with results categorized by the observers' nationality. All synesthetes in both groups tested on these conditions showed the expected dependence of character identification on the orientation of the stimulus: at and very near the cardinal orientations, character identity was corresponded to the expected character (e.g., "9" was always identified as "9"), but at intermediate orientations centered around 90 deg identification of character and of color varied over trials (e.g., "Σ" was sometimes reported as W and other times as M). We found no evidence for a shift in the "color" psychometric curve relative to the character psychometric curve. Just to reiterate a point made earlier, the character identification judgments and the "color" judgments were made on separate trials administered in separate blocks; the design of our task did not permit collecting "color" and character identification RTs on the same trial.

This equivalence in the patterns of results for character identification and synesthetic color is gratifying but not surprising, and it dovetails with earlier findings that the particular color experienced during grapheme-color synesthesia depends on how a given stimulus is perceptually organized (Bridgeman et al., 2010; Myles, Dixon, Smilek, & Merikle, 2003; Palmeri et al., 2002). Of more significance are the RT results obtained on these tasks.

Considering first the results from the digit condition, Fig. 5 plots the RTs for the digit identification task and the "color" judgment task as a function of stimulus orientation (with angular deviation expressed relative to "6"). The blue lines plot RTs for the character task and the red lines plot RTs for the "color" task; the shaded regions demarcate ±1 standard error of the mean. The seven small panels with initials above them show results for each individual, the two intermediate sized panels show results for the US participants and the Korean participants, and the large panel shows the average across all participants.

One clearly sees that RTs for the digit condition tend to be longer at and near 90 deg orientation, which makes sense because the stimuli were more ambiguous and, presumably, the task more difficult at these intermediate orientations. One could construe these curves as evidence for the involvement of mental rotation of the sort documented by Shepard and Metzler (1971), although there was nothing in the task instructions in our study implying that this was the strategy to be adopted.

Of particular relevance to the question motivating our study are the consistently faster RTs for character identification compared to "color" identification. A 2-way repeated measures ANOVA was performed across all seven participants (2 US

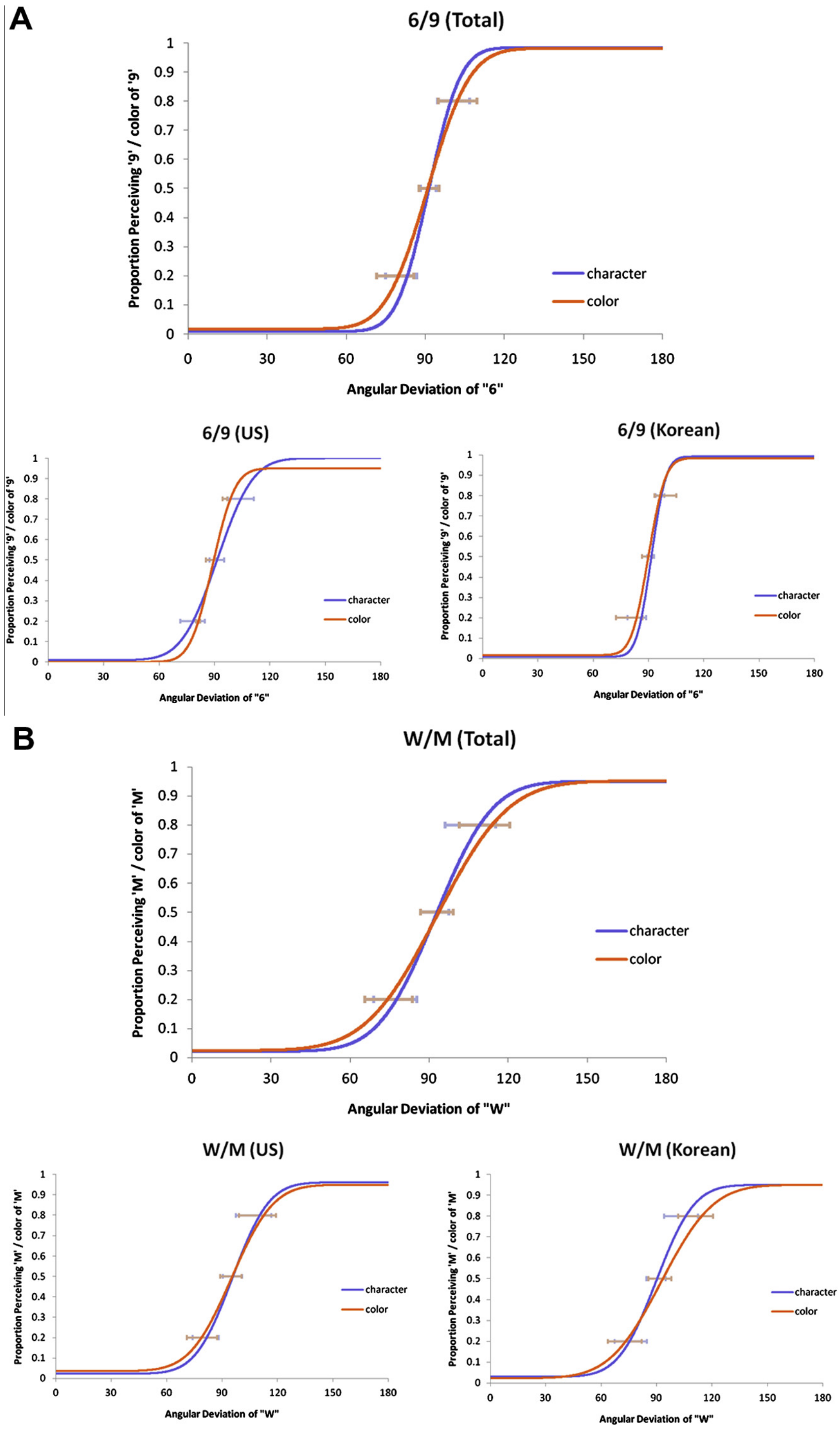

Fig. 4. Proportion of trials on which given character identification and color responses were made. (A) Fitted psychometric functions show the averaged total result (upper), averaged results from the two sub-groups of synesthetes (the US (lower left) and the Korean (lower right)). The proportion of perceiving "9" (blue; character task) and the idiosyncratic "color" of "9" (red; synesthetic color task) are plotted against degree of angular deviation from "6" (and the "color" of 6). (B) Fitted psychometric functions show the averaged total result (upper), averaged results from the two sub-groups of synesthetes (the US (lower left) and the Korean (lower right)). The proportion of perceiving "M" (blue; character task) and the idiosyncratic "color" of "M" (red; synesthetic color task) are plotted against degree of angular deviation from "W".

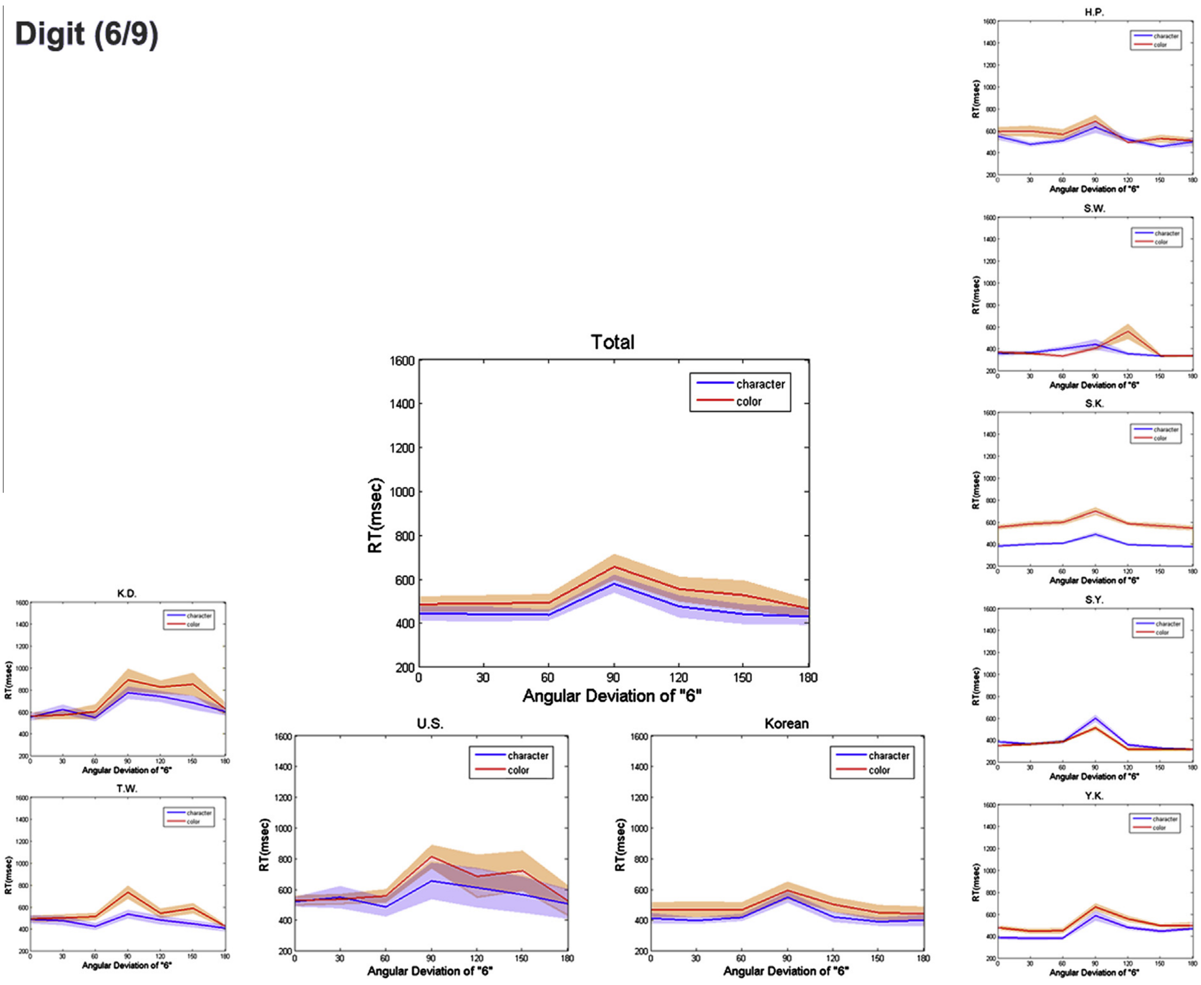

Fig. 5. RT results from the digit (6/9) condition; the averaged total (upper center), averages of the two sub-groups of synesthetes (lower center; the US (left) and the Korean (right)), and individual results. The RTs in the character task (blue line) and in the synesthetic color task (red line) are plotted against degree of angular deviation from "6". Shaded areas denote ± 1 standard error of the mean (blue: character task, red: synesthetic color task).

and 5 Korean) in which task and orientation were within-factor variables. The main effects of task and orientation were both significant statistically ($F(1, 6) = 6.879$, $p < 0.05$; $F(6, 36) = 11.097$, $p < 0.0001$). There was no statistically significant interaction between task and orientation ($F(6, 36) = 1.345$, $p = 0.2331$). These findings clearly imply that digits are being identified more quickly than their synesthetic colors are being identified.

Results from the letter condition are shown in Fig. 6, using the same format as panels in Fig. 5. Again we find the tendency for RTs to vary with character orientation, being slower at orientations where the letter's identity is most ambiguous. Moreover, we again see a consistent trend for the character identity RTs to be faster than the "color" identity RTs. These impressions are borne out by the repeated measures 2-way ANOVA performed on these data. As in the digit RT analysis, task and orientation were within-factor variables. The main effects of task and orientation were both significant statistically ($F(1, 7) = 6.591$, $p < 0.05$; $F(6, 42) = 10.918$, $p < 0.0001$), and in this condition the interaction between task and orientation was also marginally significant ($F(6, 42) = 2.018$, $p = 0.0599$). So, again, we are finding that an inducer (a letter in this case) is identified faster than its associated color.

One intriguing observation that deserves comment is revealed when we compare the average RTs for the Korean synesthetes on the two conditions: they are slower in their responses on the letter condition (W vs M) compared to the digit condition (6 vs 9). No such tendency is seen in the RT results for the US participants. Why might this be? Perhaps it is related to the Koreans' differential exposure to digits and Roman letters; they encountered digits very early in and very often throughout their lives, but their exposure to Roman characters did not start until just before adolescence and continues to be less frequent than their exposure to Korean characters. Nonetheless, it is noteworthy that their RTs to the synesthetic colors experienced when viewing these Roman characters are still slower, on average, than their RTs to identifying those characters.

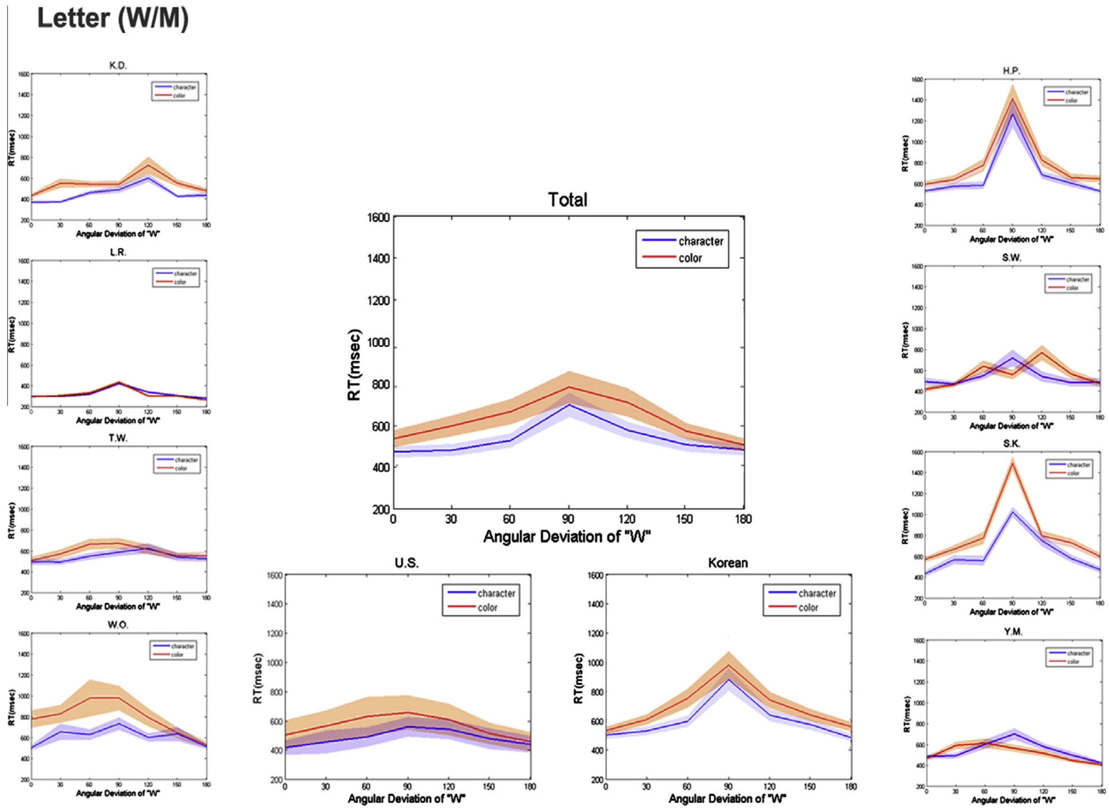

Fig. 6. RT results from the letter (W/M) condition; the averaged total (upper center), averages of the two sub-groups of synesthetes (lower center; from the US (left) and the Korean (right)), and individual results. The RTs in the character task (blue line) and in the synesthetic color task (red line) are plotted against degree of angular deviation from "W". Shaded areas denote ±1 standard error of the mean (blue: character task, red: synesthetic color task).

4. Discussion

Using inducing characters whose identity varies with orientation, we have found that grapheme identification and synesthetically perceived grapheme color covary with the orientation of the test stimulus. In our study, we did not collect identification and "color" responses on the same trial. Consequently, we cannot state for certain whether the covariation in those two performance measures seen in the psychometric curves occurs on an individual, trial by trial basis. We are gratified, however, by the nearly complete overlap of the two classes of psychometric curves.

Using rather different techniques, Bridgeman et al. (2010) also found that synethetic color depended on character orientation. On each trial they presented a single alphabetic letter that rotated in clockwise direction and instructed their synesthetic participants "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 (p. 672)". We, on the other hand, used a speeded forced-choice judgment task to assess character identification and perception of synesthetic color. Results from this objective task confirmed the phenomenological reports obtained by Bridgeman et al. and, furthermore, disclosed that "color" judgments take longer than do character identification judgments. In the following paragraphs we consider several possible implications of these RT differences.

To what can we attribute the difference in processing time between character and synesthetic color identification? One popular account of grapheme-color synesthesia posits that synesthetes have unusually dense fiber connections between the visual word-form area and color selective area within the temporal lobe/ventral stream pathway (e.g., Baron-Cohen, Harrison, Goldstein, & Wyke, 1993), a prediction that was subsequently verified using brain imaging techniques (Rouw & Scholte, 2007). There are other variants of this kind of model that emphasize long-range disinhibition (Grossenbacher & Lovelace, 2001) or aberrant re-entrant processing (Smilek et al., 2001) that amplifies feedback signals from high-tiered cortical areas to color processing areas. On all versions of this model, the signals innervating color-selective visual areas arise in those areas later in time relative to the signals originating within visual areas registering information about the inducers. It stands to reason, then, that perceptual judgments about synesthetic color could lag judgments about inducer identity. It is arguable however, whether this model would predict a difference in processing time of almost 1/10th a second for character vs "color" identification, yet that is the RT difference value we calculated from the RT data pooled across digit and letter conditions.

Another, altogether different account of synesthesia questions whether grapheme-color synesthesia is perceptual in nature in the first place (Gheri, Chopping, & Morgan, 2008). Perhaps, the argument goes, people describing synesthetic experiences are basing those descriptions on overlearned associations, meaning that synesthesia is cognitive, not perceptual, in origin. Our RT results with ambiguous characters could be construed as consistent with this view, with the additional time required to name a characters' synesthetic color arising from the involvement of lexical processing required to pair the appropriate color name with the character currently being viewed. We have no rejoinder to that interpretation of our results, other than an appeal to the subjective reports of our participants who denied employing such a strategy. But psychologists have long known that verbal reports are unreliable reflections of underlying mental processes, even when the person reporting has high confidence in his/her introspective awareness (e.g., Nisbett & Wilson, 1977). So for now, we shall avoid over-interpreting our results in terms of the origin(s) of the RT differences between character and "color" identification, and let the findings speak for themselves.

We want to reiterate two notable aspects of the present results for the two subject groups. As pointed out in the Methods section, all four US synesthetes were classified as projectors and all five Korean synesthetes were classified as associators. However, all members of these two groups performed comparably on both of the conditions reported in this paper. Evidently, then, the co-dependence of synesthetic color and character identification on orientation does not seem to differ between these putative categories of synesthesia. The second notable finding was the overall slower RTs in the Korean group when performing the tasks involving letters compared to performance of the digit task. This task-related difference in overall RT was not observed in the US group, leading us to speculate that this difference in the Koreans may have something to do with their more enduring, intense exposure to digits compared to Roman letters. In light of this possibility, it will be informative to utilize ambiguous Korean figures that evoke colors in our Korean subjects. One such figure that accomplishes this is the Korean word pair 문/곰 ("문" means "door and "곰" means "bear"). Note, these constitute words, not single letters, but still the logic of the task is the same as the characters we used in the present study. Our US subjects, of course, would be baffled by the task.

Finally, we want to mention some additional observations collected from some of our participants at the end of the study. For one set of observations, we had each of three participants view one of the characters on the video monitor with their heads maintained in the upright position. All three readily named the character and the color that it reliably evokes. Next we had them turn around and view the same display while bending over and looking between their legs. This maneuver, of course, inverts the image of the character on the retina, although participants readily understand that nothing has changed on the screen. All observers promptly and with confidence asserted that the color of the character had changed, befitting the new orientation of the image on their retina. This simple test suggests that the character orientations that we are talking about in this paper are registered in head-based, retinal coordinates and not environmental, gravitational-based coordinates. But confounding this conclusion is a second set of observations made by the four Korean participants. Specifically, we asked them to look at an inducer (e.g., upright 'W') on the screen, to imagine it being upside down, and to described what it's color appearance. All now reported a color associated with the inverted version of the character (e.g., 'M') they were looking at. In other words, mental rotation of an inducer that remains physically the same in the world can change the synesthetic color associated with that inducer. Interestingly, two synesthetes (S.K. and Y.K.) voluntarily reported that it takes long time with conscious mental efforts before they experience their (synesthetic) color of 'M' while viewing 'W' on the monitor screen. By showing this interplay between retinal image orientation and mental image orientation, these results pose an interesting challenge for any theory of synesthesia claiming that synesthesic colors are exclusively associated the meanings of the letters as they exist in the environment.

Acknowledgments

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