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OBSERVATION

Precision of Synesthetic Color Matching Resembles That for Recollected Colors Rather Than Physical Colors

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Grapheme-color synesthesia is an atypical condition in which individuals experience sensations of color when reading printed graphemes such as letters and digits. For some grapheme-color synesthetes, seeing a printed grapheme triggers a sensation of color, but *hearing* the name of a grapheme does not. This dissociation allowed us to compare the precision with which synesthetes are able to match their color experiences triggered by visible graphemes, with the precision of their matches for recalled colors based on the same graphemes spoken aloud. In six synesthetes, color matching for printed graphemes was equally variable relative to recalled experiences. In a control experiment, synesthetes and age-matched controls either matched the color of a circular patch while it was visible on a screen, or they judged its color from memory after it had disappeared. Both synesthetes and controls were more variable when matching from memory, and the variance of synesthetes' recalled color judgments matched that associated with their synesthetic judgments for visible graphemes in the first experiment. Results suggest that synesthetic experiences of color triggered by achromatic graphemes are analogous to recollections of color.

Keywords: synesthesia, grapheme-color synesthesia, color perception

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Grapheme-color synesthesia is an atypical condition wherein specific colors, such as red, are automatically experienced when reading achromatic text, like a black letter "A" (Galton, 1880; Mattingley, 2009). Grapheme-color synesthetes have given differing descriptions of their condition. Some describe their colored sensations as being in the mind's eye ("associators"; Dixon, Smilek, & Merikle, 2004; Edquist, Rich, Brinkman, & Mattingley, 2006), whereas others experience their colors externally, as if the achromatic graphemes or the space around them were physically colored ("projectors"; Palmeri, Blake, Marois, Flanery, & Whetsell, 2002; Ramachandran & Hubbard, 2001).

One interesting facet of grapheme-color synesthesia is that, for some synesthetes, seeing a grapheme automatically triggers a specific colored sensation, whereas *hearing* the name of the grapheme spoken aloud does not (Rich, Bradshaw, & Mattingley, 2005). Such synesthetes can recall, or perhaps mentally generate, the color they normally experience automatically when seeing a printed grapheme, but this is driven by either a recollection of color or by a qualitatively different volitional process relative to the automated process responsible for triggered synesthetic experiences. This dissociation between experiences evoked by seen and heard letters and digits presents an opportunity to examine the computational processes that underlie synesthetic colors. In normal color vision, people are more accurate when matching a color that can be *seen*, as opposed to a color they must recall (Cornelissen & Greenlee, 2000; Sachtler & Zaidi, 1992). Here, we measured the variability associated with color matches to synesthetic experiences triggered by visual graphemes and compared these with the variability associated with synesthetic color matches for aurally presented stimuli (whose colors had to be recalled or perhaps generated at will).

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Experiment 1: Precision of Color Matching for Visually and Aurally Presented Letters and Digits

To assess the precision with which synesthetes match automatically triggered versus recollected synesthetic colors, we exploited the fact that many such individuals experience a synesthetic color upon seeing an achromatic letter or digit, but report no corresponding color sensation when they hear the same stimuli spoken aloud. We can therefore use printed and spoken graphemes to compare the precision with which synesthetic colors are experienced and recalled. For both modes of presentation precision was quantified as the variance between two discrete matches for the same graphemic form.

If the processes that give rise to synesthetic colors are similar to those involved in perceiving the colors of physical objects in the world, then color matches for visible graphemes should be more precise (less variable) than color matches for spoken stimuli, whose colors are not triggered automatically but instead must be recalled or generated at will. By contrast, if the processes responsible for synesthetic colors are more like those underlying mental images or associations, automatically triggered color sensations should be matched with approximately equal precision to those that are recalled.

Method

Stimuli were generated using a ViSaGe stimulus generator (Cambridge Research Systems) and displayed on a gamma corrected 19" Sony Trinitron Multiscan G420 monitor (resolution 1024 × 768 pixels, refresh rate 120 Hz). The viewing distance was 43 cm, controlled using a chin rest.

Participants consisted of six synesthetes, 1 man and 5 women, aged 20 to 53 years, with a mean age of 28 years. All synesthetes were self-described "associators," meaning that they experience synesthetic colors externally (i.e., "in the mind's eye) and reported experiencing synesthetic colors for printed, but not spoken, graphemes (see Erskine, Mattingley, & Arnold, 2012; Mattingley, 2009). Three of the six synesthetes were siblings. Although the sample was relatively small compared with conventional studies of normal cognition, it was comparable to that in other studies of synesthesia, many of which have involved single-cases (see Cohen Kadosh, Cohen Kadosh, & Henik, 2007; Dixon, Smilek, Cudahy, & Merikle, 2000; Palmeri et al., 2002). Moreover, the homogeneity of the sample, in terms of subjective experiences of synesthesia, suggests qualitative individual variability should have been minimal. All participants were naïve as to the purpose of the experiment.

Prior to testing, participants completed the online Synesthesia Battery (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007; see: http://synesthete.org). The online Synesthesia Battery consists of a number of standardized tests that can be used to differentiate people with synesthesia from those who are trying to mimic the condition. All synesthetes in our study obtained a score below 1 on the Color Picker subtest and an accuracy of above 85% coupled with an average reaction time (RT) of less than 3 s on the Speed-Congruency subtest. These levels of performance are considered diagnostic of grapheme-color synesthesia (Eagleman et al., 2007).

There were two types of trial, visual and auditory. In both cases participants had to manipulate an adjustable color patch until they felt its color hue, saturation, and brightness matched their synesthetic experience. Online manipulations of the color patch were based on the Hue, Saturation, and Lightness (HSL) model of color space (Joblove & Greenberg, 1978), wherein color hue is represented as an angle and color saturation varies between 0 (*gray*) and 1 (*fully saturated*). Participants manipulated the hue and saturation of the color patch by moving a mouse. Luminance was increased by holding down the right mouse button and decreased by holding down the left mouse button. When participants were happy with a match, they held down both mouse buttons to terminate the trial.

The adjustable color patch was presented on the right of the testing monitor and subtended 7.3 degrees of visual angle at the retina (dva). The color patch was bordered by a ring of 8 colored arcs, which subtended 0.5dva in width (Figure 1). The colored arcs indicated the color change that would be caused by moving the mouse in a particular direction. Arc colors corresponded with HSL directions of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°, corresponding approximately with magenta, pink, violet, blue, cyan, green, yellow, and orange. In each case, the arc color was presented at the maximum luminance obtainable for that color on the display monitor. Arc positions were randomized on a trial-by-trial basis, by setting Magenta (0° in HSL color space) to 0°, 90°, 180°, or 270° in Cartesian space on the monitor. This prevented participants from moving a mouse to a remembered position whenever they saw a particular grapheme.

On visual trials, black graphemes were presented centered against a white rectangle (width = 8.4 dva, height = 13dva) on the left of the testing monitor (Figure 1a–b). Graphemes consisted of capital letters (A–Z) or numbers (1–9) written in an Arial font, and they subtended 4.6 dva in height. On audio trials, the participant heard a recording of the third author, an English/Australian female, pronouncing the name of a grapheme via headphones (see supplementary material for sample recordings).

On each trial within a block synesthetes were first asked to indicate whether the grapheme had triggered a synesthetic color (visual trials) or whether it would have triggered a synesthetic experience if they had seen it, as opposed to hearing its name (audio trials). In either case, if the answer was "yes" they manipulated the appearance of the color patch until they felt it matched their evoked or recalled synesthetic experience. At the start of each trial, the color patch was gray. Color matches were terminated by simultaneously pressing both mouse buttons. If the grapheme did not trigger a synesthetic experience, or if it was not associated with

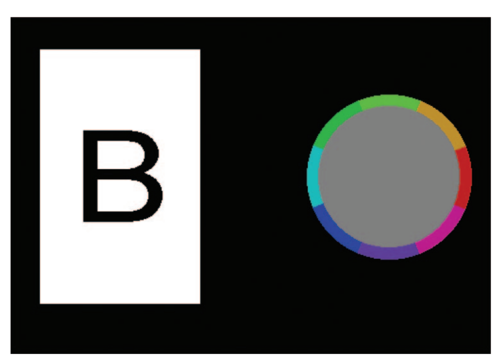

Figure 1. Depiction of the display for a visual grapheme presentation in Experiment 1.

a color, the participant was instructed to inform the experimenter and to terminate the trial without adjusting the color patch.

A block of trials consisted of 70 visual trials and 70 audio trials. These encompassed 2 presentations of each letter (A–Z) and number (1–9) for each presentation type, 140 trials in all completed in random order. The repetition of each grapheme, for each presentation type, allowed us to examine the variance between two matches for each grapheme for each modality of presentation.

At the conclusion of each trial, the CIE coordinates of the color match were recorded. These translate color hue and saturation into Cartesian (x, y) coordinates on a 2-dimensional surface, and provide a third value (Y) that reflects luminance. The variance between the two color matches for each grapheme, for each type of presentation, was given by the euclidean distance between two sets of Cartesian xy coordinates. The variance in luminance was given by the rectified difference in luminance settings. Note that any color matched to a luminance of less than 5cd/m^2 resulted in all color matches for that grapheme (in both experimental conditions) being excluded from analysis. We adopted this criterion for screening responses because such low luminance values result in colors that are very dark and can thus result in highly variable chromatic coordinate settings.

A block of trials provided up to 35 estimates of the variance between discrete pairs of color hue and saturation matches for each modality of presentation, and up to 35 estimates of the variance between discrete pairs of luminance matches for each modality of presentation (Figure 2). Individual variance estimates for each modality of presentation were determined by averaging across these values.

Results

We calculated difference scores between individual estimates of the variance between discrete color matches for visual trials (automatically triggered synesthetic colors) and for audio trials (recalled synesthetic experiences). If matches on visual trials were more precise difference scores would be positive; by contrast, if matches on audio trials were more precise difference scores would be negative. As can be seen in Figure 3, variance in both color (paired $t_5 = 0.57$, $p = .59$) and luminance (paired $t_5 = 1.56$, $p = .18$) was not significantly different across visual and audio trials (Figure 3).

Discussion

Experiment 1 revealed that there was no difference between the precision with which participants matched the color and luminance of automatically triggered synesthetic colors, and the precision with which they could recall synesthetic colors upon hearing spoken stimuli. This is consistent with the hypothesis that automatically triggered synesthetic experiences are generated in an analogous manner to recollections of color. Another possibility, however, is that the experimental apparatus and protocol used in Experiment 1 were insensitive to any subtle increase in variance that one might expect of matches to recollected colors, as opposed to physical colors that can be seen (see Cornelissen & Greenlee, 2000; Sachtler & Zaidi, 1992).

Experiment 2: Precision of Color Matching for Seen and Recalled Colors

Experiment 2 was conducted to assess the sensitivity of our experimental apparatus and protocol to any subtle increase in variance when matching to recollections of color, as opposed to physical colors that can be seen. This precaution was particularly important as our protocol differs substantially from previous investigations of color memory (Cornelissen & Greenlee, 2000; Sachtler & Zaidi, 1992).

To compare the precision of matching to recollected colors, as opposed to physical colors that can be seen, we measured precision when matching colored disks after they had disappeared (matching to a recollected color) and when matching a persistent colored disk that could still be seen. We expected color matching to be more variable when matching to recollected colors.

Method

Experimental details for Experiment 2 were as for Experiment 1, with the following exceptions.

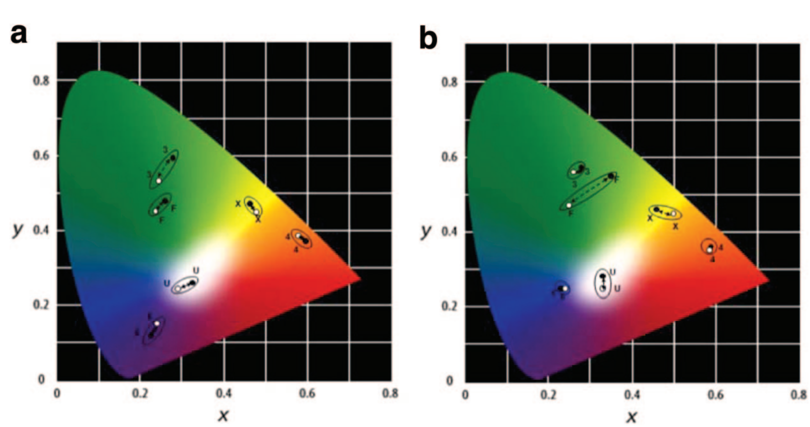

Figure 2. Depiction of the variance between discrete color hue and saturation matches for synesthetic colors either triggered by visual grapheme presentations (a), or recalled upon hearing spoken graphemes (b). Data are from a sample participant and reflect matches for 6 graphemes.

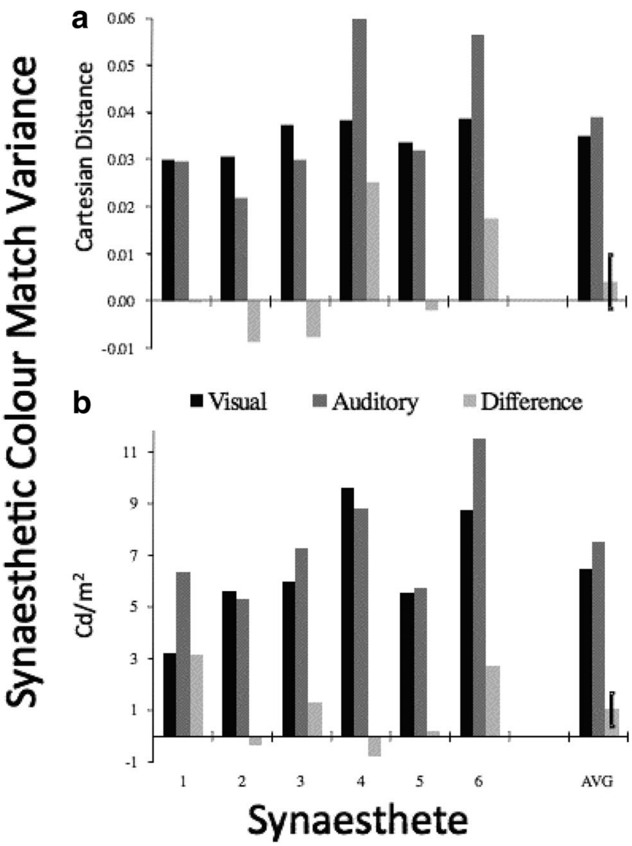

Figure 3. Variance between discrete color hue and saturation (a) and between discrete luminance matches (b) to synesthetic colors triggered by visual grapheme presentations, or recalled from spoken presentations. Differences in the variance for triggered and recalled synesthetic matches are also shown. Error bars show +/− 1 *SEM.*

In addition to the six synesthetes who had participated in Experiment 1, we recruited six volunteer control participants (1 man and 5 women, ages ranging from 20–53 years, with a mean age of 28 years), who were matched with individual synesthetes on the basis of age and gender.

There were two types of trial: "seen" and "recalled." In both types of trial, participants had to manipulate an adjustable color patch until they felt its color hue, saturation, and brightness were matched to that of a circular test stimulus that remained visible on the display (seen trials), or that had been displayed and removed (recalled trials). Viewing was free, so in seen trials participants could repeatedly look back and forth between the adjustable color patch and the test stimulus, thereby minimizing the impact of memory relative to recalled trials, where matching only commenced after test stimulus offset and was consequently entirely dependent on memory for color.

Details concerning the adjustable color patch were as described for Experiment 1. The circular test stimulus subtended 7.3 dva in diameter and was positioned in the center of the display screen (Figure 4). Its color hue, saturation and luminance were set to one of 16 unique combinations, corresponding to color directions of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° in HSL color space, all presented at the maximum possible saturation and at either 25% or 75% of the luminance intensity that the monitor could produce for that color hue and saturation.

On seen trials, the test stimulus and adjustable color patch appeared together at the beginning of the trial and persisted until the participant terminated the trial by pressing both mouse buttons to indicate that the appearance of the color patch was matched to that of the test stimulus. On recalled trials the test stimulus appeared alone in the center of the display for 5 s followed by a 500-ms interstimulus interval, during which the screen was black, until the adjustable color patch appeared. Participants then manipulated the color patch until they felt that it matched the test stimulus they had just seen.

A run of trials consisted of each of the 16 unique combinations of test stimulus color hue, saturation and luminance presented once for each modality of presentation, 32 trials in all completed in random order. As in Experiment 1, at the conclusion of each trial the CIE coordinates of the color match were recorded, and these were compared with the actual coordinates of the test stimulus on that trial. We determined the distance between the two sets of Cartesian *x y* points, for the actual test colors and matched colors. Similarly, the variance in luminance was given by the rectified difference in actual and matched luminance values.

Results

For each participant we determined the average of the color and luminance variance estimates for seen and recalled trials. As depicted in Figure 5a, a repeated-measures analysis of variance (ANOVA) on data for color variance revealed significant main effects for both group (synesthetes vs. controls), $F(1, 10) = 21.3$, $p = .001$, and experimental condition (seen vs. recalled color), $F(1, 10) = 22.9$, $p = .001$. These data show that synesthetes were more precise than controls in matching the color hue and saturation of test stimuli, and that both synesthetes and matched controls were less precise when matching color from memory, as opposed to a stimulus that could still be seen. There was no interaction between group and condition, $F(1, 10) = 1.37$, $p = .27$, indicating that the advantage for matching seen versus recalled colors was equivalent for synesthetes and controls.

As depicted in Figure 5b, a repeated-measures ANOVA for luminance data revealed a qualitatively similar pattern of results to those obtained in color matching. There was a marginally significant main effect for group, $F(1, 10) = 4.82$, $p = .053$, and a robust

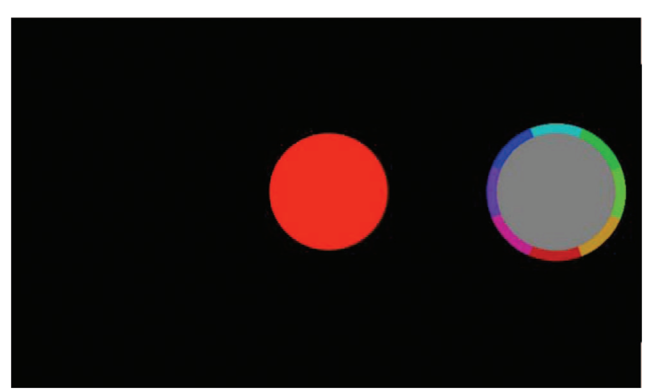

Figure 4. Depiction of the display for a seen trial in Experiment 2.

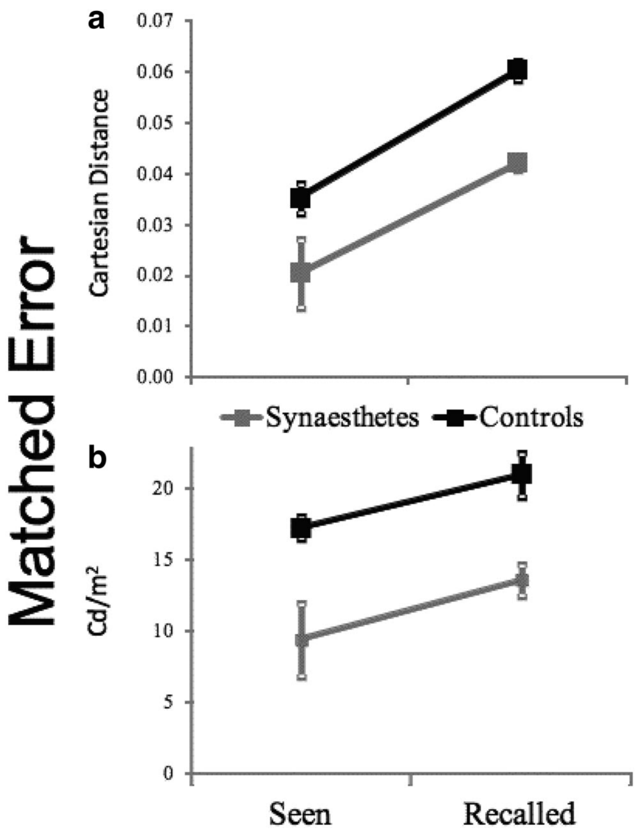

Figure 5. Discrepancy between color hue and saturation (a) and luminance (b) values matched to colored disks that could be seen or that had to be recalled.

effect of experimental condition, $F(1, 10) = 21.5$, $p = .001$. These results suggest that synesthetes were more precise than controls in matching the luminance of test stimuli and that both synesthetes and controls were less precise in matching luminance for recalled versus seen trials. Again, there was no interaction between these factors, $F(1, 10) = 0.06$, $p = .82$, indicating equivalent effects of matching luminance across experimental conditions for synesthetes and controls.

The results of Experiment 2 revealed a cost in precision when synesthetes had to match the color of a physical stimulus from memory, as opposed to a physical stimulus they could see. We also compared the precision of synesthetes' matches for seen and recalled trials, with those obtained from their matches of induced synesthetic colors in Experiment 1 (compare Figures 3a and 5a). These analyses revealed that synesthetes matched physical colors that could still be seen (Experiment 2) with significantly greater precision than they matched their synesthetic colors for printed graphemes in Experiment 1 (paired $t_5 = 5.67$, $p = .002$). By contrast, there was no reliable difference between the precision of the synesthetes' matches for recalled colors and the precision of color matches made on the basis of printed graphemes (Experiment 1; paired $t_5 = 0.35$, $p = .74$).

In Experiment 2, our measure of variability was given by differences between a physical color and the participants' attempt to match that color. In Experiment 1, our measure involved two discrete matches for each grapheme in each condition. Theoretically, these varied relative to an *actual* synesthetic color. While both estimates were therefore given by differences between two sets of color coordinates, one might expect Experiment 1 to result in more variable estimates than Experiment 2. This is because in Experiment 1 participants could offset color matches in different directions relative to an actual synesthetic color on discrete trials, whereas in Experiment 2 single matches could only be offset in one direction. Assuming that the direction of errors was random from trial to trial, this predicts a proportional increase in variability of ~1.27 for Experiment 1 relative to Experiment 2 (the average distance between two points on the circumference of a circle with a radius of 1 unit, which in turn would be the average distance between synesthetic colors and individual color matches). When we applied this multiple to estimates from Experiment 2 we still found that synesthetes matched physical colors that could be seen (Experiment 2) with significantly greater precision than they matched synesthetic colors (Experiment 1; paired $t_5 = 3.47$, $p = .02$). Moreover, there was still no reliable difference between matches for recalled colors (Experiment 2) and synesthetic colors (Experiment 1; paired $t_5 = 1.57$, $p = .18$).

General Discussion

The focus of the present investigation was the nature of the computational processes responsible for synesthetic colors. Do they behave like those for physical colors that can be seen, or do they behave more like the processes enacted when recollecting color? Results suggest that, for the synesthetes who participated in this study, the processes that give rise to synesthetic colors behave more like processes for recollecting color than the computations engaged by physical colors that can be seen. This was evident as synesthetes matched automatically triggered and recalled synesthetic experiences with equal precision (Experiment 1). This was not because of the experimental protocol being insensitive to the decrement in precision when matching from memory as synesthetes (along with controls matched in terms of age and gender) were more precise when matching a physical color that could still be seen than when matching a recently seen color from memory. Moreover, the precision with which synesthetes matched synesthetic colors (Experiment 1) was equivalent to their precision when matching recalled colors (Experiment 2), but *inferior* to their precision when matching a physical color that could still be seen (Experiment 2).

We note with interest that in Experiment 2 synesthetes were better than controls at matching color hue and brightness, both when the test stimulus could be seen and when it had to be recalled. This might indicate generally heightened sensitivity to color and brightness in synesthetes, which would be broadly consistent with a previous report (Banissy, Walsh, & Ward, 2009) and with evidence of superior memory for items relating to color (Smilek, Dixon, Cudahy, & Merikle, 2002; Yaro & Ward, 2007). We cannot, however, rule against the possibility that synesthetes were simply more motivated when making these judgments. Consequently, we have placed more emphasis on how synesthete data varied, the pertinent observations being that synesthetes were worse when matching color hue and brightness from memory (Experiment 2) and that their performance when matching synesthetic colors (Experiment 1) was akin to their performance when matching color from memory (Experiment 2).

While the findings suggest that the processes responsible for synesthetic colors behave more like those involved in recollections of color, as opposed to those engaged when seeing a persistent colored input (see also Erskine et al., 2012), they do not call into question the reality of the experience. There is ample evidence that synesthesia is experienced automatically when synesthetes are exposed to specific inputs, and that this can impact other sensory judgments, such as naming the physical color of text (Dixon et al., 2004; Mattingley, Rich, Yelland, & Bradshaw, 2001; Odgaard, Flowers, & Bradman, 1999; Paulsen & Laeng, 2006; Wollen & Ruggiero, 1983). Just as compelling are data linking synesthesia to enhanced activity in specific brain regions (Hubbard, Arman, Ramachandran, & Boynton, 2005; Rich et al., 2006) and to increased connectivity between discrete regions of the brain (Rouw & Scholte, 2007). These observations, however, do not dictate that the processes underlying synesthesia need be like those that generate a sensory experience in response to a physical colored input. Rather, they are consistent with synesthesia resulting from an automated recollection of sensation, or an automated process of mental imagery (see Barnett & Newell, 2008; Mattingley, 2009).

To some extent, our data suggest that automatically triggered synesthetic experiences and recollections of those experiences are similar, in that they result in a matched level of performance when matching color. While our synesthetes did not report experiencing synesthetic colors for heard graphemes, previous evidence suggests that synesthetic color signals may not always reach the level of conscious visual awareness (see Ward et al., 2010). One could therefore take our data as evidence that synesthetic color signals can be generated at will, and that a willfully generated synesthetic color signal is indistinguishable from an automatically triggered experience in terms of our performance measure. This is consistent with evidence that synesthetic colors can be generated simply by evoking a concept (see Dixon et al., 2000; Nikolic, Jürgens, Rothen, Meier, & Mroczko, 2011). Conceptually, this might be similar to the visual imagery that most people can engage in at will. Our data suggest, however, that the processes that underlie synesthetic experiences, be they automatically triggered or conjured at will, provide a less precise estimate of color than do the processes responsible for colored perceptions of physical objects in daily life.

It should be stressed that synesthesia is thought to be a heterogeneous condition (Dixon & Smilek, 2005). For instance, exposure to sounds can induce colored sensations in some synesthetes (Baron-Cohen, Wyke, & Binnie, 1987), but taste sensations in others (Pierce, 1907). The synesthetes in this study were grapheme-color synesthetes, who experience colors when reading achromatic text (Galton, 1880). It has been suggested that even this subtype of synesthesia is heterogeneous, with some individuals reporting sensations like those experienced when looking at a physical colored object (projectors), whereas others (associators) experience a vivid form of mental imagery (Dixon et al., 2004). The synesthetes in this study were self-described associators, but the authors have some doubt about this distinction and readers should be aware that this proposal is not without controversy (see Edquist et al., 2006; Mattingley, 2009; Ward, Li, Salih, & Sagiv, 2007).

The experimental paradigm established here could be used to distinguish between grapheme-color synesthetes who experience colors as a vivid form of automated mental imagery, and the possibility of other synesthetes for whom induced colors are indistinguishable from the sensation of looking at a physically colored object. This could be achieved by looking at the precision with which synesthetes match induced colors relative to the precision with which they can match the color of a physical object that can be seen. If synesthetic colors result from a form of automated mental imagery one would expect that, like the self-described associators in this study, individuals would be less precise when matching synesthetic colors than they are when matching the color of physical input. In contrast, if synesthetic colors are indistinguishable from physical colors one would expect the two to be matched with equal precision. This was not true for the synesthetes in the present study.

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