

Do Synesthetic Colors Grab Attention in Visual Search?

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Abstract Recent research on synesthesia has focused on how the condition may depend on selective attention, but there is a lack of consensus on whether selective attention is required to bind colors to their grapheme inducers. In the present study, we used a novel change detection paradigm to examine whether synesthetic colors guide the subject's attention to the location of the inducer or whether selective attention is required to act as a unique feature during visual search. If synesthetic experiences are elicited by inducers (e.g., digits) without selective attention, then a target that is distinct from the distractors by virtue of its unique synesthetic color should capture attention. This should lead to efficiency in the search that is analogous to the efficiency in searches involving unique display colors (e.g., a display of red digits among black). If, however, an inducer does not elicit a synesthetic color until the subject selectively attends to it, then the search should be as inefficient as for control subjects. We found that, not only does synesthesia not provide an advantage in complicated visual search tasks, it offers a slight disadvantage, supporting the re-entrant processing hypothesis about the mechanism underlying synesthesia.

1 Background

Synesthesia is a condition in which sensory or cognitive input gives rise to atypical binding of objects and properties (Rich and Mattingley 2002; Edquist et al. 2006; Brogaard 2012). In grapheme-color synesthesia, a common form of the condition,

Bullet Points

- Previous studies measuring pre-attentive effects of synesthesia suffer from significant limitations.
- The present study presents a novel version of a standard visual search paradigm.
- Synesthetes perform significantly worse than controls when performance requires the use of pre-attentive visual cues.
- These results demonstrate that focused attention occurs prior to grapheme-color binding in synesthesia.

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looking at or thinking about an achromatic letter or numeral (the inducer) gives rise to the sensation or thought that the numeral has a specific color with a highly specific hue, brightness and saturation (the concurrent). The attribution of color to the grapheme is not a simple memory association of the sort that leads us to attribute red to love. The synesthetic connection is idiosyncratic (although with some underlying patterns), immediate and consistent over time (Baron-Cohen et al. 1993; Rich et al. 2005; Simner et al. 2005).

One recent debate concerns the question of whether selective attention is required to bind inducers with their synesthetic concurrents (Mattingley et al. 2001; Ramachandran and Hubbard 2001a, b; Rich and Mattingley 2002, 2003, 2010; Robertson 2003; Smilek et al. 2003; Mattingley and Rich 2004; Edquist et al. 2006; Sagiv et al. 2006). Visual search paradigms are supposed to be indicators of whether synesthetic experience requires focused attention. The idea is that if synesthetic experience does not require focused attention, then digits with unique synesthetic colors should capture attention, which would lead to highly efficient identification of the digits. If, on the other hand, synesthetic experience does require focal attention, then synesthetic colors do not capture attention and the identification process should be inefficient (Edquist et al. 2006). Perceptual features must be processed early enough in the visual system for them to attract attention and lead to segregation (Beck 1966; Treisman 1982). So the appearance that synesthetic experience can lead to pop-out and segregation indicates that synesthesia is a early visual phenomenon (Ramachandran and Hubbard 2001a, 2003).

Studies purporting to show that synesthetic experience leads to pop-out have tested the speed at which synesthetes could find a shape made up of target graphemes hidden among a matrix of similar distractor graphemes and their accuracy (see Fig. 1). Although synesthetes are not remarkably better than controls at finding the shapes, synesthetes appear to have a slight advantage, evidenced by a higher accuracy or a quicker response time (Ramachandran and Hubbard 2001a; Hubbard et al. 2005a, b; Rich and Karstoft 2013).

An alternative to the above studies' findings of synesthetic experiences being preattentive, however, is that the synesthetic experience may only make visual searches more efficient, allowing for synesthetes to better and more easily remember the location of previously discovered targets or reject distractors (Cytowic and Eagleman 2009). Although synesthetes scan a matrix for targets in the same way as non-synesthetes,

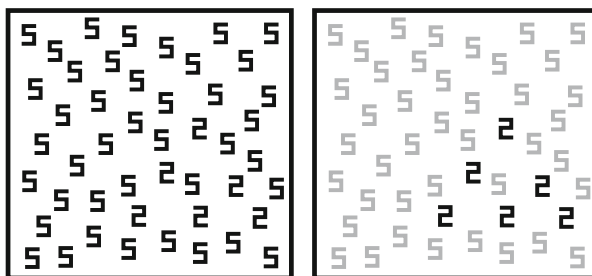


Fig. 1 When normal subjects are presented with the figure on the *left*, it takes them several seconds to identify the hidden shape. Some *grapheme-color* synesthetes instantly see the *triangular shape* purportedly because they experience the 2 s and the 5 s as having different colors. See e.g., Meier and Rothen 2009; Rich and Karstoft 2013)

additional post-attentional color cues may reduce the time necessary for stimuli to become available for conscious reporting. Thus, it cannot be concluded that the higher accuracy or quicker response time of synesthetes to graphemes that induce vivid color experience is due to that synesthetic color experience occurring prior to selective attention to graphemes. Other research has supported the theory of scan efficiency explaining synesthetes' quicker response times in visual search tasks. One study found that increasing the number of elements in a matrix causes a corresponding increase in reaction time for synesthetes (Palmeri et al. 2002). If true color-based pop-out is occurring in synesthetes' searches, then the target color-inducing graphemes should capture attention at the same rate regardless of the number of achromatic distractors in an array. However, the observed increase in reaction time when there is a greater number of elements in a display matrix is indicative of a limitation on the speed by which graphemes may be processed after selective attention, further supporting the hypothesis that synesthetic experience may only make visual searches more efficient.

A different set of studies have shown results indicating that greater search efficiency of grapheme-color synesthetes over controls may turn on implicit biases in visual search paradigms. One subject PM showed more efficient search than non-synesthetic controls when the graphemes inducers were close to the initial focus of attention (Laeng et al. 2004; see also Laeng 2009). In another variation of the standard search paradigm, Smilek et al. (2003) showed that subject J was more efficient in her search when the colored background was incongruent than when it was congruent with the synesthetic color of the inducer, indicating that the synesthetic colors attracted attention when they were clearly distinct from the background (see also Smilek et al. 2003). Further research by Edquist et al. (2006) carried out a group study involving 14 grapheme-color synesthetes and 14 controls. Each subject performed a visual search task in which a target digit differed from the distractor digits in terms of its synesthetic color or its display color. Both synesthetes and controls identified the target digit efficiently when the target had a unique display color but the two groups were equally inefficient when the target had a unique synesthetic color. The researchers concluded that for most grapheme-color synesthetes, graphemes elicit synesthetic color only once the subject attends to them. This indicates that synesthetic colors cannot themselves attract attention because they are not processed early enough in the visual system.

Despite the results reported in the above studies, the idea that synesthetic grapheme-color binding occurs pre-attentively persists (see e.g., Kim et al. 2006). However, many paradigms used to measure the advantages of synesthesia in visual search inherently are subject to bias, in that it is possible that the apparent abilities of synesthetic participants emerge from the participants' interest in showing that synesthesia provides one with special abilities. In response to Kim et al., two recent studies aimed to address the weaknesses of former studies purporting to show the lack of a pre-attentive effect of synesthesia.

Gheri et al. (2008) introduced a novel paradigm they expected would demonstrate an effect of pre-attentive grapheme-color binding only if synesthetic participants performed *worse* than neurotypical controls. Synesthetes were shown a 4×4 matrix of different achromatic numerals displayed in the center of a screen under two conditions: for condition I, a target numeral was chosen such that its concurrent was significantly different in color from the concurrents for the remaining distractor numerals; for condition II, the target numeral shared its concurrent color with one of the distractor

numerals. Aged-matched neurotypical controls viewed the same achromatic matrices as synesthetes in both conditions. It is well known that neurotypical subjects experience a “pop-out” effect when viewing matrices consisting of targets and distractors whose colors contrast significantly (Treisman and Gelade 1980). The authors hypothesized that if grapheme-color binding occurs pre-attentively, then synesthetes would score higher than controls on condition I and lower than controls on condition II. They argued that if synesthetic binding is a low-level perceptual process, then the synesthetic color of the target would aid synesthetes in identifying an achromatic target among achromatic distractors, reducing the time necessary to report identification of the target. Furthermore, if the synesthetic color of the target matched the synesthetic color of one of the distractors, an additional step would be required to reject the similarly colored distractor, placing synesthetes at a disadvantage. However, the authors did not find a significant difference between synesthetes and controls under both conditions and concluded that binding does not occur pre-attentively.

Ward et al. (2010) conducted a revised version of the Ramachandran and Hubbard (2001a) and Hubbard et al. (2005a, b) studies: in addition to the tasks included in the former studies, subjects were asked to report on their experiences of synesthetic colors after completing each task. Synesthetes scored higher than controls on visual search tasks, confirming the results of the former studies. However, the reported instances of synesthetic color experience did not correlate with the number of synesthetic inducers displayed to synesthetic participants, suggesting the lack of a relationship between synesthetic phenomenology and task performance. The authors concluded that the better performance of synesthetes could not be due to cues provided by pre-attentively bound synesthetic color experience.

Although many take the Gheri et al. (2008) and Ward et al. (2010) studies to have demonstrated that pre-attentive grapheme-color binding does not occur, we believe this conclusion is premature. The paradigm used for the Gheri et al. study was designed only to provide positive evidence that pre-attentive binding *does* occur; its weakness lies in its inability to demonstrate that pre-attentive binding *does not* occur. Gheri et al. admit this much, stating “the possibility remains that synaesthetic colours are perceptual but too weak to impair performance like wavelength-based colours” (Gheri et al. 2008). The fact that synesthetes did not perform worse under condition II merely could be an artifact of the paradigm.

The Ward et al. (2010) study also suffers from a significant limitation, as suggested by the authors of the study. The study found that synesthetes who claimed to perceive the majority of graphemes in the array as colored significantly outperformed synesthetes who reported little or no color experience. This finding suggests that synesthetic color experience does have some bearing on task performance. But it does not follow from this result that *reportable* color experience must occur for performance to be impacted. The study does not rule out the possibility that the color experiences of the synesthetes under the particular conditions of the study paradigm were simply too weak to be available for reporting, yet strong enough to influence task performance. Thus the fact that subjective reports of color experience did not correlate with task performance is not a reason by itself to rule out pre-attentive binding of colors to graphemes. Furthermore, it should be mentioned here that Meier and Rothen (2009) failed to replicate the embedded figures effect (See also Rich and Karstoft 2013).

In the present study, we used a novel visual search paradigm to examine whether synesthetic colors guide the subject's attention to the location of the inducer or whether selective attention is required to act as a unique feature during visual search. If synesthetic experiences are elicited by inducers (e.g., digits) without focused attention, then an inducer that is distinct from the distractors by virtue of its unique synesthetic color should capture attention. This should lead to efficiency in the search that is analogous to the efficiency in searches involving unique display colors (e.g., a display of red digits among black). If, however, an inducer does not elicit a synesthetic color until the subject selectively attends to it, then the search should be as inefficient as for control subjects.

Since disagreement remains as to whether synesthetic colors guide the subject's attention to the location of the target or whether selective attention is acquired for a pop-out effect to occur, we decided to use a different type of search paradigm, inspired by studies of change blindness. We used heavily camouflaged change flicker images. For normal subjects it can take several minutes or longer to identify the change in the image. If synesthetic binding occurs in early visual processing, we would expect that synesthetic colors could guide visual search like regular colors do. A grapheme camouflaged within a low-contrast scene therefore should give rise to a high-contrast color experience for synesthetes, resulting in a significantly faster reaction time for synesthetes than controls.

2 Methods

The study was approved by the local ethics committee. Synesthetes and control subjects gave informed consent to participate in the study. Subjects did not receive any compensation for their participation. All data were analyzed anonymously.

2.1 Participants

Synesthete group: 33 right-handed synesthetes from the Vancouver area (mean age=31 +/- 12) were surveyed about their synesthetic experiences. Of the 33 participants, 16 synesthetes met the inclusion and exclusion criteria. Participants did not receive any compensation for their participation.

2.1.1 Inclusion Criterion

To test for inclusion in the synesthesia group, we asked subjects if they experienced a pop-out effect in the standard grapheme 2–5 visual search task. All synesthetes were grapheme-color synesthetes registered with local research groups, and had all undergone classification using the Eagleman et al. (2007) Synesthesia Battery.

2.1.2 Exclusion Criterion

To test for exclusion in the synesthesia group, we asked subjects to share their results from the Eagleman et al. (2007) Synesthesia Battery. If the grapheme '2' elicited the synesthetic color experience of green, then the synesthetes were excluded, since the

synesthetic experience of 'green' for the grapheme '2' presumably would not offer sufficient contrast against the background image (a forest scene with green foliage).

2.1.3 Control Group

Sixteen controls from the St. Louis area (mean age=26 +/- 8) who reported not having synesthesia were used as a control group against the synesthetes.

2.2 Stimuli

E-prime stimuli were displayed for 1 s each with a white screen displayed in between for 0.2 s (see Fig. 2a and b). Target stimuli were separated into six groups by location (i.e., 1 bottom right location, 1 top left location, 1 middle location, and 3 near-middle locations) and four subsequent groups by kind (i.e., red '2' grapheme, green '2' grapheme, blue '2' grapheme, or a small leaf in the original image) Each stimulus condition consisted of one of the four target stimuli appearing and disappearing in one of the six locations for a total of 24 distinct conditions. Only one target stimulus appeared and disappeared within each trial. Each stimulus condition was viewed only once. All target stimuli appeared within the same forest background.

2.3 Trial Procedure

Both synesthetes and controls were divided up into two groups. A "target known" condition or a "target unknown" condition was assigned to each of the two groups. In the "target known" condition, participants were instructed to search for a numeral before they were shown the flicker image. In the "target unknown" condition, they were informed to look for either a small change in the foliage (leaf) in the image or a numeral change in the scenery prior to being presented with the flicker image.

Participants were presented with a fixation cross for 500 msec, followed by the stimulus display.

In presenting the stimuli, each stimulus display remained on the screen until a response was made via subject vocalization of the phoneme "Ta", at which point the experimenter would stop the timer and ask for clarification of the type of target stimuli and its location. If the participant was correct, the reaction time would be recorded; if the participant was incorrect, reaction time for the specific slide was not recorded and participants advanced to the next slide. There was a break between each stimulus condition wherein the participant would indicate to the experimenter that they were ready to proceed to the next block. Participants completed the green, red and blue numeral search task and leaf search tasks in a single session. The starting point in the slideshow was alternated randomly from participant to participant to minimize the possibility that reaction time was affected by the order of presentation.

3 Results

For synesthetic participants, the time it took them to find green '2' graphemes ranged from 0.0 to 223.0 s with a mean of 28.10 s and a standard deviation of 41.10 s. For

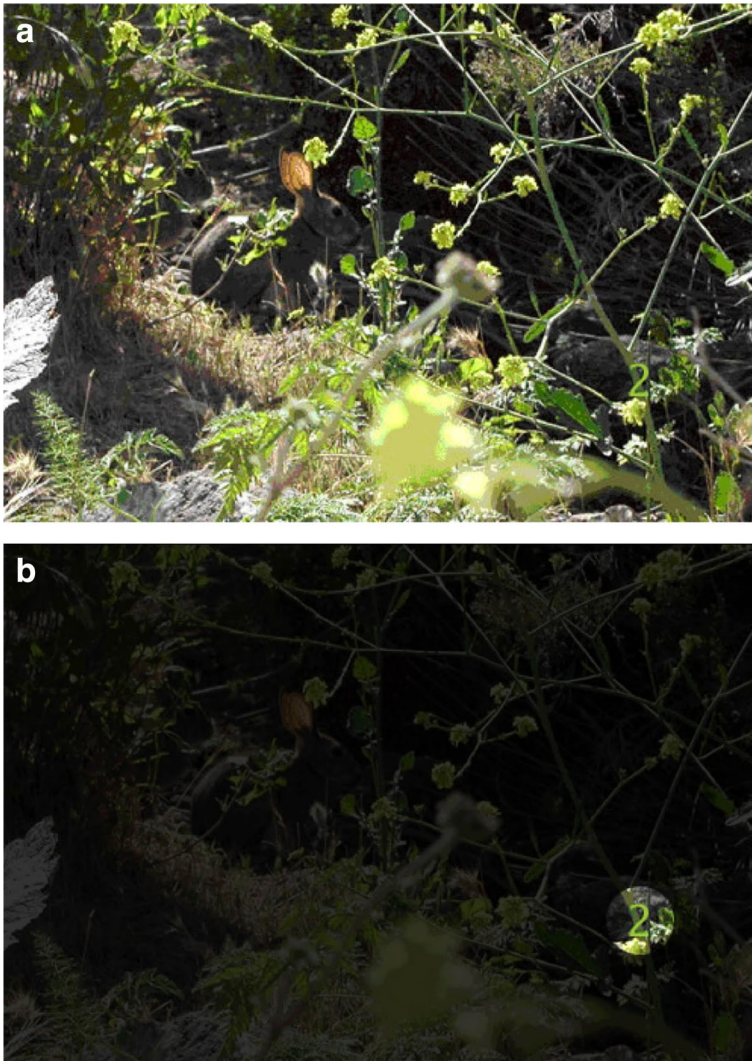


Fig. 2 **a** and **b** Example of GIF image with and without target superimposed over a forest scene. The '2' grapheme has been *circled* to better assist the reader in noticing the change

controls, the time to find green '2' graphemes ranged from 1.800 to 281.7 s with a standard deviation of 42.49 s. Synesthetes took significantly longer than controls to find green '2' graphemes ($p < .001$) (see Fig. 3). For synesthetes, the time to find red or blue '2' graphemes ranged from 0.01000 to 6.000 s with a mean of 2.326 s and a standard deviation of 1.265 s. Synesthetes took significantly longer to find green '2' graphemes than either red or blue '2' graphemes ($p < .001$) (see Fig. 4).

To determine whether synesthetes and controls differed in their general abilities to detect changes between images, we compared the time it took for each group to detect a minor change in scenery. For synesthetes, the time to detect changes among scenery ranged from 11.00 to 452.0 s with a mean reaction time of 88.47 s and a standard deviation of 84.87 s. For controls, the time to detect changes in scenery ranged from

Mean Reaction Time of Controls and Synesthetes for Green '2's

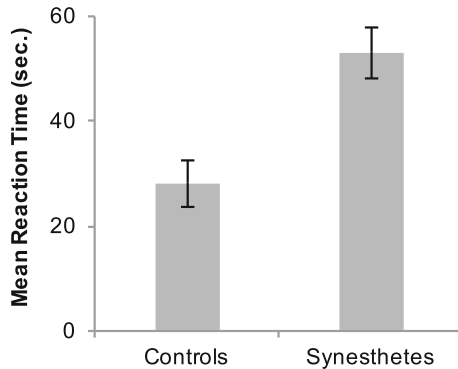


Fig. 3 Synesthetes take significantly longer than controls to find green '2' graphemes

4.600 to 712.8 s with a mean of 97.42 s and a standard deviation of 104.2 s. There was no significant difference between groups in detecting changes in scenery ($p=.560$).

We also looked at whether knowing what type of change was about to occur would influence the time it took to detect the change. For synesthetes under the “target known” condition, the time to detect a green '2' grapheme ranged from 2.000 to 223.0 s with a mean of 55.83 s and a standard deviation of 46.56. For synesthetes under

Mean Reaction Time for Synesthetes Based on Instruction and Color

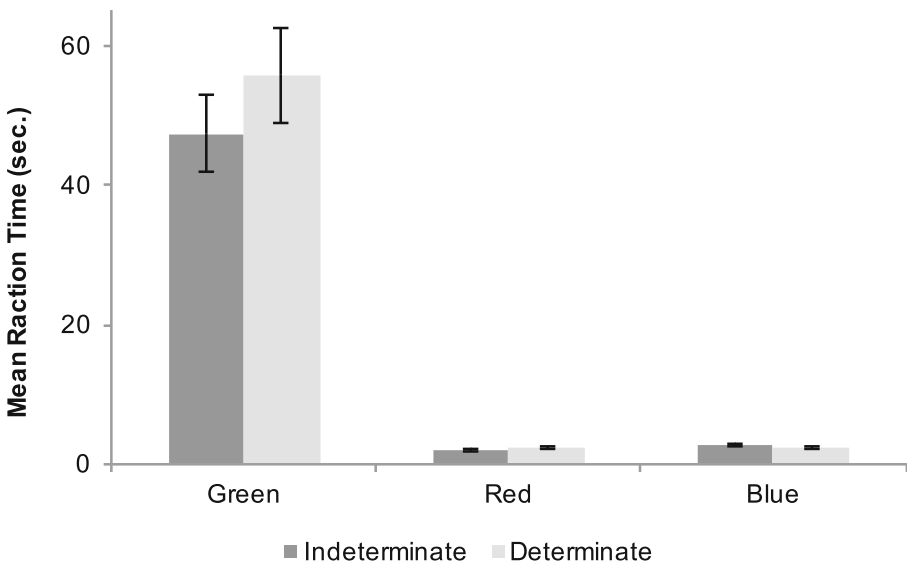


Fig. 4 Synesthetes take significantly longer to find *green* '2' graphemes than either red or blue '2' graphemes but exhibit no difference in reaction time between determinate and indeterminate conditions for *green* '2' graphemes

the “target unknown” condition, the time to detect a green ‘2’ grapheme ranged from 0.001 to 114.0 s with a mean of 47.391 s and a standard deviation of 26.75 s. For controls under the “target known” condition, the time to detect a green ‘2’ grapheme ranged from 2.700 to 64.40 s with a mean of 16.66 s and a standard deviation of 17.01 s. For controls under the “target unknown” condition, the time to detect a green ‘2’ grapheme ranged from 1.800 to 281.7 s with a mean of 39.54 s and a standard deviation of 55.61 s. Target determination had no effect on finding green ‘2’ graphemes for synesthetes ($p=.852$) but did show an effect for controls ($p=.036$).

4 Discussion

4.1 Early Visual Processing Versus Later Visual Processing

The chief aim of this study was to investigate whether focused attention is required to bind concurrent colors with their inducing characters. If synesthetic binding occurs in early visual processing, we would expect that synesthetic colors could guide visual search like regular colors do. A grapheme camouflaged within a low-contrast scene therefore should give rise to a high-contrast color experience for synesthetes, resulting in a faster reaction time for synesthetes than controls.

Both synesthetes and non-synesthetic control groups showed highly efficient searches for the red and blue numerals. However, not only did synesthetes take longer to find green ‘2’ graphemes than red or blue ‘2’ graphemes, synesthetes took significantly longer to find green ‘2’ graphemes than controls. The finding that synesthetes and controls do not differ in their abilities to detect more general changes to scenery indicates that the differences in detection time for synesthetes is related to the synesthetic condition.

A slower reaction time for synesthetes than controls for finding camouflaged green ‘2’ graphemes may be result of a Stroop effect on visual search. A Stroop effect occurs when there is difficulty in processing a grapheme, caused by an incongruence between the color of the grapheme and the color the grapheme denotes (Stroop 1935) (see Fig. 5).

Prior empirical research has supported the occurrence of a synesthetic stroop effect, indicated by synesthetes’ responses being slower in conditions when the colors of the inducer and concurrent are incongruent, compared to conditions when the colors of the inducer and concurrent are congruent (Odgaard et al. 1999; Mattingley et al. 2001; Elias et al. 2003; Dixon et al. 2004; Ward et al. 2007). In the present study, this synesthetic stroop effect may explain the synesthetes’ longer search times for the camouflaged green ‘2’ graphemes compared to controls. The incongruence of the green grapheme ‘2’ and the participant synesthetes’ color concurrent may have caused a delay in the time it took for the green ‘2’ graphemes to make it to conscious awareness for the synesthetes.

It has also been observed that similar grapheme-color stroop effects can occur in non-synesthetic individuals after undergoing conditioning where non-synesthetes are trained to learn specific grapheme-color associations (Nunn et al. 2002; Elias et al. 2003; Meier and Rothen 2009). From this, it has been argued that a synesthetic stroop effect may not be unique to synesthetes if non-synesthetes can learn grapheme-color



Fig. 5 The word ‘red’ is here displayed in the color black (*top*) and the color green (*bottom*). It takes longer for subjects to read the word ‘red’ when it is printed in green than when it is printed in black or red

associations and similarly display the stroop effect. However, the related studies also indicated that synesthetes displayed unique levels of elevated functional magnetic resonance imaging (fMRI) activity in the V4/V8 areas of the temporal cortex during stroop effect tasks (Nunn et al. 2002). Even further, non-synesthetes reported that they only experienced the trained grapheme-color association when perceiving the colors but not when perceiving the numbers, contrasting with synesthetes’ reports (Meier and Rothen 2009).

Even if the synesthetic stroop effect may not be completely distinctive to grapheme-color synesthetes’ experiences, the present study’s observation of slower response times for synesthetes compared to controls in searching for the camouflaged green ‘2’ still indicates the unique occurrence of an idiosyncratic synesthetic stroop effect interfering with synesthetes’ perception of the green ‘2’ grapheme. Further evidence for the occurrence of a unique synesthetic stroop effect for synesthetes could be inferred from the observation that there was also no difference between the determinate and indeterminate conditions for synesthetes in locating the camouflaged green ‘2’ grapheme, indicating that prior knowledge about the target stimuli did not influence synesthetes’ ability to locate the camouflaged green ‘2’ grapheme. However, prior knowledge about the target stimuli did influence the ability for controls to locate the green ‘2’ graphemes. One possible explanation of this difference is that it is a side effect of the differences between synesthetes and controls in detecting green ‘2’ graphemes.

4.2 Mechanism

As the timing was done with an experimenter-operated timer, and Powerpoint was used for presentation of stimuli, the variances are significant. While the use of the new paradigm that ought to increase differences between synesthetes and controls if

synesthetic binding is pre-attentive may compensate for the variances, it is important not to over-interpret these data. However, a few remarks on which of the leading mechanisms underlying synesthesia the data may support are in order.

The most plausible mechanism underlying developmental grapheme-color synesthesia synesthesia is some unusual crosstalk between normally separated brain areas, such that activity in one area stimulates activity in another (Baron-Cohen et al. 1993; Grossenbacher and Lovelace 2001; Ramachandran and Hubbard 2001b; Nunn et al. 2002; Simner et al. 2005; Weiss et al. 2005; Hubbard and Ramachandran 2005; Hubbard et al. 2005a, b; Rouw and Scholte 2007; Weiss et al. 2005; Gaschler-Markefski et al. 2011). The question, however, is how and where this cross-talk takes place.

The different proposed mechanisms can be divided into categories based on two factors: whether the mechanism suggests structural or functional differences from the neurotypical brain (Bargary and Mitchell 2008; Ward 2013) and whether the mechanism suggests a direct or indirect binding of grapheme and color. As for the first factor, structural mechanisms suggest that the cause of unusual connectivity lies in the brain structure, whereas functional mechanisms take the cause to be a difference in how an otherwise neurotypically structured brain processes perceptual information. Visual search and attention paradigms are not suitable for settling this issue.

As for the second factor: The best known hypotheses among the direct mechanisms take the unusual connectivity to be the result of an atypical feed-forward connection between color areas in the visual cortex and the adjacent visual word form area (Ramachandran and Hubbard 2001a, b; Hubbard et al. 2005b; Rouw and Scholte 2007). This suggestion is inspired by the observation that local crossover phenomena can explain other illusory and hallucinatory experiences, such as phantom limb sensations. Rouw's and Scholte's (2007) research using fMRI and diffusion tensor imaging (DTI) has also shown that grapheme-color synesthetes' experiences could be due to elevated anisotropic diffusion of white matter in localized areas of the inferior temporal, frontal, and superior parietal cortices in synesthetes. The localized hyper-cortical-connectivity for synesthetes may be taken to indicate a unique cross activation of color and word areas of the brain in grapheme-color synesthetes. Even further, observed differences in terms of greater activity in the inferior temporal cortex for projector versus associator grapheme-color synesthetes may offer a local crossover account for the differences in the subjective nature of the synesthetic experiences (Rouw and Scholte 2007).

Models proposing indirect mechanisms take the unusual binding of graphemes and colors to be the result of aberrant feedback from number or word processing areas to color areas. (Armel and Ramachandran 1999; Grossenbacher 1997; Grossenbacher and Lovelace 2001; Smilek et al. 2001; Myles et al. 2003; Gaschler-Markefski et al. 2011; Neufeld et al. 2012). The indirect model has received support from studies of how visual context and meaning can influence which synesthetic colors a grapheme gives rise to (Armel and Ramachandran 1999; Myles et al. 2003; Dixon and Smilek 2005; Cytowic and Eagleman 2009: 75).

The findings from the present study lend some support to the suggestion that synesthetic experience is the result of unusual feedback processes as opposed to aberrant feedforward mechanisms. Our results showed no pop-out effect for synesthetes when searching for green '2' graphemes, indicating that top-down attention is needed for the synesthetic experience to occur. The disinhibited feedback hypothesis may

account for why the synesthetes had significantly slower reaction times for locating the green '2' graphemes when compared to the controls. If higher-level information of meaning and context reenter lower color processing areas of the brain, then there could be some sort of interference between the top-down feedback and the bottom up visual information. This interference could have been further exacerbated by the camouflaged context of the green '2' graphemes adding additional bottom-up interference to the top-down color association.

5 Conclusion

Recent research on synesthesia has focused on how the condition may depend on attention, but there remains a lack of consensus on whether selective attention is required to bind colors to their grapheme inducers. We demonstrated that, not only does synesthesia not provide an advantage in complicated visual search tasks, it offers a slight disadvantage, supporting the re-entrant processing hypothesis about the mechanism underlying grapheme-color projector synesthesia.

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