

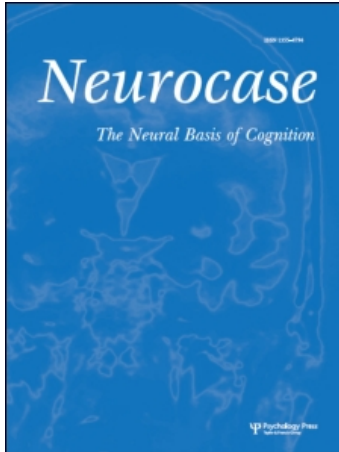
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Visual field heterogeneity, laterality, and eidetic imagery in synesthesia

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JS was a grapheme-color synesthete in whom numerals and letters of the alphabet consistently evoked colors. In the first set of experiments we showed that the color – in a consistent and reliable manner – was most pronounced in the left visual field and in central vision. In the second experiment we devised a novel test for eidetic imagery and showed that his self-report of enhanced imagery could be verified experimentally. The implications of these findings for the level at which synesthesia occurs, the ‘enhanced cross-activation’ model, and the mechanisms of visual memory are discussed.

Keywords: Synaesthesia; Memory; Bidirectional; Vision; Multisensory.

INTRODUCTION

Synesthesia is a heritable condition in which stimulation of one sensory modality (e.g., hearing) will cause unusual activation in a second, unstimulated modality (e.g., colors). Synesthesia can occur between any two senses; indeed even instances of synesthesia have been shown between touch and emotion, implying cross-activation between somatosensory and limbic centers (tactile-emotion synesthesia; Ramachandran & Brang, 2008a). But most commonly, synesthesia is experienced as the perception of color while looking at numbers or letters (grapheme-color synesthesia; Baron-Cohen, Burt, Smith-Laittan, Harrison, & Bolton, 1996; Cytowic & Eagleman, 2009; Simner et al., 2006). For over a century after its discovery by Francis Galton (1883; Sachs 1812) it was considered an unreliable ‘fringe’ phenomenon, but in the last 7 years there has been a tremendous resurgence of interest (Dixon, Smilek, Cudahy, & Merikle, 2000; Mattingley, Rich, Yelland, & Bradshaw, 2001; Nunn et al., 2002; Palmeri, Blake, Marois, Flanery, & Whetsell, 2002; Simner & Ward, 2006; Ramachandran & Hubbard, 2001a, 2003; Ramachandran, 2003).

In some grapheme-color synesthetes (projectors or lower synesthetes), the evocation of color appears to be an authentic sensory effect based on cross-activation between early sensory areas (Ramachandran & Hubbard, 2001a, 2001b) rather than conceptual centers or simple memory associations. We therefore suggested that synesthesia was due to a gene mutation(s) causing defective pruning of axons between color area V4 and the number/grapheme area – which lie adjacent to each other in the fusiform gyrus, or alternatively, a transmitter-based disinhibition of these connections (Brang & Ramachandran, 2008). Our brain imaging results (using fMRI) confirmed the predicted cross-activation in the fusiform gyrus; black numbers evoked activity in adjacent V4 (Hubbard, Arman, Ramachandran, & Boynton, 2005). Recent work using diffusion tensor imaging has also directly shown increased white matter between fusiform gyrus and V4 in grapheme-color projectors (Rouw & Scholte, 2007), supporting our original conjecture. We suggested too, that some forms of the condition might result from hypertrophy or hyperactivity of ‘back projections’ (Armell

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& Ramachandran, 1999) that are known to exist linking difference stages in the virtual hierarchy; e.g., high level visual areas representing more abstract shapes might feedback and activate lower sensory maps.

We put forward several pieces of evidence favoring this ‘sensory’ hypothesis. First, in lower synesthetes (projectors), the synesthetically induced color can lead to perceptual texture segregation resulting from the color difference; e.g., if 2s are embedded in an array of randomly scattered 5s, the 2s are more readily detected by synesthetes than by normal individuals (Ramachandran & Hubbard, 2001a; Palmeri et al., 2002). This effect is seen only in a minority of synesthetes. Nevertheless, it resulted in a testable anatomical hypothesis (subsequently confirmed) and was instrumental in suggesting that psychophysical experiments can be performed on the phenomenon, thereby spawning a whole host of subsequent experiments.

Second, many synesthetes report that individual numbers can have different colors in different parts, consistent with errors in cross-wiring but not with high level memory associations (Ramachandran & Brang, 2008; Ramachandran & Hubbard, 2001b). Third, the colors produced by graphemes can drive the perception of apparent motion in displays that no normal person can see (Kim, Blake, & Palmeri, 2006; Ramachandran & Azoulay, 2006; Ramachandran & Hubbard, 2002). Finally, as noted above, we confirmed the cross-activation hypothesis with fMRI in subjects with grapheme-color synesthesia (Hubbard et al., 2005).

We now report the results of two experiments on a projector synesthete, JS, the results of which support the ‘early sensory cross activation’ model of the phenomenon and also suggest that there may be excessive activity of back-projections (Armel & Ramachandran, 1999) leading to eidetic imagery.

CASE REPORT

JS (25 years old) is a right-handed, male university student with no history of neurological or psychiatric disorder. Upon the presentation of numbers and letters, JS perceives a persistent and salient color projected onto the physical page, consistent with previous reports of grapheme-color synesthesia projectors (also called ‘lower synesthetes’). In addition, and critically, JS’s synesthetic experiences occur bidirectionally; both graphemes elicit colors *and* colors elicit the conscious percept of

numbers and letters. He reports having had these experiences from as far back in childhood as he can remember. He demonstrated over 95% consistency for his synesthetic associations both immediately and 6 months later.

Two aspects of his perceptual experience – judging from his self-report – intrigued us: first, JS reported that the synesthetic colors became less vivid as a function of eccentricity and laterality. Second, he claimed to have extremely compelling visual imagery/memory, seemingly separate from his synesthetic experience. He reported he could glance at a complex visual scene and retain a vivid mental picture of it for a relatively long period, although he had not timed it or investigated it on his own. To test his purported ability we devised a novel set of visual memory tests (Experiment 2) that could not be ‘faked’. This is particularly important as eidetic imagery is often regarded an elusive and unreliable phenomenon.

EXPERIMENT 1: VISUAL FIELD LATERALITY EFFECTS

We had previously observed informally that synesthetically induced colors were especially pronounced in central vision and – more surprisingly – in the left visual field for a synesthete, JC (Ramachandran & Hubbard, 2001a) which was consistent with subsequent brain imaging studies (Nunn et al., 2002) showing laterality. We decided to measure these effects quantitatively in a new participant, JS, given their potential implication that synesthesia in projectors (lower synesthetes) may be based on sensory cross activation rather than high-level cognitive associations. Furthermore, hemifield and eccentricity biases may help in identifying specific visual areas involved in synesthesia (e.g., left vs. right V4 or magnocellular vs. parvocellular processing).

The subject was seated 54 cm from a color CRT monitor and presented with a centrally presented white grapheme subtending 2 degrees of visual angle against a uniform grey background. A second grapheme was presented at 4, 8, or 12 degree visual eccentricity either above, below, left, or right of the central white grapheme (i.e., each trial pair included one centrally presented grapheme and the same grapheme at a specific eccentricity). The subject was instructed to change the color of the central grapheme from white to a color matching the grapheme in the periphery. Color

matching was completed via Adobe Photoshop color picker palette, and the subject had unspecified time to complete each trial to maximize accuracy.

Three graphemes were used at each of the 12 possible eccentric locations, for a total of 36 trials. The graphemes selected (4, 6, A) elicited synesthetic colors nearly equal in saturation and luminance when presented centrally, and these graphemes evoked the colors blue, green, and red, respectively.

JS was instructed to use a standard criterion for setting a color ‘vividness’ (his term) match and was able to do the matching consistently and effortlessly. Results showed clear eccentricity and hemifield biases in JS. Items presented in right visual field subjectively seemed less ‘vivid’ compared to the left visual field and in fact required less color luminance $t(16) = 2.80, p < .05$ to achieve a subjective match. Interestingly, the targets in the upper visual field were also seen as more vividly colored than in the lower visual field, luminance $t(16) = 2.87, p < .05$. Eccentricity findings were equally striking. Synesthetic color intensity for items presented at the 3 eccentric locations were significantly less than for the centrally presented grapheme, one-sample t -test $t(35) = 6.53, p < .0001$. Tests were repeated 6 months later with a select set of the stimuli only along the horizontal axis, and results were identical: luminance greater in the left visual field compared to the right $t(5) = 2.58, p < .05$; luminance reduced at eccentricity compared to central presentation, one-sample t -test $t(11) = 13.53, p < .0001$. These eccentricity and hemifield biases have been informally confirmed on a second synesthete JC but, having moved out of the area, he has been unavailable for further careful testing.

The same experiment was repeated (using identical procedures but physically colored graphemes) on 4 control subjects – none of whom showed any hemifield effects: left visual field compared to right, paired t -test $t(3) = 1.31, p > .10$; top hemifield compared to bottom, paired t -test $t(3) = 0.66, p > .10$; eccentricity compared to centrally matched color $t(3) = 2.18, p > .10$. We also showed JS an ‘Anstis Chart’ (an eye chart that enlarges letter size with eccentricity; Anstis, 1974) and he verified that the pattern of reduction in color vividness was identical to eccentric letters of the same size. This indicates that the falloff of color with eccentricity is not a result of declining visual acuity. In any event, no such falloff or heterogeneity of color matching was seen in normals even with stimuli

matched to those used for JS. Nor can the visual field *laterality* effects be explained in terms of the falloff of acuity in peripheral vision. Additionally, JS reported that he saw the peripherally presented letters perfectly clear, so lack of clarity is unlikely to have influenced the evoked colors.

EXPERIMENT 2: EIDETIC IMAGERY

To explore JS’s eidetic capacities, we used ‘find the hidden object’ tests common to children’s puzzle books. The test was administered twice over a 6-month period. The stimulus was a large visual scene cluttered with multiple complex (‘distractor’) objects and either a single ‘target’ object or several identical ones (e.g., violins of different sizes and orientations) scattered throughout the scene (this is similar to ‘Find Waldo’). Since these are complex objects in a complex visual scene, they did not ‘pop out’ perceptually (Treisman, 1985). Normal subjects require several minutes to find the hidden objects. If the picture is removed after a relatively brief period (e.g., 30 s) and the subject is asked to inspect the internal mental picture, they perform very poorly. Our conjecture was that if JS really had eidetic imagery as he claimed, he should be able to hold the visual image in his mind for much longer, allowing him to search this mental picture for the object in question.

Subjects were presented with three 45.75×30.5 -cm images containing scattered objects. Images were presented for 30 s, and then replaced with a white sheet of the same size. A list of target items was then read to the subjects, and subjects were instructed to mark the previous location of the item using the white sheet. Targets were recorded as correct if identified within a 4cm radius (less than 10% the total area of the page) of the original location of the item. JS was indeed able to determine the location of more objects (8) than any of the 15 control subjects tested (mean 2.1, SD 1.5), and was confirmed as an outlier from the group via the test of extreme standardized deviations and p -values computed with the more modern Crawford and Howell’s method ($z = 3.87, p < .01$; Crawford & Garthwaite, 2007). This empirically validates his unusually accurate eidetic memory (Figure 2a). It is especially important to note that JS experienced no colors with these complex objects, which means he could not have been using evoked colors as a memory aid – earlier studies have noted anecdotally that memory for phone numbers was

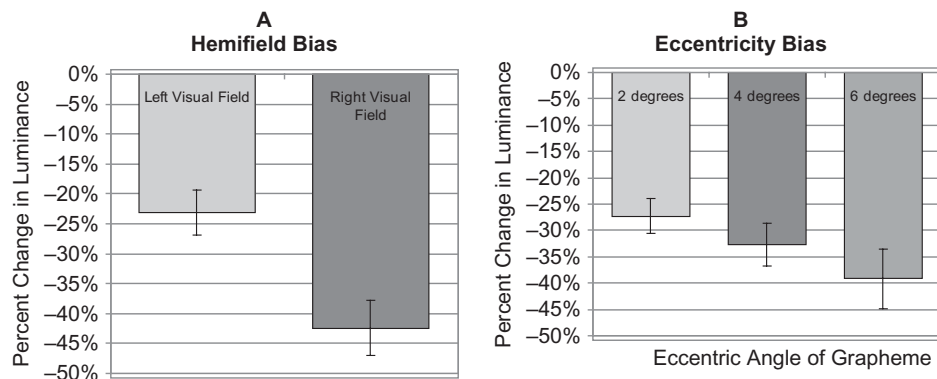


Figure 1. Luminance values for Subject JS for identical graphemes presented in different hemifields (A) or at varying eccentricities (B).

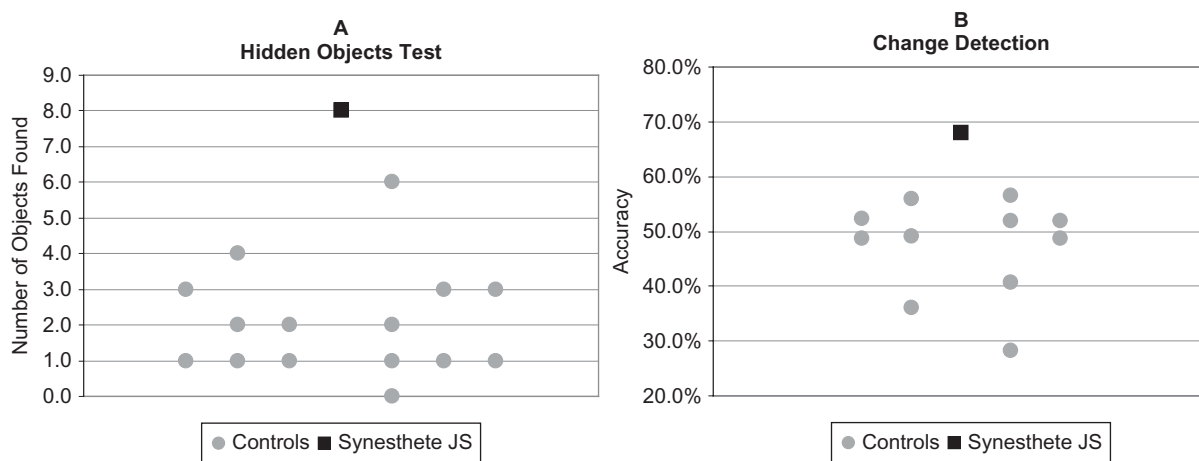


Figure 2. Performance of subject JS and controls on two tests of memory.

aided by synesthetic colors (Ramachandran & Hubbard 2001b); more elegantly designed formal studies made the same point (Smilek, Dixon, Cudahy, & Merikle, 2002).

As an additional test of JS's eidetic memory, he was presented with pairs of complex visual images, one image at a time, with extremely small changes existing between one picture and the other, and was instructed to identify the changes (spot the difference task; change detection). If the visual image is in fact persisting for JS, then noticing changes in the visual landscape should be easy for him. Again, JS outperformed each of the 11 control subjects, JS mean accuracy 68.1%, controls mean accuracy 47.3% ($SD = 8.7\%$), $z = 2.38$, $p < .05$; Figure 2b.

Results from the each of these two tests were confirmed 6 months later with different stimuli and using a new group of control subjects, with similar

results. Synesthete JS again outperformed all 8 controls both on a visual search task ($z = 1.87$, $p = .06$; one-tailed), and a spot the difference task ($z = 3.53$, $p < .05$), again highlighting the superiority of his memory.

DISCUSSION

The results provide clear-cut evidence that at least in some synesthetes the cross-activation occurs relatively early in visual processing. High-level associative learning is almost always invariant with respect to visual field location (e.g., if you show someone a novel visual shape in the lower right visual field even once he/she has no difficulty identifying it in the left upper field). On the other hand, if the cross activation were occurring in the extrastriate visual areas themselves, this heterogeneity is

precisely what one would expect, given the possible differential emphasis of center and periphery in their representation of color and form combined with some degree of spatial scatter via the abnormal cross-connections. Furthermore, as V4 mostly processes information from the contralateral visual field, this finding also suggests a right-hemisphere bias in at least in JS (and previously noted informally in JC). While this right hemisphere bias may be sufficient to account for the weakening of synesthetic intensity in the right visual field, our eccentricity finding may reflect differences in magnocellular/parvocellular streams. Items viewed at eccentric locations would preferentially activate the magnocellular pathway whereas synesthetic colors may be evoked mainly in parvocellular (color) pathways. This could in principle be tested using flickering or low contrast stimuli (Livingstone & Hubel, 1987).

This early cross-activation model is also supported by our observation (Ramachandran & Brang, 2008b) that even within an individual grapheme, different parts can show strikingly different colors. Although there may have been such reports in ‘surveys’ its significance for the early cross-activation model (as opposed to higher order memory associations) appears to have been overlooked (refrigerator magnets are not multi-colored). It remains to be seen, however, whether such visual field and intra-grapheme heterogeneity of evoked colors would hold in higher synesthetes (those who experience the color only in their mind’s eye; associators). Even if higher-synesthetes do not explicitly report differences in synesthetic intensity between the hemifields, it is possible this same bias may be present simply at a subconscious level. This would be easily testable with lateralized presentation of graphemes colored either to match or interfere with the subject’s synesthetic association. We would expect reduced synesthetic Stroop interference (where 2 is associated with blue for a particular synesthete, they are slowed to read the ink-based color of a red 2) in the right visual field compared to the left.

The findings with eidetic imagery are especially intriguing in the context of the postulated over-connectivity in synesthesia. High-level visual imagery is known to reactivate ‘low level’ visual areas, as though the brain needs to use low-level areas in running virtual reality simulations – to generate qualia – in order to enjoy the luxury of choosing between different behavioral options (Ramachandran & Hirstein, 1997). It seems likely

that this involves ‘back projections’ that are known to project from higher to lower areas. If there is increased cross activation caused by defective pruning (or transmitter imbalance) *across* extrastriate areas (e.g., V4 and the number area), it is also possible that in some synesthetes (like JS) the same defective pruning may lead to enhanced back-projections, thereby explaining his enhanced visual (eidetic) imagery. In other words, even in normals, quale-laden visual imagery may require back and forth echo-like reverberation between different levels of the visual hierarchy and the imagery is enhanced when these connections are strengthened as (perhaps) in JS. These enhanced reciprocal projections along the hierarchy may also account for the explicit bidirectionality that JS experiences for colors to numbers/letters. If so, we may expect a higher incidence of eidetic memory in other bidirectional synesthetes.

In summary, the variation of synesthetically induced colors with eccentricity and laterality suggest strongly that in some ‘lower’ (projector) synesthetes the cross activation occurs early in the visual processing cascade. Second, we postulate that if the synesthetic cross-activation ‘gene’ is more diffusely expressed in the brain (instead of just the fusiform gyrus) back projections might also be stronger – leading to enhanced imagery and (sometimes) bidirectionality of synesthetic experiences. These conjectures need to be tested on additional subjects employing both psychophysical and brain-imaging techniques. If they hold up they would have important implications for understanding the neural basis of visual imagery in normal individuals.

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