Published in final edited form as:
Psychol Sci. 2013 March 1; 24(3): 258–265. doi:10.1177/0956797612452573.

Learning, Memory, and Synesthesia

Nathan Witthoft and **Jonathan Winawer**
Department of Psychology, Stanford University

Abstract

People with color-grapheme synesthesia experience color when viewing written letters or numerals, usually with a particular color evoked by each grapheme. Here we report on 11 color-grapheme synesthetes with startlingly similar color-grapheme pairings traceable to childhood toys containing colored letters. These data are the first and only to show learned synesthesia of this kind in a group larger than a single case. While some researchers have focused on genetic and perceptual aspects of synesthesia, these results indicate that a complete explanation of synesthesia must also incorporate a central role for learning and memory. We argue that these two positions can be reconciled by thinking of synesthesia as the automatic retrieval of highly specific mnemonic associations, where perceptual contents are brought to mind, akin to mental imagery or the perceptual reinstatement effects found in the memory literature.

Introduction

A person is said to have synesthesia when their perception of a physical stimulus, such as this black letter ‘A’, automatically produces an impression which is not ordinarily derived from the stimulus, for example that this ‘A’ is red. Experiencing colors in response to reading achromatic printed letters and numbers (grapheme-color synesthesia) is among the most common and widely studied kinds of synesthesia, (Simner et al., 2006). Other pairings within and between sensory modalities have also been reported, including colors evoked by musical pitches, (Marks, 1975), spatial arrangements elicited by numbers, (Galton, 1881; Calkins, 1893), and tastes in response to words (Ward & Simner, 2003).

Over a century ago, Galton (1881) prefaced his description of color-number synesthesia by cautioning readers that the contents of every sane person’s mind are not the same as their own. He was aware that to some, synesthesia appeared implausible, or at best, an anomaly with little relation to the study of ordinary cognition. Since then, many results in psychophysics and neuroimaging have attested to the perceptual and neural basis of synesthesia (Ramachandran & Hubbard, 2001; Kim & Blake, 2005; Blake, Palmeri, Marois, & Kim, 2005; Kim, Blake, & Palmeri, 2006; Hubbard & Ramachandran, 2005; Witthoft & Winawer, 2006). Researchers have argued that synesthesia matters because relationships between ideas or modes of experience, such as pitch and brightness, or space and number that are implicit in the non-synesthete are made explicit in the synesthete, (Marks, 1975; Ramachandran & Hubbard, 2001b; Martino & Marks, 2001; Cohen Kadosh & Henik, 2007), providing an unobscured view of the representations underlying normal cognitive processes like cross-modal perception, abstraction, and metaphor.

The idea that grapheme-color synesthetes learn their colors from childhood toys was proposed over a hundred years ago (Calkins, 1893), but documented cases are exceedingly rare. In one large-scale investigation, Rich et al. (2005) compared colored letters and

Correspondence concerning this article should be addressed to: Nathan WItthoft, 416 Jordan Hall, Department of Psychology, Stanford University, Stanford, CA, 94305. witthoft@stanford.edu.

numbers found in 46 Australian children's books and toys with matches generated from 150 synesthetes and found 'little evidence' that color grapheme correspondences were learned. Subsequently, two papers, including one by the present authors, examined cases where grapheme-color matches were learned from a childhood toy, one half of a pair of monozygotic twins, (Hancock, 2006), and a single individual (Witthoft & Winawer, 2006). Blake et al (2005) also noted that one of their well-studied synesthetes reported learning her colors from a set of refrigerator magnets. Given the limited number of cases and failure to find additional examples in a large survey, these findings have failed to impact the general theoretical perspective on synesthesia (Ward & Mattingly, 2006). Rather, they are considered by some to be an irrelevant 'red herring' (Spector & Maurer, 2009), or instances of 'pseudosynesthesia', (Baron-Cohen & Harrison, 2005), while others worry reasonably of an unfruitful case study approach to synesthesia (Novich, Cheng, & Eagleman, 2011).

In this paper, we present data from 11 grapheme-color synesthetes, all with highly similar letter-color pairings, apparently learned from a very common letter toy in the United States. In 10 of 11 cases the subjects recalled owning or still own the toy. In all cases the correspondence between the letter-matches and the toy is obvious, demonstrating that the pairings in color-grapheme synesthesia can be learned from external letter-color pairings. We propose that this result along with other recent findings showing more general influences of experience on synesthesia indicate that learning has a central role in synesthesia. A coherent framework for organizing many results in the literature can be constructed by defining synesthesia as comprised by relatively fixed and unusually detailed memories, and that synesthesia points to a strong relationship between memory and perception.

General Methods

Participants

Our subjects are 11 color-grapheme synesthetes (U.S. born 1970–1985; 5 female). S5 was encountered first and details on her synesthesia including the influence of lightness illusions on her color matches can be found in our 2006 paper. S7 was contacted prior to publication of our original paper in response to a post he made to a synesthesia mailing list stating he had learned his colors from a childhood toy. S1, 2, 3, 8, 10, & 11, contacted us after seeing our paper on the American Synesthesia Association website (http://www.synesthesia.info/). S1 had already participated in several studies with the Vanderbilt vision group, and more details about the perceptual nature of her synesthesia can be found in their papers, including mention that her colors derived from a childhood toy, (Kim & Blake, 2005; Blake et al., 2005; Kim et al., 2006). The connection between S1 and our original subject did not become clear until we saw her color matching data, which have not been published before. S9 is a synesthesia researcher and put us in touch with one of his subjects (S5) who also has similar letter-color pairings. S6 is a vision scientist encountered at a conference while presenting data from the first 10 subjects. Additional information about each person's synesthesia can be found in the supplementary materials (Supp Table 1).

Procedure

Early researchers noted that the particular synesthetic experience a stimulus evokes in a synesthete is highly specific, automatically elicited, and remains relatively constant over time (Galton, 1881). This fixed relationship has been demonstrated many times and is a defining characteristic of synesthesia, usefully distinguishing synesthesia from the relative but consistent cross-modal matching behavior found in most people (Marks, 1974; Martino & Marks, 2001; McDermott, Lehr, & Oxenham, 2008).

Grapheme-color matching data from 10 of 11 subjects were collected using the synesthete.org website. In the letter-color matching task, subjects were presented with all 26 upper-case letters and 10 single digits (0–9) three times each in random order and adjusted the color of each letter using an RGB color picker until it matched their synesthetic color, (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007). Data from the remaining subject were collected using in-house software. Each subject participated in two matching sessions and the consistency of matches was evaluated both within and between sessions.

Further evidence for genuine synesthesia for 10/11 subjects was evaluated using a speeded congruency task on the synesthete.org website (Eagleman et al., 2007). Subjects were presented with colored letters for 1 second each and required to rapidly determine whether the color was consistent with their synesthesia. Inconsistent colors were prevented from coming from somewhere nearby in the color space.

Results

Speeded Congruency Task

Previous work suggests that scoring at or above 85% on the speeded congruency task is typical for synesthetes(Eagleman et al., 2007), and all 10 subjects exceeded this threshold (lowest accuracy = 90%, mean accuracy 93.5+−0.7%). Subjects performed this task rapidly (mean rt of 1.2+−0.1 sec; Figure 1b). Stroop data showing automatic elicitation of synesthesia by graphemes for S5 can be found in Witthoft and Winawer, 2006.

Color matching is extremely reliable within and between matching sessions

Within session reliability was calculated by comparing the distances between the RGB image indices (ranging from 0 to 1) for each of the three matches for each grapheme. A distance metric was defined by summing the city block distances for each of three pairwise matches, and averaging over graphemes. A perfect reliability score of 0 is achieved by producing identical RGB matches for each presentation of a given grapheme. A reliability score of 3.0 +/− .77(mean +/− SD) is obtained by randomly selecting RGB values for each match from a uniform distribution. This metric is computed for all users of the synesthete.org website and so is useful for assessing reliability. A threshold of 1.0 has been observed to best discriminate synesthetes from controls attempting to produce consistent matches by association, (Eagleman et al., 2007). All 10 of our subjects scored well below this threshold (mean 0.517 +− 0.03, max 0.66, Figure 1a).

Matches across sessions proved to be nearly as reliable as matches within a single session. Subjects participated in a second color matching session at least 54 days after the first (10 of 11 with delay > 1year, max delay 2854 days). We quantified between session reliability as the correlation between the hue of the first matching session (average of three matches) and the second matching session (average of three matches). While the RGB metric used for the within session data was useful for comparison to non-synesthetic performance reported in previous work, (Eagleman et al., 2007), distances in RGB color space do not closely correspond to psychological distance. Hue correlations on the other hand give a better though not perfect intuition for the variability across matching sessions, and our previous research indicated that S5 was especially precise about matching hue (Witthoft & Winawer, 2006). RGB color matching data were converted to HSV, and a circular correlation generated between the average hue of each letter from session 1 and session 2, (Berens, 2009). Letters with achromatic color matches (total of 20 across all subjects) were excluded, as they have no hue. Subjects' letter-color pairings proved to be highly reliable, with a mean circular correlation (Rho) of 0.96 and some correlations greater than 0.99 (Figure 1c) even with 1–8 years intervening between testing sessions (see Supp Text 1 for details on color calculations). These numbers demonstrate the longevity and specificity of the synesthetic associations in these subjects.

Letter-color pairings were learned from childhood toys

The degree of similarity between the subjects' letter-color pairings along with the clearly visible regular repeating pattern in the colors found in each individual's set of matches (Figure 2a) is striking. In all cases, with the exception of S9, they report having owned one of 3 toys widely sold by Fisher-Price between 1972 and 1989 (see Supp Text 2 and thisoldtoy.com). Each of these toys contained a set of magnetic letters that always had the same color scheme (S5 was previously reported in Witthoft & Winawer, 2006). Four of the synesthetes still own their version of toy (S2, S3, S4, and S5) and photographs of these are shown in Figure 2b. The color matches shown in Figure 2 are ordered from left to right based on how well they correspond to the colors in the letter set. S11 shows the fewest matches to the letter set at 14. We estimate the probability of observing 14 or more matches in 26 chances is less than 1 in 1 billion, and the probability of having 11 sequences meet this criterion is substantially less (see Supp Text 3 for details of probability calculations).

Each synesthete has some reliably different matches from the group

Despite the strong similarity between the subject matches, each subject's letter-color pairings shows some subtle but reliable specificity in the exact hue match to each letter. We noted qualitatively that when shown Figure 2, individual synesthetes could easily pick out which set of matches was their own. To quantify the individual differences in matches, we computed the circular correlation between every pair of subjects' matches (HSV hue) and compared these to the circular correlation obtained for each subject with themselves over the two matching sessions. We then ranked the correlations for each subject, from 1 to 11, where a rank of 1 indicates that a subject's cross-session matches are better correlated than any of the between-subject matches and a rank of 6 indicates that a subject's cross-session matches are no better correlated than the one subject's matches to another's. The inability to differentiate different subjects' matches is what might be expected if subjects simply picked colors corresponding to a verbal label such as red. The mean rank of the cross session matching data was 1.5 however, demonstrating that the individual differences are specific and reliable.

Letter-color pairings that deviate from the group pattern are similar to those found in other color-grapheme synesthetes

One possible explanation for the similarity between our subjects is that the pattern of color matches common to this group of 11 subjects is found in many synesthetes. Available published work demonstrates that the letter-color pairings corresponding to the toy do not reflect tendencies in all color-grapheme synesthetes. Surveys of large numbers of synesthetes and non-synesthetic English speakers have shown significant agreement on color choices for some letters and numbers. Depending on the survey, roughly 33–40% of synesthetes will report that the letter 'A' is red and 40–50% will say that 'Y' is yellow, (Rich et al., 2005; Simner, 2005; Barnett et al., 2008), with above chance agreement usually found for 12 or so letters. With the exception of the frequent choice of red for A, none of the modal color choices of synesthetes for letters matches the letters in the toy or our group. Instead, when the synesthetes in our group do deviate from the letter set in their matches, it is their deviations that match the modal choice from the surveys more than 50% of the time (see supp Figure 1). For example, ~45% of synesthetes in one survey by Rich et al (2005) chose yellow for 'Y'. 9 of the 11 synesthetes in our group made 'Y' orange as it is in the set, but the other two chose yellow.

The fact that the synesthetes reported in this paper only match the data from synesthetes at large when they deviate from the letter set leads to two important conclusions. First, the matches that correspond to the letter set are likely learned from the letter set, rather than from general influences. Second, deviations from the letter set appear to be subject to more general influences, confirming prior results and arguing against a distinction between the synesthetes in this paper and other color-grapheme synesthetes (though see Tomson et al 2011 for evidence of multiple subtypes of grapheme-color synesthesia). It reinforces the view that these subjects had some tendency toward synesthesia, and that the presence of the toy shaped rather than invented it.

Number-color matches

All of the synesthetes also reported number color associations. The colors evoked by each number showed strong consistency over time with 9 of 11 of the subjects showing a circular correlation in hue across matching sessions of greater than 0.97 (supp Figure 2). The one exception was S3 who transposed the colors of 2, 3, 7 and 9, showing a reliable pattern during a particular matching session but not between them (though other numbers remained the same). S1 did not generate number matches in the second session.

Of the 11 subjects, only S2, S3, S4, and S6 explicitly recall having colored number sets in childhood. Two of the toys that Fisher-Price manufactured contained colored number magnets as well as letters, both with the same color scheme for the numbers (Figure 3 left). S2, S4, and S6, show 10, 8, and 6 matches respectively (Figure 3 left). Fisher-Price also made a third toy (Figure 3 bottom center) consisting of a tray containing number magnets and arithmetic symbols. S3 supplied a photo of her toy and shows 5/10 matches (6/10 if the yellow 0 is taken from the yellow O). We estimate the probability of finding 5 or more matches given 10 trials is less than 1 in 50000 (see supp Text 3). Most of the other subjects show 0–2 matches with either number set ($p(\text{matches}>=2) = .22$), and one (S7) shows 4 matches to one of the sets. Given his date of birth it seems plausible that S7 owned one of the toys that came with the numbers, but S7 cannot recall this. As with most grapheme-color synesthetes, the origin of the particular pairings for the remaining subjects is unknown. In some cases (for example S1) it seems that the colors found in the numbers are chosen from the available colors in the letters, but we do not see any obvious overall pattern, though there are intriguing similarities (e.g. seven – yellow).

Discussion

Researchers from the late 19th and early 20th centuries often proposed learning as a cause for synesthesia (e.g., Calkins, 1893), though examples were non-existent. By contrast, for many modern researchers, the questionable theoretical relevance of the few recently discovered instances and the fact that synesthesia itself is uncommon, means these case studies are viewed as anomalies among the anomalous, (Ramachandran & Hubbard, 2001b; Baron-Cohen & Harrison, 2005; Marks & Odgaard, 2005; Ward & Mattingly, 2006). The data presented here provide clear evidence that synesthetic grapheme-color correspondences can be learned from external correspondences, and that although such cases may be exceptional, they should be accounted for in any theory of synesthesia.

Nonetheless, some researchers will feel that even if such cases as the ones shown in this paper are brought to light, learning cannot serve as an explanation for synesthesia. The main objections to learning accounts of synesthesia may be summarized as follows. First, synesthesia is perception rather than memory (Ramachandran & Hubbard, 2001b). Second, learning alone cannot explain why only some people become synesthetes (Marks & Odgaard, 2005, Spector & Maurer, 2009). Finally, most synesthetic pairings are not learned. Nonetheless, the data here along with the growing number of papers showing cultural influences on synesthetic matches (Rich et al., 2005; Simner, 2005; Barnett et al., 2008; Beeli, Esslen, & Jancke, 2007), and the fact that a large majority of synesthesias (>= 88%) are induced by learned linguistic sequences such as phonemes, graphemes, and numbers (Simner, 2005), show that learning and memory must play some role (Marks & Odgaard, 2005).

In recent years, there has been growing evidence that synesthesia can be a genuine perceptual phenomenon and not the explicit recall of a previously observed correspondence. Ramachandran and Hubbard (2001b) for example, argue that synesthesia is not ‘just remembering a childhood magnet set you played with’. While many grapheme-color synesthetes do not experience their synesthesia as part of the visual scene, this insistence on the perceptual nature of synesthesia in at least some cases (including two of the synesthetes in this paper) has been invaluable in demonstrating that the color associated with a grapheme can have a great deal more specific content than just associating a letter with a color name and may in some cases interact with the visual scene (Kim & Blake, 2005; Blake et al., 2005; Kim et al., 2006; Witthoft & Winawer, 2006).

We do not wish to argue *against* a perceptual component of synesthesia, but rather *for* a role of learning and memory. Associative learning and the perceptual experiences of synesthetes are not only compatible, but lie on a continuum with ordinary experience. Suppose the introduction to this article had been written as follows, “A person may be said to have synesthesia when a stimulus such as this letter A, automatically produces an additional idea, for example that it has the sound/a/”. Under this description, some readers will recognize themselves as synesthetes as many (though not all) report that reading is accompanied by auditory imagery (hearing words while reading, Alexander and Nygaard, 2008). It seems safe to state that the arbitrary, consistent, and automatic pairing some readers experience between visual symbols and the associated ‘sounds’ is the product of learning. That people judge that their internal speech has perceptual qualities is no guarantee that their experience is supported by any of the same mechanisms as perception, (Pylyshyn, 2002), but a large body of evidence supports a strong overlap between memory, imagery, and perception, (Paivo, 1969; Harrison & Tong, 2009; Wheeler, Petersen, & Buckner, 2000; Winawer, Huk, & Boroditsky, 2010).

So what makes synesthetes different from non-synesthetes if it is not the difference between seeing and remembering? Like readers who experience auditory imagery, synesthetes can separate their synesthesia from the external world (Marks, 1975, Blake et al., 2005). However, synesthetes differ from most people in that their ‘imagery’ is fixed and automatic. For example, when asked to match pitches to patches of varying brightness, most people will match brighter patches to higher pitches, but this matching is relative and they will simply distribute the range of available brightnesses (Marks, 1975). Pitch-color synesthetes also tend to have brighter colors for higher pitches, but for each pitch there is a particular color, and changing the range of available matches will not change their choices. This distinction has been most fully developed by Martino and Marks (2001), who referred to the two types of matching behavior as ‘weak’ and ‘strong’ synesthesia respectively (see Cohen Kadosh & Henik, 2007 for a related point about synesthesia making cross-modal relationships explicit).

For the average person to be a synesthete then, it would be as if every time they read the letter ‘a’, they automatically heard it whispered into their left ear by a particular person from six inches away (Galton, 1881; Tyler, 2005). We hypothesize that it is just the reliability and specificity (what in imagery studies is loosely called vividness) of the content of the memory that causes subjects to experience it as part of (or attribute it to) some external stimulus, (Martino & Marks, 2001). Synesthesia is not 'just' remembering, but it is remembering nonetheless.

While learning is compatible with synesthesia as a perceptual phenomenon, most synesthetes probably do not learn their synesthetic correspondences from some external object present in childhood. This fact could reasonably be taken to suggest that this type of learning is irrelevant to understanding synesthesia. However, considered from a different perspective, learning is the defining characteristic of synesthesia. As noted, synesthetes experience a fixed and automatic synesthetic response to some stimuli. These responses across many types of synesthesia do not appear to be entirely random, but alignable with choices made by non-synesthetes. Thus, an important way in which synesthesia informs normal cognition, is that both synesthetes and non-synesthetes are influenced by similar factors when matching two domains, say space and number (Cohen Kadosh & Henik, 2007), and studying synesthesia makes it easier to uncover these implicit correspondences in non-synesthetes. However, when answering the question, 'what is synesthesia?' we would point again to the fixed nature of the synesthetic association and say, it is the learning of that association that makes someone a synesthete. The information guiding the association may be relatively innate as suggested for brightness and size, or due to environmental statistics such as the proposed relationship between frequency and grapheme brightness (Beeli, Esslen, & Jancke, 2007), or come from some specific stimulus as with the subjects in this paper.

Finally, why do only some people become synesthetes (Ward & Mattingly, 2006; Ramachandran & Hubbard, 2001b; Marks & Odgaard, 2005)? We do not argue that the presence of the magnet set was sufficient to induce synesthesia (though it possibly increased the chances), and we have met many non-synesthetes who owned the same toy. Furthermore, most attempts to induce synesthesia via repeated association in adults have failed, (Kell, 1934; Marks, 1975; Marks & Odgaard, 2005). There is little to address why only some people become synesthetes beyond data suggesting synesthesia is heritable (Barnett et al., 2008), and one could propose that something about learning mechanisms that is inherited (Marks & Odgaard, 2005). Many researchers before us have noted that prevalence of culturally learned sequences as inducers of synesthesia is overwhelming, and it seems that synesthesia arises around the age at which children are learning the alphabet and counting (Simner, Harrold, Creed, Monro, & Foulkes, 2009). In searching for mechanisms which are likely genetically specified, the field might be well served by considering or expanding the existing developmental and memory literature on how children learn and use these sequences (Rich et al., 2005; Marks & Odgaard, 2005).

Our proposals that synesthesia is best described as highly detailed and automatically retrieved memories and that particular mappings can be derived from external contingencies when present are intended to apply to synesthesia generally. However, it is possible that it applies only to some types of synesthesia (in particular those involving learning sequences), or even some subtypes of color-grapheme synesthesia. For example, Novich et al (2011) examined data from a large group of synesthetes (1200+) and found that individuals with one of synesthesias authors termed colored –sequence synesthesias (colors paired with letters, numbers, days of the week, and months) were likely to have another of the synesthesias from this group. However, having a colored-sequence was 'roughly independent of other types of synesthesia such as colors evoked by pitches. It has also been suggested based on genetic evidence grapheme-color synesthesia be divided into at least two groups (Tomson et al 2011). Given this evidence it may be that the kind of learning found in our data is only possible because of the type of mechanisms associated with either a particular subgroup of synesthesia, though whether that line should be drawn at sequences, colored-sequences, or a subtype of color grapheme synesthesia is unknown.

In summary, pairings in color-grapheme synesthesia can be learned from experience in childhood, producing color-grapheme mappings that are highly precise and stable over many years. The synesthetic responses retain many of the details of the original stimulus, but also take on some specific idiosyncratic features. These results demonstrate an important role for learning and memory in synesthesia but are consistent with a role for perception in synesthetic experience. The two ideas are made compatible by positing that the learned associations between stimulus and response are highly detailed and automatically triggered, two important characteristics for giving a representation a perceptual quality. These associations may be determined by internal or external contingencies, though we emphasize that external contingencies are not sufficient to produce synesthesia, which is likely dependent on genetic factors.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

References

Alexander JD, Nygaard LC. Reading voices and hearing text: Talker specific auditory imagery in reading. Journal of Experimental Psychology: Human Perception and Performance. 2008; 34(2): 446–59.10.1037/0096-1523.34.2.446 [PubMed: 18377181]

Barnett KJ, Finucane C, Asher JE, Bargary G, Corvin AP, Newell FN, Mitchell KJ. Familial patterns and the origins of individual differences in synaesthesia. Cognition. 2008; 106(2):871–93.10.1016/j.cognition.2007.05.003 [PubMed: 17586484]

Baron-Cohen, S.; Harrison, J. Nadel, L., editor. Synesthesia. Encyclopedia of Cognitive Science. 2005. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/0470018860.s00295/full10.1002/0470018860.s00295

Beeli G, Esslen M, Jancke L. Frequency Correlates in Grapheme-Color Synesthesia. Psychological Science. 2007; 18(9):788–792.10.1111/j.1467-9280.2007.01980.x [PubMed: 17760774]

Berens B. CircStat: A MATLAB Toolbox for Circular Statistics. Journal of Statistical Software. 2009; 31(10)

Blake, R.; Palmeri, TJ.; Marois, R.; Kim, C-Y. On the perceptual reality of synesthetic color. In: Robertson, L.; Sagiv, N., editors. Synesthesia: Perspectives from Cognitive Neuroscience. Oxford University Press; 2005. p. 47-73.

Calkins MW. A statistical study of pseudo-chromesthesia and of mental of mental forms. American Journal of Psychology. 1893; 5:439–464.

Cohen Kadosh R, Henik A. Can synaesthesia research inform cognitive science? Trends in Cognitive Science. 2007; 11(4):177–84.10.1016/j.tics.2007.01.003 10.1016/j.cognition.2006.12.007

Eagleman DM. The objectification of overlearned sequences: A new view of spatial sequence synesthesia. Cortex. 2009; 45:1266–1277.10.1016/j.cortex.2009.06.012 [PubMed: 19665114]

Eagleman DE, Kagan AD, Nelson SS, Sagaram D, Sarma SK. A standardized test battery for the study of synesthesia. Journal of Neuroscience Methods. 2007; 159:139–145.10.1016/j.jneumeth.2006.07.012 [PubMed: 16919755]

Galton F. Visualized Numerals. Journal Anthropological Institute. 1881; 10:85–102.

Hancock P. Monozygotic twins' colour-number association: a case study. Cortex. 2006; 42:147–150.10.1016/S0010-9452(08)70338-1 [PubMed: 16683487]

Harrison SA, Tong F. Decoding reveals the contents of visual working memory in early visual areas. Nature. 2009; 458:632–635.10.1038/nature07832 [PubMed: 19225460]

Hubbard EM, Ramachandran VS. Neurocognitive mechanisms of synesthesia. Neuron. 2005; 48:509–20.10.1016/j.neuron.2005.10.012 [PubMed: 16269367]

Kelly EL. An experimental attempt to produce artificial chromaesthesia by the technique of conditioned response. Journal of Experimental Psychology. 1934:315–341.10.1037/h0074963

Kim C-Y, Blake R. Watercolor illusion induced by synesthetic colors. Perception. 2005; 34:1501–1507.10.1068/p5422 [PubMed: 16457169]

Kim C-Y, Blake R, Palmeri TJ. Perceptual interaction between real and synesthetic colors. Cortex. 2006; 42:195–203.10.1016/S0010-9452(08)70344-7 [PubMed: 16683493]

Marks LE. On Associations of Light Sound: The Mediation of Brightness Pitch and Loudness. American Journal of Psychology. 1974; 87(1–2):173–188. [PubMed: 4451203]

Marks LE. On colored-hearing synesthesia: Cross-modal translations of sensory dimensions. Psychological Bulletin. 1975; 82:303–331.10.1037/0033-2909.82.3.303 [PubMed: 1096209]

Marks, LE.; Odgaard, EC. Developmental constraints on theories of synesthesia. In: Robertson, L.; Sagiv, N., editors. Synesthesia: Perspectives from Cognitive Neuroscience. Oxford University Press; 2005. p. 214-236.

Martino G, Marks LE. Synesthesia: Strong and Weak. Current Directions in Psychological Science. 2001; 10(2):62–65.10.1111/1467-8721.00116

McDermott JH, Lehr AJ, Oxenham AJ. Is Relative Pitch Specific to Pitch? Psychological Science. 2008; 19(12):1263–71.10.1111/j.1467-9280.2008.02235.x [PubMed: 19121136]

Novich S, Cheng S, Eagleman DM. Is synaesthesia one condition or many? A large-scale analysis reveals subgroups. Journal of Neuropsychology. 2011; 5:353–371.10.1111/j.1748-6653.2011.02015.x [PubMed: 21923794]

Paivio A. Mental imagery in associative learning memory. Psychological Review. 1969; 76(3):241–263.10.1037/h0027272

Pylyshyn ZW. Mental imagery: In search of a theory. Behavioral Brain Sciences. 2002; 25(2):157–182.

Hubbard, Ramachandran. Psychophysical investigations into the neural basis of synaesthesia. Proceedings of the Royal Society: Biological Sciences. 2001; 268(1470):979–83.10.1098/rspb.2001.1576 [PubMed: 11370973]

Ramachandran VS, Hubbard EM. Synaesthesia - A Window into Perception, Thought and Language. Journal of Consciousness Studies. 2001; 8(12):3–34.

Rich AN, Bradshaw JL, Mattingley JB. A systematic, large-scale study of synaesthesia: implications for the role of early experience in lexical-color associations. Cognition. 2005; 98:53–84.10.1016/j.cognition.2004.11.003 [PubMed: 16297676]

School Days Play Desk. http://www.thisoldtoy.com/L_FP_Set/toy-pages/100-199/176-schooldaysplaydesk.html. retrieved November 2011

Simner J. Non-Random associations of graphemes to colours in synaesthetic and non-synaesthetic populations. Cognitive Neuropsychology. 2005; 22(8):1–17.10.1080/02643290500200122

Simner J, Mulvenna C, Sagiv N, Tsakanikos E, Witherby SA, Fraser C, Scott K, Ward J. Synaesthesia: The prevalence of atypical cross-modal experiences. Perception. 2006; 35:1024–1033.10.1068/p5469 [PubMed: 17076063]

Simner J, Harrold J, Creed H, Monro L, Foulkes L. Early detection of markers for synaesthesia in childhood populations. Brain. 2009; 132:57–64.10.1093/brain/awn292 [PubMed: 19015159]

Spector F, Maurer D. Synesthesia: A New Approach to Understanding the Development of Perception. Developmental Psychology. 2009; 45(1):175–89.10.1037/a0014171 [PubMed: 19210000]

Tomson SN, Avidan N, Lee K, Sarma AK, Tushe R, Milewicz DM, Bray M, Leafe SM, Eagleman DM. The Genetics of Colored Sequence Synesthesia: Suggestive Evidence of Linkage to 16q and Genetic Heterogeneity for the Condition. Behavioral Brain Research. 2011; 223:48–52.10.1016/j.bbr.2011.03.071

Tyler, C. Varieties of synesthetic experience. In: Robertson, L.; Sagiv, N., editors. Synesthesia: Perspectives from Cognitive Neuroscience. Oxford University Press; 2005. p. 34-44.

Ward J, Simner J. Lexical-gustatory synaesthesia: linguistic and conceptual factors. Cognition. 2003; 89:237–61.10.1016/S0010-0277(03)00122-7 [PubMed: 12963263]

Ward J, Mattingley J. Synaesthesia: an overview of contemporary findings and controversies. Cortex. 2006; 421:129–136.10.1016/S0010-9452(08)70336-8 [PubMed: 16683485]

Wheeler ME, Petersen SE, Buckner RL. Memory's echo: Vivid remembering reactivates sensory-specific cortex. Proceedings of the National Academy of Science: USA. 2000; 97(20):11125–11129.10.1073/pnas.97.20.11125

Witthoft N, Winawer J. Synesthetic colors determined by having colored refrigerator magnets in childhood. Cortex. 2006; 42:175–183.10.1016/S0010-9452(08)70342-3 [PubMed: 16683491]

Winawer J, Huk AC, Boroditsky L. A motion aftereffect from visual imagery of motion. Cognition. 2010; 114(2):276–284. [PubMed: 19853246]

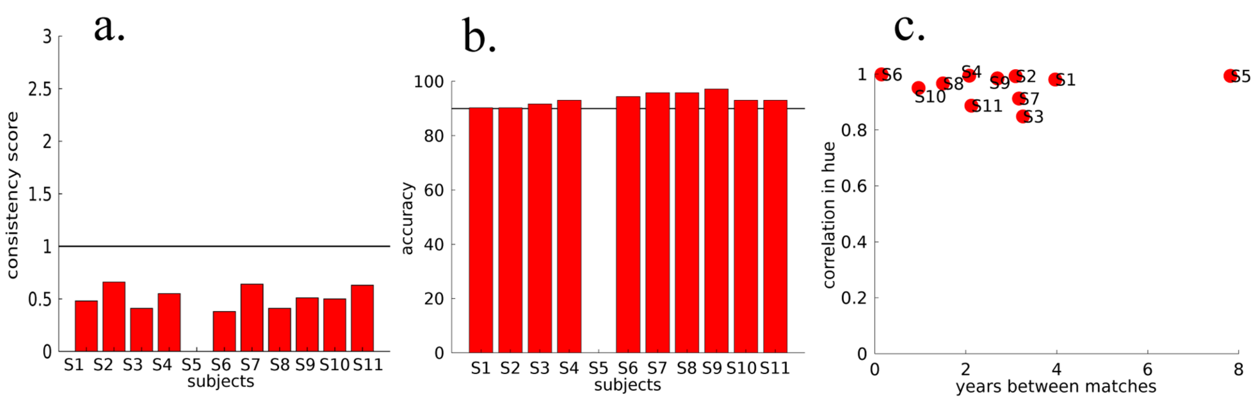

Figure 1. Evidence for synesthesia

Panel a shows within-session consistency in each subject's color match for 26 letters and 10 numbers. Consistency score is the normalized geometric distance between RGB values for each of 3 matches for letters and numbers, summed over the 3 pairs of matches and averaged over graphemes during each subject's first match session (Eagleman et al., 2007). All subjects perform well within the range typical of synesthetes with scores below 1 (indicated by the horizontal bar). **Panel b** shows subjects' accuracy in a speeded letter-color recognition task, (Eagleman et al., 2007). Again all subjects perform above the threshold for synesthetes (90%, indicated by the horizontal bar). S5 was tested in the lab rather than using this method and data of this kind can be found in our previous paper (Witthoft & Winawer, 2006). **Panel c** shows the consistency in subject letter color matches across sessions. The y-axis shows the average circular correlation between hues in the first session and the second session. Subjects give highly consistent results even when test and retest are separated by nearly 8 years. The minimal delay was 54 days (Subject 6). There is no indication that matching consistency declines over time.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

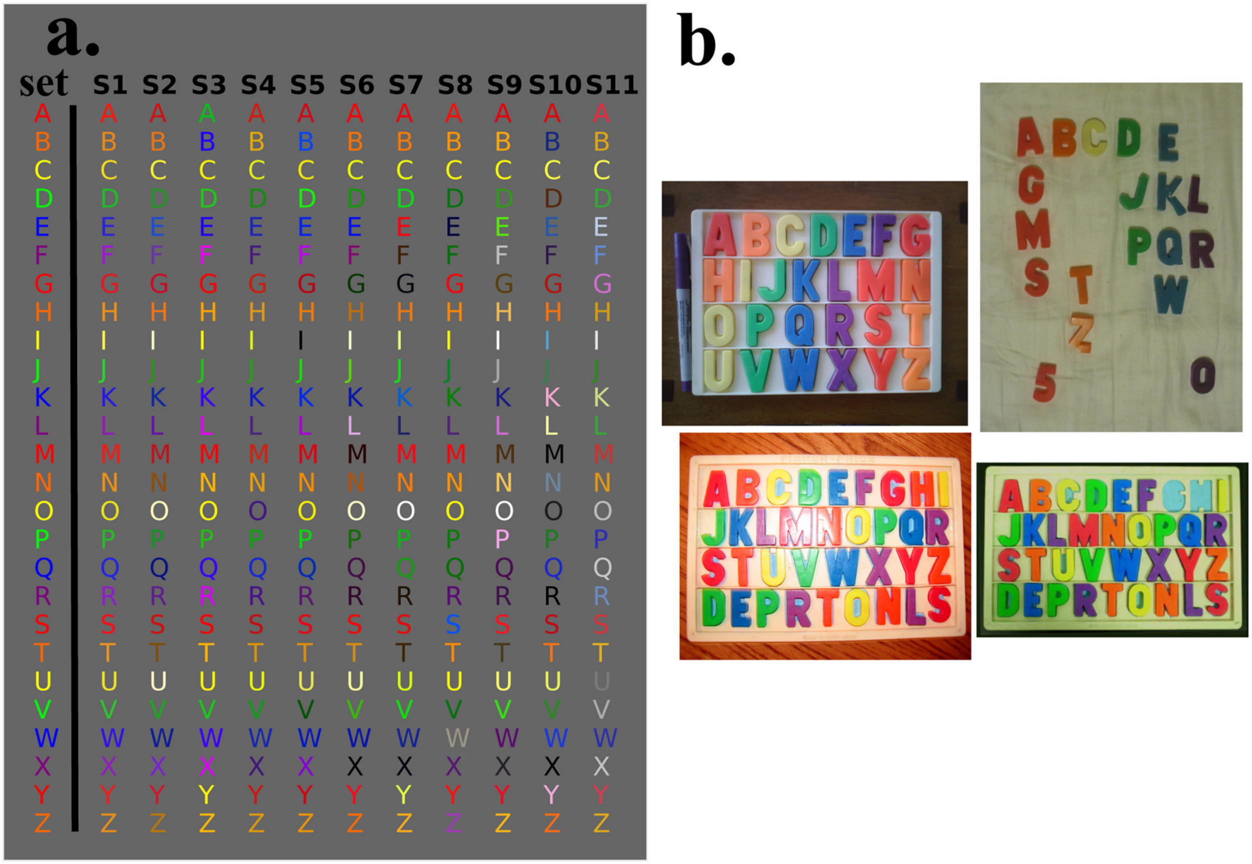

Figure 2. Letter-Color Matches from 11 Synesthetes

Color matches collected from 11 color-grapheme synesthetes are shown in **panel a**. Subject have been ordered by their resemblance to the original set of letters (from left to right). The left-most column labeled set represents the repeating pattern in the toy. 10 of the 11 synesthetes recall owning a set of colored refrigerator magnets manufactured by Fisher Price as children. S2, S3, S4, and S5 still own these toys (or parts of them) and supplied the photos in **panel b**.

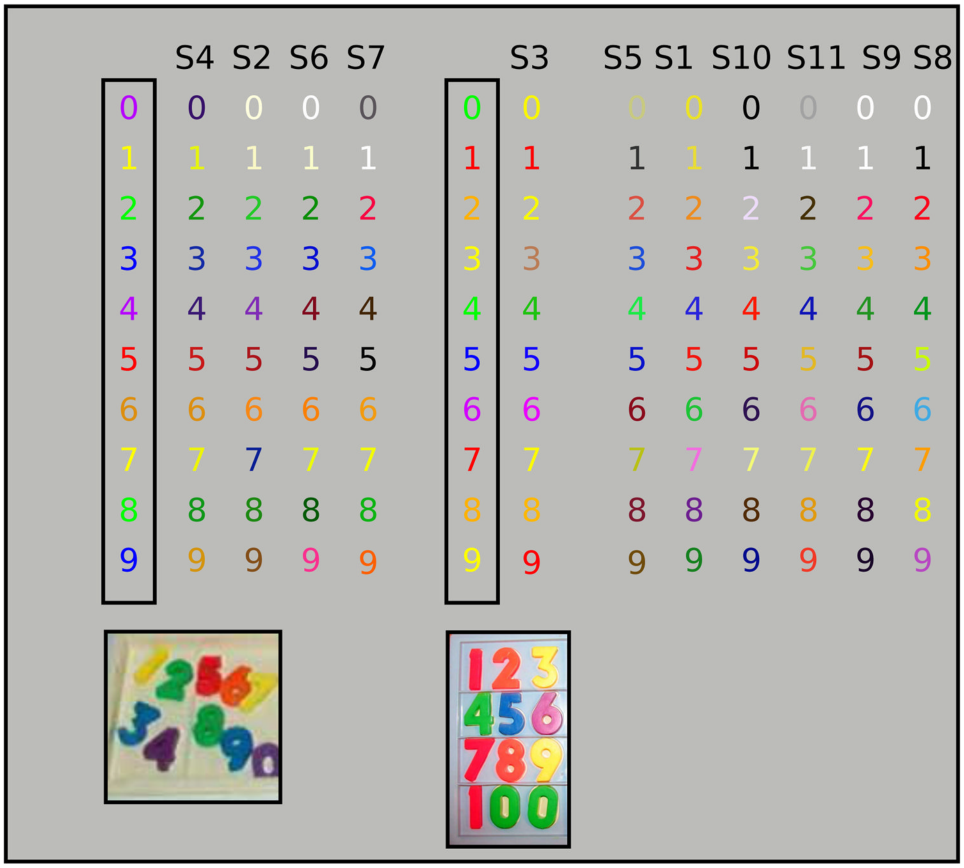

Figure 3. Number-Color Matches from 11 Synesthetes

The numbers in the two black boxes represent the repeating pattern in the two toys pictured beneath. S2, S4, S6, and S3, recall owning colored magnets for the numbers. S4, S2, S6, S7, show 5 or more matches to the numbers shown in the lower left which is statistically improbable if the color choices are random. These 4 subjects form the leftmost grouping in the color matching data. S3 shows 6 matches to the number set shown at bottom right (7 if you accept that the yellow letter O is the source for number 0). S3 supplied the photograph shown at bottom center. The remaining subjects' number-color matches are shown at right.