

The Colors of the Alphabet: Naturally-Biased Associations Between Shape and Color

Ferrinne Spector and Daphne Maurer
McMaster University

Many letters of the alphabet are consistently mapped to specific colors in English-speaking adults, both in the general population and in individuals with grapheme-color synaesthesia who perceive letters in color. Here, across six experiments, we tested the ubiquity of the color/letter associations with typically developing toddlers, literate children, and adults. We found that pre-literate children associate O with white and X with black and discovered that they also associate I and ameboid nonsense shapes with white; Z and jagged nonsense shapes with black; and C with yellow; but do not make a number of other associations (B blue; Y yellow; A red; G green) seen in literate children and adults. The toddlers' mappings were based on the shape and not the sound of the letter. The results suggest that sensory cortical organization initially binds specific colors to some specific shapes and that learning to read can induce additional associations, likely through the influence of higher order networks as letters take on meaning.

Keywords: synaesthesia, shape, color, development, letters

Adults associate information between sensory modalities everyday. Many of these associations make sense based upon learning: for example, the smell of a banana is associated to the color yellow and a crescent shape. However, some of these associations cannot be explained by experiential learning: for example, adults associate sounds of a higher pitch to a lighter color (Marks, 1996; Ward, Huckstep, & Tsakanikos, 2006). It is interesting to note that this association between pitch and lightness also occurs in individuals with colored hearing synaesthesia, who actually perceive color in response to sounds. Synaesthesia, which occurs in about 5% of adults (Simner et al., 2006), refers to the phenomenon in which stimulation of one sense elicits a concrete perception in that sense *and in* another sense (e.g., sound → color) or in a different dimension of the same sense (e.g., shape → color). There is growing evidence of similarities in the sensory associations made by synaesthetic and non-synaesthetic adults as well as by young children (e.g., Marks, 1975; Marks, 1996; Mondloch & Maurer, 2004; Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005; Spector & Maurer, 2008; Ward et al., 2006). Combined with the evidence of similar mechanisms underlying synaesthesia and typ-

ical perception (e.g., Esterman, Verstnen, Ivry, & Robertson, 2006; Hubbard Arman, Ramachandran, & Boynton, 2005; Sperling, Prvulovic, Linden, Singer, & Stirn, 2006), such consistencies in associations suggest that synaesthesia and typical perception are not as different from one another as they can appear.

One of the most common forms of synaesthesia is color-grapheme synaesthesia. For an individual with color-grapheme synaesthesia, letters and/or digits printed in black evoke specific idiosyncratic colored percepts that are consistent over time (e.g., Cytowic, 2002). Evidence for the perceptual reality of the synaesthetic colors comes from studies showing that the synaesthetic colors interact with the perception of real-world stimuli as would be expected if they were perceptual phenomena. The most prominent example is Stroop interference (Stroop, 1935). Much as a color word (e.g., "green") interferes with naming an incompatible color of ink (e.g., red), individuals with color-grapheme synaesthesia have difficulty naming the ink color of a letter or digit if it induces an incompatible synaesthetic color (Dixon, Smilek, Cudahy, & Merikle, 2000; Mattingley, Payne, & Rich, 2006; Mattingly, Rich, Yelland, & Bradshaw, 2001; Ward et al., 2006). Stroop-like interference is largest when the real-world and synaesthetic colors are opponent colors (red/green or blue/yellow), an effect suggesting that synaesthetic color arises from the same opponent-color mechanisms that mediate normal color vision (Nikolic, Lichti, & Singer, 2007).

A role for the parietal cortex was confirmed by two studies using transcranial magnetic stimulation (TMS) to temporarily interfere with activity in specific areas of the parietal cortex in synaesthetes with colored graphemes: TMS over the right parietal-occipital area and, in some subjects the right parietal area or the left parietal-occipital area, reduced the interference between synaesthetically-induced and physically presented colors (Esterman et al., 2006; Muggleton, Tsakanikos, Walsh, & Ward, 2007; see Rouw & Scholte, 2007, for converging evidence of increased parietal connections in the left parietal cortex of color-grapheme

This article was published Online First January 24, 2011.

Ferrinne Spector and Daphne Maurer, Department of Psychology, Neuroscience and Behaviour, McMaster University.

This research was supported by a discovery grant from the Natural Sciences and Engineering Research Council of Canada awarded to DM and an Ontario Graduate Scholarship to FS. We thank Crystal Robertson for testing the toddlers in Experiments 1 and 2, Sophia Fanourgiakis for testing toddlers in Experiment 5, and Laura White for testing the toddlers in Experiment 6, in each case as part of an independent study project at McMaster University. Thanks also to Sally Stafford for collecting data from adults in Experiment 5.

Correspondence concerning this article should be addressed to Daphne Maurer, Department of Psychology, Neuroscience, and Behaviour, McMaster University, 1280 Main Street West, Hamilton, Ontario, Canada L8S 4K1. E-Mail: maurer@mcmaster.ca

synaesthetes). These findings suggest a role for areas of the parietal cortex in color-grapheme synaesthesia that also play a role in binding color to form in non-synaesthetic adults (Donner et al., 2002; Sagiv, Heer, & Robertson, 2006). Combined with the evidence of fMRI activation in V4/V8 (e.g., Hubbard et al., 2005), the results for the parietal areas suggest that the brain connections mediating synaesthesia are similar to those mediating typical perception.

Despite the overall variability between synaesthetic individuals in the mapping of specific letters to specific colors, large-scale studies do show some consistency among adults with color-grapheme synaesthesia for a subset of letters (e.g., A tends to be red, G tends to be green, Z tends to be black, etc; Rich et al., 2005; Simner et al., 2005). It is interesting to note that when non-synaesthetic adults are asked to make color associations to that subset of letters, they frequently choose the same letter/color combinations as those reported by synaesthetic adults (Marks, 1975; Rich et al., 2005; Simner et al., 2005). Some of these associations may be based in literacy learning: for example, A is for apple, and apples are canonically red, so A is associated to red by English-speaking adults. However, not all consistent color-letter associations can be explained by literacy: O is consistently associated to white (in addition to orange) and there is no common word associated with white that begins with an O. It is, therefore, possible that something in addition to literacy and semantic associations influences the observed color/letter associations of non-synaesthetic adults and the color percepts of adults with color-grapheme synaesthesia.

The consistent color mappings observed for a subset of letters may in part reflect interactions among contiguous brain areas based on exuberant connections that were not pruned (Maurer & Mondloch, 2005; Ramachandran & Hubbard, 2001). Evidence from a number of species supports the existence of connections among sensory cortical areas early in development that are pruned by experience during childhood. Anatomical evidence for transient connections among all sensory cortical areas has been found in kittens, and evidence for a specific connection from the auditory cortex to area V4/V8 has been found in infant monkeys (Dehay, Bullier, & Kennedy, 1984; Dehay, Kennedy, & Bullier, 1988; Kennedy, Batardiere, Dehay, & Barone, 1997). Human infants show indirect evidence of such connections in the form of increased activity in the somatosensory cortex when touch is accompanied by white noise (Wolff, Matsumiya, Abrohms, van Velzer, & Lombroso, 1974) and activity in the visual cortex as well as the auditory cortex when hearing spoken language, which diminishes with age and disappears around age 3 (Neville, 1995).

Despite the typical pruning process of development, a few of these connections may remain in all adults to influence sensory associations. In synaesthetic adults, many theorists posit reduced pruning, resulting in stronger connections between contiguous cortical areas that mediate their extra percepts (e.g., Ramachandran & Hubbard, 2001). The fusiform gyrus, which is implicated in the processing of letters, lies adjacent to V4 and V8 in the visual extrastriate cortex, which are implicated in the processing of color (Hubbard et al., 2005; Sperling et al., 2006) and other surface features like texture, which is a common feature of color grapheme percepts (Eagleman & Goodale, 2009). In both areas, there is a systematic organization such that neurons with similar preferences lie contiguous to each other, allowing systematic associations of

specific word forms to specific colors and textures. This explanation helps to explain why color-grapheme synaesthesia is more common than forms of synaesthesia involving non-contiguous areas (e.g., colored odors; Ramachandran & Hubbard, 2001). An alternative account is that synaesthesia is also based on the initial interconnectedness of contiguous cortical regions but posits that it results from the failure to inhibit such connections (Grossenbacher & Lovelace, 2001).

Thus, some color/letter associations may result from the initial cortical organization among cortical areas, remnants of which persevere into adulthood. We use the term *naturally-biased* to refer to such associations, provided that they cannot easily be explained by the learning of specific associations from the environment. For letters, the patterns of consistency in color/letter associations for synaesthetic and non-synaesthetic adults suggest that some associations may be naturally-biased (O/white) while others may be based on literacy and semantic associations (A/red). To differentiate between naturally-biased and learned color/letter associations, we have been studying pre-literate toddlers. Toddlers may recognize the letter A and may know that apples are red, but they do not know that the word apple begins with the letter A and, hence, cannot make the association based on semantic associations to the written word.

In a recent study, we took this approach and found evidence that some systematic mapping of shape to color is naturally-biased (Spector & Maurer, 2008). Specifically, we tested toddlers, older children, and adults on letters that are consistently mapped in adults (i.e., A/red, G/green, O/white, X/black). We found that all three age groups consistently mapped O to white and X to black (Spector & Maurer, 2008), whereas only the literate groups mapped A to red and G to green. Further, the consistent association in toddlers was based upon the shape of the letter and not its sound, suggesting a natural bias between shape and color. This study was the first to suggest that color/letter associations in adulthood could result from the joint influence of naturally-biased and literacy-based learned influences. It is possible that sensory cortical organization may initially determine the binding of color to letter shape in a systematic manner that changes with learning during development.

In the present study, we aim to support the evidence for natural biases between color and shape by exploring the generality of our earlier findings, documenting previously unstudied naturally biased color/letter associations, and determining the characteristics of shape that lead to consistent color mapping. In the first experiment, we investigated whether the results were dependent on having used a forced choice between opponent colors. Specifically, we replicated the findings from Spector and Maurer (2008; toddlers, older children, and adults mapped O/white and X/black; only older children and adults mapped A/red and G/green), using a choice between non-opponent color pairs. In Experiment 2, we examined whether consistent letter/color mapping in toddlers extends to other letters that are consistently mapped to specific colors in both synaesthetic and non-synaesthetic adults, including two that appear related to literacy (B/blue, Y/yellow) and two for which no literary basis is obvious (I/white, Z/black). In Experiments 3 and 4, we looked at whether toddlers' consistent mapping of I to white and Z to black is based upon the sound or the shape of the letter and whether they map smooth and jagged shapes in a similar manner. In Experiment 5, we explored whether toddlers

map letters to colors other than black and white by using letters that synaesthetic and non-synaesthetic adults map consistently to chromatic colors without an apparent literary basis (E/green, M/red, T/blue, C/yellow). The results provide new evidence for shape-color mappings in pre-literate children that appear to be naturally biased and for additional mappings that are acquired as the child learns to read.

General Methods

Design

Each experiment consisted of a training session to introduce the game, validity trials to test for understanding of the task (and hence the *validity* of the experimental data), and experimental trials to test for shape/color associations. In each experiment, training trials were followed by alternating validity and experimental trials. All trials involved a forced choice between two color alternatives, and, unless otherwise noted, each experiment included eight training trials, two experimental and two validity trials with one color pair, and two experimental and two validity trials with a different color pair.

Participants

Toddlers and children were recruited from an established database of parents who volunteered their children for testing during hospital visits shortly after birth. There were different children in each study. Adults were undergraduates originally recruited to participate in other experiments being conducted in the lab, who were subsequently asked if they would like to participate in an additional short experiment ("Would you be interested in participating in an additional experiment that will take two minutes?"). All adults approached agreed to participate in the additional experiment. See Table 1 for details on the participants in each experiment.

General Materials

The test used opaque plastic boxes (16 cm deep \times 31 cm wide \times 18 cm tall) with an interior wooden divider and the outside of each half of the box painted a different color (e.g., red versus green,

black versus white). On the front of each box were two slots with hinged doors through which an assistant (who would not be involved in the testing) could place stimuli before the session and through which participants could reach to remove stimuli. Each box had a wooden occluder (41 cm high \times 61 cm wide) on the back to prevent the experimenter from seeing the colors.

The experimental stimuli consisted of transparent plastic (plexiglass) letters (Experiments 1–3 & 5–6) or shapes (Experiment 4) approximately 10.5 cm wide and 12 cm long. Validity stimuli were made of the same transparent plastic material, of approximately the same size, and represented objects with known colors with which the toddler would be familiar (e.g., tree for green, snowflake for white).

General Procedure

This program of research was approved by the Research Ethics Board of McMaster University. Before testing, the procedure was explained and informed consent was obtained from each participant or from a parent if the participant was a minor. Verbal assent was obtained from older children.

Participants were presented with one colored box at a time and asked to look for each stimulus on the side of the box in which they thought it was "hiding." Toddlers learned the task during a training session with two levels of four trials each (two for each color in the experiment; see Table 2 for training stimuli). In the first training level, the experimenter explained the game by asking the toddler to look for certain color-specific objects in the appropriately colored side of the box (e.g., "We are looking for a frog, frogs are green, can you look in the green side of the box for the frog?"). In the second level, the experimenter asked the toddler what color each object was and what side of the box it was hiding in (e.g., "Now we are looking for a firetruck. Do you know what color a firetruck is? Great, what side of the box do you think the firetruck is hiding in?"). If the child made an error on either level, the experimenter explained the task in a different way (e.g., "Hmmm, what color is a firetruck? OK, so you do you think the firetruck is hiding in this side or this side?") The experimenter pointed to one side, then the other side.). Older children and adults were given an explanation of the task in lieu of the training session.

After training on both color pairs to be included in the test, each participant received a test sequence of four trials in which validity

Table 1

Details on Participants for All Experiments. All Excluded Toddlers Failed to Pass Validity Criterion, and Were Replaced in the Final Sample

| Experiment | # Subjects | Mean age | Age range | # Male | # Excluded |
|------------|-------------------|-------------|--------------|--------|------------|
| 1 | 20 toddlers | 33.1 months | 30–36 months | 9 | 4 |
| 2 | 20 toddlers | 32.5 months | 30–36 months | 11 | 3 |
| | 20 older children | 7.8 years | 7–9 years | 7 | |
| | 10 adults | 20.9 years | 18–28 years | 3 | |
| 3 | 40 toddlers | 33.6 months | 30–36 months | 23 | 9 |
| 4 | 20 toddlers | 32.2 months | 30–36 months | 8 | 2 |
| | 20 older children | 8.1 years | 7–9 years | 12 | |
| | 20 adults | 19.9 years | 18–28 years | 2 | |
| 5 | 20 toddlers | 31.5 months | 30–36 months | 10 | 1 |
| | 20 older children | 7.6 years | 7–9 years | 9 | |
| | 20 adults | 22.3 years | 18–28 years | 10 | |
| 6 | 20 toddlers | 33.4 months | 30–36 months | 9 | 11 |

Table 2
Training and Validity Stimuli for Each of the Colors Used in the Experiments

| Training level | Color | | | | | | | |
|----------------|-----------|-------|------------|--------|-------------|-----------|------------|--------|
| | red | green | blue | yellow | black | white | brown | yellow |
| Level 1 | cherry | leaf | jeans | lemon | witch's hat | tooth | teddy bear | sun |
| Level 2 | firetruck | frog | blueberry | sun | bat | milk | | |
| Validity | heart | tree | water drop | banana | spider | snowflake | n/a | n/a |

and experimental trials alternated within the first color pair (e.g., red/green; see Table 2 for validity stimuli), and then four trials with the second color pair. The order of color pairs was counterbalanced across participants in each age group such that one child received one pair first (e.g., red/green, then black/white) and the next child received the other pair first (e.g., black/white, then red/green). The order of stimulus presentation within color pairs was also counterbalanced across participants in each age group such that if one child received the A first for the red/green color pair (for example), the next would receive the G first. In addition, the side on which each color appeared (e.g., red on the right or on the left) varied across trials for each child during both the training and test phases.

All validity and experimental stimuli were placed in the boxes prior to testing by a second experimenter. On validity trials, the item was placed only on the correct side; the experimenter looked at the front of the box after the child chose to see if the child gave the correct answer and provided feedback. For example, the tree was placed on the green side of the box and the child was told “I am looking for my friend the tree, what side of the box do you think the tree is hiding in?” If the participant reached on the correct side, he/she found the requested object. If a participant reached on the wrong side of the box, the experimenter said “Hmmm . . . maybe it’s on the other side,” and recorded the initial wrong response. If a toddler failed to search for these familiar objects on the appropriate side of the box, we concluded that they did not understand the task and treated their experimental data as *invalid*. Specifically, to be included in the final analysis, participants needed to respond correctly on at least three out of four validity trials (Experiments 1–4) or four out of six validity trials (Experiments 5 & 6).

On experimental trials, the item was placed on both sides of the box and the occluder on the back of the box prevented the experimenter from seeing which side had the color of the expected answer. In all experiments except for 3 and 4, participants were shown the experimental stimulus as it was spoken out loud (e.g., “I am looking for my friend A [ay], A looks like this . . .”). In Experiments 3 and 4, they were either shown the shape (“I am looking for my friend who looks like this”) or heard the sound (“I am looking for my friend A [ay]).” Participants were praised regardless of their response.

To assess knowledge of the alphabet, each toddler was shown a card with four letters; two letters from the experiment and two additional letters. Toddlers were asked to point to a letter on the card as it was named (e.g., “Can you show me the letter O?”). There were two letter cards per experiment, together including all four letters in each experiment, and the letter card used alternated between toddlers. Although all toddlers pointed to two letters on each card, no toddlers correctly identified all four target letters.

Data Analysis

Each participant was given a score based on the proportion of associations made in the expected direction for each pair of experimental letters. For each color pair, we performed a one-sample t-test to see if the proportions were significantly higher than a chance value of .5, one-tailed because we had a directional prediction based upon the literature. Results for individual letters are also presented in the figures for information.

Experiment 1

In our previous study using forced choices between opponent colors, we found that toddlers consistently mapped O to white and X to black but failed to map A to red and G to green (Spector & Maurer, 2008). We initially chose opponent colors because they are maximally distinctive and because Stroop interference in adults with colored grapheme synaesthesia is maximal for opponent colors (Nikolic et al., 2007), a result suggesting that any natural biases might be most likely to be apparent if participants are forced to choose between opponent colors. However, the use of only two choices can lead to what look like strong associations that reflect the color the letter is clearly *not* associated with rather than the color it is perceived to match. For that reason, in Experiment 1, we tested whether our initial results could be replicated when the color pairings were mixed. Specifically, we mixed the red/green opponent color pair with the white/black opponent color pair so that red and green could appear with either black or white, but neither opponent color pair appeared together.

Procedure. We used the same letters (A, G, O, X), and the same colors (red, green, white, black) as Spector & Maurer (2008) but manipulated the color choices so that they were not opponent colors. Each toddler received two experimental trials for each letter pair (O/X, A/G). For the O/X pair, each toddler received one experimental trial in which he/she looked for O in either a red/white or green/white box, and one trial in which he/she looked for X in either a red/black or green/black box. For the A/G pair, each toddler received one experimental trial in which he looked for A in either a red/white or red/black box, and one trial in which he looked for G in either a green/black or green/white box. The color choices alternated between toddlers such that if one child looked for O in the red/white box, then the next child was presented with the green/white box in which to search for O.

Results/Discussion. For the O/X letter pair, toddlers chose in the expected direction (O/white, X/black), $M = .73$ $t(19) = 2.44$, $p = .014$. For the A/G letter pair, toddlers chose colors randomly (A/red, G/green), $M = 0.45$, $t(19) = -0.81$, $p = .21$. See Figure 1). Results for individual letters indicate that the significant effect for O/X was not carried by only one letter in the pair (i.e.,

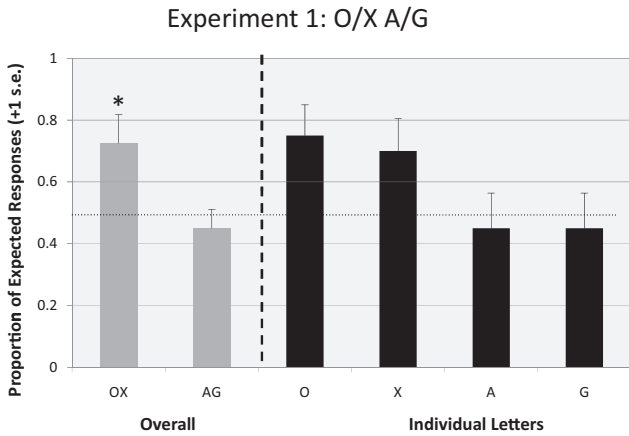


Figure 1. Proportion of responses in the expected direction in Experiment 1, in which toddlers were presented with non-opponent color pairs. The left panel is the overall proportion of responses for each color pair. The dotted line indicates the level expected by chance; the asterisk indicates the significant color-letter pair. Toddlers made color choices in the expected direction for O and X (O-white X-black) and chose randomly for A and G (A-red, G-green). The right panel is the proportion of responses for each individual letter.

O for white was not chosen more than X for black; Figure 1). The mapping of O to white and X to black did not vary systematically whether the competing color was red or green. The findings replicate our original results and suggest that toddlers map O to white and X to black even when given the opportunity to choose a chromatic (and likely preferred) color instead. In the rest of the studies presented in this paper, we explored the generality of these patterns of naturally biased versus literacy-based associations with opponent color choices because they provide the strongest test of whether toddlers make any such associations.

Experiment 2

The purpose of Experiment 2 was to examine additional letters that are consistently associated in non-synaesthetic adults and for which synaesthetic adults have the same consistent color percepts. Specifically, we tested toddlers, older children, and adults on color associations to the letters B, Y, I, and Z (Marks, 1975; Rich et al., 2005; Simner et al., 2005).

Procedure. We tested for the expected associations of one color pair with a literacy explanation, B/blue and Y/yellow, and one color pair with no obvious literacy basis: I/white (with serifs), and Z/black (Canadian pronunciation “zed”) in toddlers, older children, and adults. Each participant received two experimental trials with I and Z and the black/white box and two experimental trials with B and Y and the blue/yellow box, always intermixed with validity trials (see Table 2).

Results/Discussion. For the I/Z letter pair, toddlers, older children, and adults chose in the expected direction (I/white, Z/black), toddlers: $M = .73, t(19) = 2.65, p = .008$; older children: $M = .73, t(19) = 3.33, p = .004$; adults, $M = .80, t(9) = 2.25, p = .025$. For the B/Y letter pair, older children and adults chose in the expected direction (B/blue, Y/yellow), older children: $M = .83, t(19) = 5.94, p < .001$; adults, $M = .95, t(9) = 9.0, p < .001$, whereas toddlers chose randomly, $M = 0.43, t(19) = -0.900, p = .19$. See Figure 2. Results for individual letters indicate that the significant effects are not carried only by one letter of the pair (i.e., I for white was not chosen more than Z for black; Figure 2).

Toddlers mapped both letters without an obvious literary-based association to the expected colors (I/white; Z/black) but responded randomly for the two letters for which it is easy to imagine a literary basis (B/blue; Y/yellow). This is the same pattern that we found in our previous work (Spector & Maurer, 2008) and Experiment 1 in which toddlers consistently mapped the two letters without an obvious literacy basis to their expected colors (O/white, X/black) but responded randomly for the two letters with an

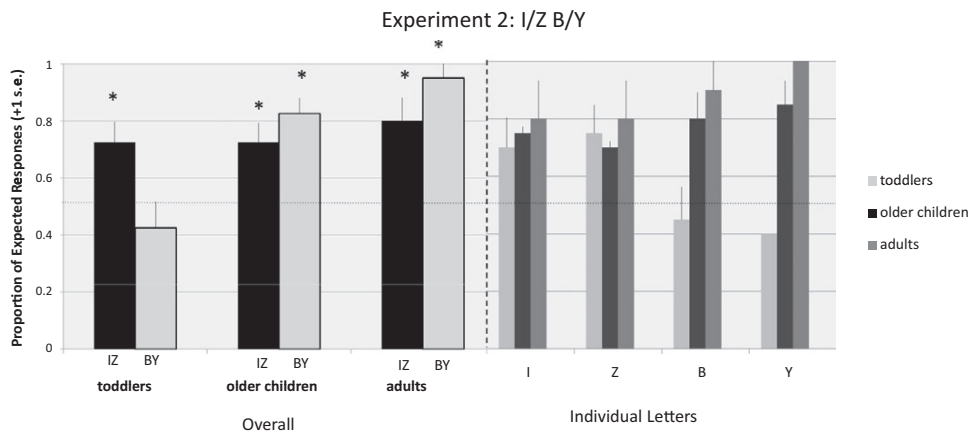


Figure 2. Proportion of responses in the expected direction for the I/Z and B/Y color pairs in Experiment 2. The left panel is the overall proportion of responses for each color pair. The dotted line indicates the level expected by chance; the asterisks indicate the significant color-letter pairs. All three age groups made color choices in the expected direction on the I/Z color pair (I-white, Z-black). Only older children and adults made color choices in the expected direction on the B/Y color pair (B-blue, Y-yellow). The right panel is the proportion of responses for each individual letter in each age group.

obvious literacy basis for their mapped colors (A/red, G/green). Combined, the data suggest that some color/letter associations may be naturally-biased whereas others develop with literacy. Learned associations may override an initial natural bias and/or cause a novel association to form between two previously unconnected attributes. For example, B may be naturally associated to a color other than blue, but learning that B is the first letter of the word “blue” reinforces this new or different association so strongly that it overrides any previous natural biases. Consistent with this, O is commonly associated to orange and I to indigo (classified as blue in some studies; Rich et al., 2005; Simner et al., 2005). However, if no such learning occurs for a particular stimulus or if the naturally biased association is strong enough to appear as a significant association along with those that are learned, then the naturally biased association may remain into adulthood, as we see in the perseverance of the association of I and O to white and Z and X to black in adults. The evidence that the percepts of adults with color-grapheme synaesthesia duplicate the adult associations reported here and in our previous work (Barnett et al., 2008; Day, 2005; Rich et al., 2005; Simner et al., 2005) suggests that the origins of the mappings of synaesthetic percepts and adult associations may stem from the same interaction of learning (BYAG) and natural biases (OXIZ).

Experiment 3

In Experiment 2, toddlers consistently associated I to white and Z to black after hearing the sound of the letter and seeing its shape. The purpose of Experiment 3 was to examine the influence of the sound versus the shape of those letters in a new group of toddlers.

Procedure. Half of the participants ($n = 20$) were shown the letter shape with no verbal label (e.g., “I am looking for my friend who looks like this . . .”) and half of the participants ($n = 20$) were given a verbal label and not shown the letter (e.g., “I am looking for my friend I . . .”). Each toddler received two experimental trials intermixed with four validity trials during each of which they

chose whether the letter was hiding in the black or white side of the box.

Results/Discussion. Toddlers chose the expected colors (I/white, Z/black) when presented with shape only, $M = .73$, $t(19) = 2.94$, $p = .009$, but chose randomly when presented with sound only, $M = .55$, $t(19) = .27$, $p = .789$, See Figure 3. Results for individual letters reveal similar patterns for the two letters (Figure 3).

The results indicate that toddler’s consistent mapping of I to white and Z to black is based upon the shape of the letter and not its sound. This is similar to our previous finding that toddlers map O to white and X to black based upon the shape and not the sound of the letter (Spector & Maurer, 2008). Together, the results indicate that preliterate children consistently map some shapes to white and other shapes to black. Because none of the toddlers could identify all four of the letters on the alphabet test (see general design), it is possible that they processed the letters as basic shapes, rather than graphemes.

Experiment 4

The consistent mappings that we have found in toddlers between shape and color (O and I to white and X and Z to black) persist in older groups and might be determined by angularity of shape. I and O are simple shapes in which the contour is straight or changes direction gradually. Z and X are more complex shapes containing acute angles because the contours abruptly change direction. The purpose of this experiment was to examine the influence of angularity of shape on color mapping by using nonsense shapes instead of letters. Specifically, we presented nonsense shapes with rounded continuously varying contours versus jagged contours with many angles and asked toddlers, literate children, and adults to choose whether the shape was hiding in the black or white side of the box.

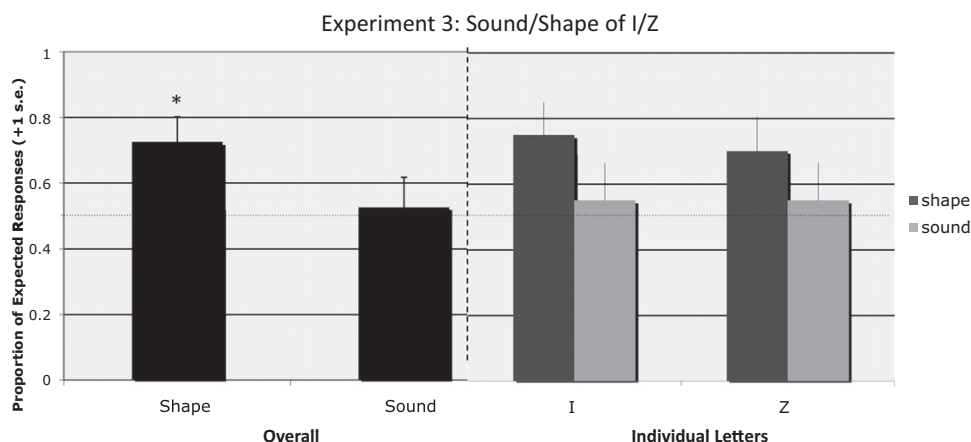


Figure 3. Proportion of toddlers’ choices in the expected direction (I-white, Z-black) for the shape only and sound only conditions in Experiment 3. The dotted line indicates the level expected by chance; the asterisk indicates the significant letter pair. The left panel is the overall proportion of responses for each condition. Toddlers made choices in the expected direction when they were only shown the shape of the letter but not when they only heard its sound. The right panel is the proportion of responses for each individual letter in each condition.

Procedure. We presented toddlers, older children, and adults with a black and white box and two pairs of rounded and angular shapes. Each participant received one pair of rounded/angular shapes matched on contour perimeter, and one pair matched on surface area, intermixed with four validity trials (see Figure 4 for shape examples).

Results/Discussion. Toddlers, older children, and adults chose in the expected direction (jagged/black, rounded/white), toddlers, $M = .66$, $t(19) = 1.83$, $p = .042$; older children, $M = .74$, $t(19) = 2.10$, $p < .024$; adults, $M = .75$, $t(19) = 3.0$, $p = .004$; See Figure 5). Results for the individual shapes suggest a stronger effect for the rounded shape, but the mapping for the angular shape to black was nevertheless above a chance value of .50 for all three age groups (all $ps < .05$; Figure 5).

The results indicate that the roundness versus angularity of shapes' contours influences its color mapping to black and white. This association between non-angular shapes and white and angular shapes and black could reflect experience with the world, such as the shading of jagged versus non-jagged shapes or valence judgments (black/ bad, white/ good). It is also possible that the associations of black to jagged and white to rounded contours reflect natural biases between shape and color lightness, associations which help to bootstrap the later learning of valence judgments for these object characteristics (see General Discussion for elaboration).

Experiment 5

In the results so far, all of the shape/shape associations we have identified in toddlers have involved black or white. Naturally biased associations could be limited to black/white and related to general properties of shape, such as shape angularity, and to affective associations to black and white. The purpose of Experiment 5 was to test for naturally-biased associations between letter shapes and chromatic colors. To do so, we re-examined the corpus of letters with common color percepts in adults with color-grapheme synaesthesia and the letters for which non-synaesthetic adults make consistent color associations both in English and German (Rich et al., 2005; Simner et al., 2005). We restricted the

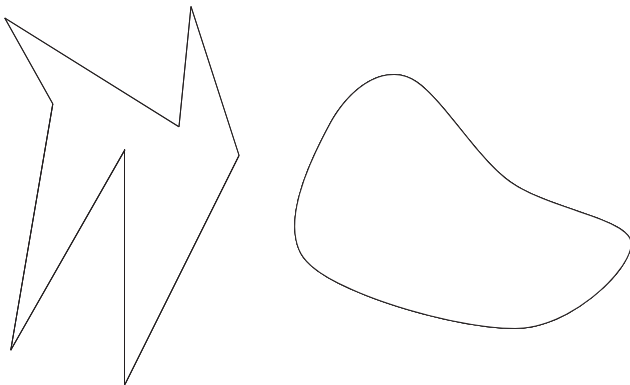


Figure 4. Example of shape stimuli used in Experiment 4. The shape on the left is the jagged angular shape; the shape on the right is the continuous non-angular shape.

choices to letter associations with no obvious literary basis. Specifically, we tested E/green, M/red, C/yellow, and T/blue, in toddlers, older children, and adults. In addition, because the results from Experiment 4 suggest that shape angularity influences color mapping, we examined whether the shapes of the letters in this experiment (E, M, C, T) would be mapped onto black and white based upon shape angularity. Specifically, we predicted that the letter shapes E, M, and T would be more likely to be mapped to black than white, and that C would be more likely to be mapped to white than black.

Procedure. Each participant was tested with two experimental trials (E, M) with the red/green box or black/white box and two experimental trials (C, T) with the yellow/blue box or black/white box, as well as the standard intermixed validity trials. The presentation of colored boxes alternated within each age group such that if one participant was tested on E/M black/white and C/T blue/yellow, then the next child was tested on E/M green/red and C/T black/white, with the order of letter presentation within each pair also counterbalanced. Unlike other experiments, toddlers received only two training trials, and there were two additional validity trials at the end with non-opponent colors (brown/ teddy bear and yellow/sun). We included the additional validity trials because of the possibility, unlike previous experiments, that toddlers would not map any of the experimental letters to the expected choice and, hence, become used to performing randomly. The extra validity trials allowed us to assess whether toddlers were still "playing the game" at the end of the procedure. Toddlers were included in the results only if they were correct on at least four of the six validity trials.

Results/Discussion. For the C/T blue/yellow color pair, toddlers, older children, and adults chose in the expected direction of C with yellow and T with blue, toddlers: $M = .675$, $t(19) = 2.101$, $p = .049$; older children: $M = .68$, $t(19) = 2.33$, $p = .031$; adults: $M = .75$, $t(9) = 3.32$, $p < .001$. For the E/M red/green color pair, toddlers and older children chose randomly, E/M red/green: toddlers: $M = .5$, $t(19) = .83$, $p = .42$; older children: $M = .58$, $t(19) = 1.0$, $p = .33$, while adults chose in the expected direction of E with green and M with red, $M = .682$, $t(19) = 2.16$, $p = .042$; Figure 6). For the black/white comparisons, choices were random in each of the three age groups: C/T black/white [toddlers: $M = .45$, $t(19) = -.81$, $p = .214$; older children: $M = .55$, $t(19) = .7$, $p = .297$; adults: $M = .38$, $t(9) = 1.39$, $p = .095$] and E/M black/white, [toddlers: $M = .575$, $t(19) = .83$, $p = .21$; older children: $M = .5$, $t(19) = .000$, $p = .5$; adults: $M = .5$, $t(9) = .000$, $p = .5$].

Results for the individual letters in the significant C/T pairing revealed that the effects in toddlers, older children, and adults were strong for the C/yellow association, toddlers: $M = .7$, $t(19) = 1.90$, $p = .036$; older children: $M = .8$, $t(19) = 3.27$, $p < .002$; adults: $M = .86$, $t(19)$, $p < .001$, but weaker and inconsistent across age for the T/blue pairing, toddlers: $M = .65$, $t(19) = 1.37$, $p = .093$; older children: $M = .35$, $t(19) = -1.37$, $p = .093$; adults: $M = .6$, $t(19) = .847$, $p = .406$. Toddlers, older children, and adults showed no consistent mapping for any of the individual letters with the other tests (see Figure 6).

The results indicate that at least one letter (C) is mapped to chroma in preliterate children and that the mapping persists into adulthood. The mapping is unlikely to be based on language

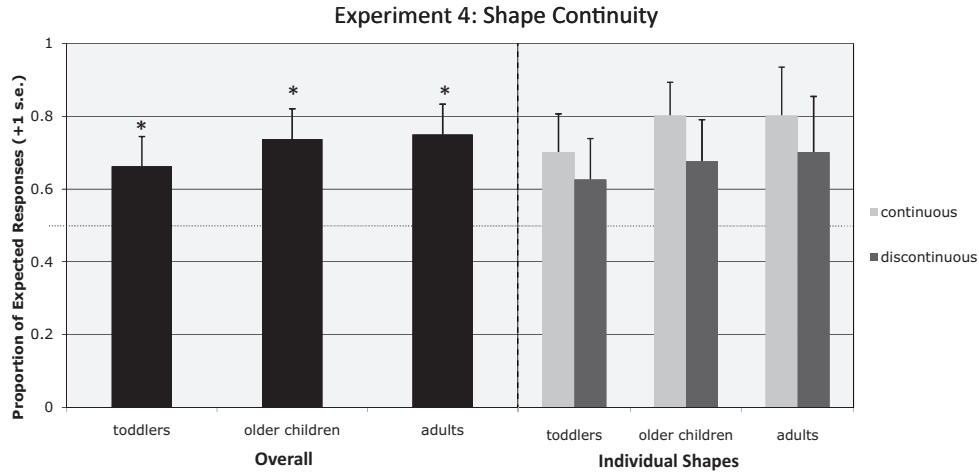


Figure 5. Proportion of responses in the expected direction for the discontinuous and continuous shapes in Experiment 4. The dotted line indicates the level expected by chance; the asterisks indicate the significant pairings. The left panel is the overall proportion of responses in the expected direction for each age group. All three age groups mapped continuous shapes to white and discontinuous shapes to black. The right panel is the proportion of expected responses for each shape in each age group.

associations because the toddlers did not consistently recognize the letters of the alphabet, and there is no obvious language basis for the association. Thus, the results suggest that there are some natural biases to associate letters to both chromatic (this experiment) and achromatic colors (Experiments 1–3).

C, T, E, and M were not mapped to black or white. It is possible that the letters in the present experiment do not differ sufficiently in shape angularity to elicit consistent associations to black and white because the roundness versus jaggedness/angularity of the shape must be pronounced in order to drive those associations. These letters also differ from the letters with consistent mappings to black and white in Experiments 1–4 (O, I, X, Z) in that consistent chromatic associations have been reported (Rich et al.,

2005; Simner et al., 2005) that might interfere with the mapping to black and white.

It is surprising that the adults in this experiment did not map E/green, M/red, and T/blue, as these color-letter pairs were chosen based upon reports of consistent associations among non-synaesthetic English and German-speaking adults as well as synaesthetic adults (Barnett et al., 2008; Day, 2005; Rich et al., 2005; Simner et al., 2005). However, non-synaesthetic adults' color associations to the letters E, M, and T are not as consistent as the color associations to the letters tested in Experiments 1–4 (A, G, O, X, B, Y, I, Z). Perhaps the associations for E, M, and T are too weak to be apparent in a sample of twenty adults, unlike the stronger associations examined in the other experiments.

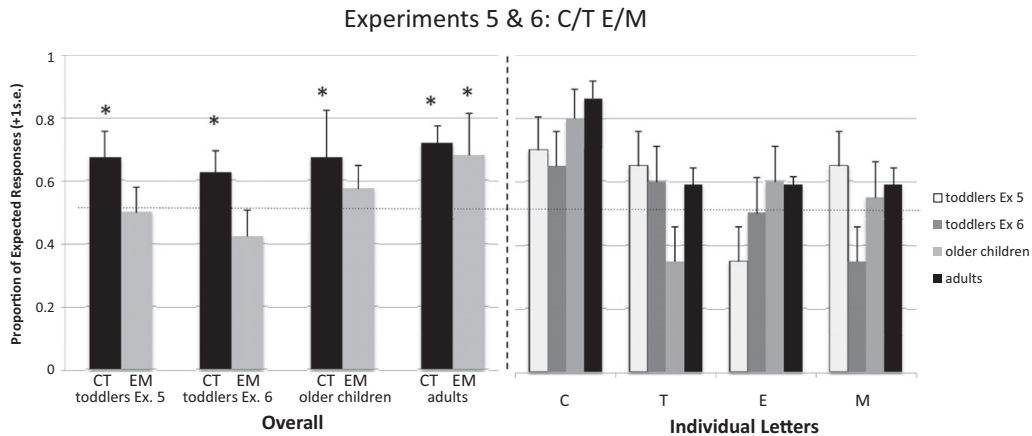


Figure 6. Proportion of responses in the expected direction for the E/M and C/T color pairs in Experiment 5 and 6. The dotted line indicates the level expected by chance; the asterisks indicate the significant letter pairs. The left panel is the overall proportion of responses for each color pair. All four groups made choices in the expected direction on the C/T color pair (C-yellow, T-blue) but not the E/M color pair (E-green, M-red). The right panel is the proportion of responses for each individual letter in each group.

Experiment 6

The purpose of Experiment 6 was to determine whether toddlers' association of C to yellow in Experiment 5 is reliable and whether the trends for any of the other letters could be replicated. We tested a new group of toddlers with the letters used in Experiment 5 and our standard methodology involving four training trials. Only toddlers were tested.

Procedure. Each toddler received two experimental trials (E, M) with the red/green box and two experimental trials (C, T) with the blue/yellow box. As in Experiment 5, we included two extra validity trials at the end involving the presentation of two additional opponent colors (black/spider; white/snowflake). As in Experiment 5, toddlers were included only if they were correct on at least four of the six validity trials.

Results/Discussion. For the C/T pair, toddlers chose the expected color of yellow for "C" and blue for "T" ($M = .63$, $t(19) = 1.75$, $p = .02$). For the E/M red/green pair, toddlers' choices were random ($M = .58$, $t(19) = .90$, $p = .19$, Figure 6). Analyses of individual letters indicated a trend for C/yellow, $M = .65$, $t(19) = 1.37$, $p = .093$, but for none of the other letters (Figure 6). Combining the results across Experiments 5 and 6 indicated that toddlers associated C to yellow, $M = .68$, $t(39) = 2.33$, $p = .025$, but not T to blue, $M = .63$, $t(39) = 1.61$, $p = .115$, E to green, $M = .43$, $t(39) = -.95$, $p = .349$, or M to red, $M = .5$, $t(39) = .00$, $p = 1.0$.

The results of Experiment 5 and 6 indicate that toddlers consistently map C to yellow. This pattern is the same as that shown by literate children and adults in Experiment 5. It indicates that the natural associations between letters and colors extend beyond black and white to include at least one pairing to a chromatic color. Toddlers did not map C to white in Experiment 5, so the consistent mapping of C to yellow is unlikely to be based on the brightness of the color yellow (in contrast to the dullness of the color blue) or a general matching of continuous contours to lighter colors. Although not tested in this experiment, the results of Experiment 3 and our previous work (Spector & Maurer, 2008) suggest that the mapping is likely to be based on the shape of the letter C and not its sound.

General Discussion

The findings suggest that there are natural biases to associate certain shapes to specific colors. In Experiment 1, toddlers searched for O on the white side of the box and X on the black side of the box, in preference to a variety of alternative color choices. Likewise, in Experiment 2, toddlers searched for I on the white side of the box and Z on the black side of the box. There is no obvious literary basis for these mappings, and even if there were, they are unlikely to influence the associations of children who have not yet learned to read. Experiment 3 indicated that the consistent mapping of I to white and Z to black in toddlers is based upon the shape and not the sound of the letter, as we found previously for toddlers' mappings of O to white and X to black (Spector & Maurer, 2008). These mappings may be determined at least in part by angularity of shape: in Experiment 4, all three age groups mapped ameboid shapes formed from non-angular contours to white and irregular jagged shapes formed from acute angles to black. Experiments 5 and 6 indicated that the natural bias to

associate shape to color may not be limited to achromatic color: pre-literate children associate C to yellow, as did the literate children and adults. Collectively, these results suggest that there are natural associations between shape and color.

In contrast to the consistent patterns across age for I, O, X, Z, and C, the results for A/G in Experiment 1 and B/Y in Experiment 2 suggest that learning to read may induce additional color-letter associations. Toddlers did not consistently map A to red and G to green or B to blue and Y to yellow, whereas literate children and adults did. These associations—for which there is a ready literary explanation—appear to be acquired after children learn to read and realize that these are the first letters of the words apple, green, blue, and yellow, which are dominant word associations to these letters. Combined, the results suggest that letter/color associations in adulthood result from the joint influence of intrinsic sensory cortical organization and of the experience of specific associations.

It is possible that the association between shape angularity and color lightness results from experience with the world. For example, under typical lighting, jagged shapes (e.g., Z and X) are likely to have a higher proportion of shaded surfaces than non-jagged shapes. Toddlers may have enough visual experience to associate jagged shapes to black based upon these statistics of the visual world. It is also possible that the associations of jagged shapes to black and non-jagged shapes to white are based upon valence judgments as black and white have very polarized connotations (i.e., black/bad, white/good). Adults seem to automatically process the valence of black and white: they are slower and less accurate in assessing the valence of the word (e.g., happiness, bully) presented in the wrong color (e.g., happiness presented in black) versus the right color (e.g., bully presented in black; Meier, Robinson, & Clore, 2004; see also Sherman & Clore, 2009). There appears to be a similar association between curved contours and valence: adults rate smoothly contoured objects higher on a likeability scale and pointed objects lower, a finding that could result from associations between sharp visual angles and potentially harmful or threatening objects (Bar & Neta, 2006). Adults' valenced judgments of contour angularity and black/white may affect the way parents use language around children, use that, in turn, will come to affect how children treat objects with these characteristics. Consistent with this is evidence that preschool children do make valenced judgments of black and white (Stabler & Johnson, 1972; Stabler, Johnson, & Jordan, 1971; Zentner, 2001). Thus, it is possible that the associations we observed between non-angular shapes (including I and O) and white and angular shapes (including X and Z) and black may be related to the valences associated to non-angular and angular shape and to white and black. While there are clear experiential and cultural cues for learning these valences — sharp objects hurt, dark rooms are scary — it is possible that associations between contour and color lightness may in part reflect some natural biases that help bootstrap later environmental learning.

This interpretation does not easily explain the consistent associations between C and yellow in toddlers, older children, and adults. C has rounded contours but is not associated to white, as we might expect if toddlers were making valence judgments between contour angularity or smoothness and color lightness. It is possible that there is something readily seen by toddlers that is driving the association of C to yellow. However, the similarity of this finding to the findings for the other letters suggest that there may also be

natural biases to associate letters to chroma that are later modified as the child learns to read.

The foundations for natural biases between shape and color (chromatic and achromatic) may lie in initial sensory cortical connections. In adults, each sensory cortical area is specialized for the processing of information from one sensory modality: neurons in the visual cortex respond to input from the eyes; neurons in the auditory cortex respond to input from the ears, etc. There is evidence that sensory cortical areas are initially not as specialized as they will become. Instead, there are functional transient connections among sensory cortical areas that are pruned during childhood in an experience-dependent manner. For example, in the newborn, tactile stimulation of the wrist evokes activity over the somatosensory cortex, as it does in adults, but unlike in adults, the response is enhanced if accompanied by the sound of white noise (Wolff et al., 1974). In young infants, spoken language elicits activity over the auditory cortex, as expected, but, unlike in adults, it evokes just as much activity over the visual cortex; with age, the activity over the visual cortex diminishes, but it does not disappear until about age 3 (Neville, 1995). Converging evidence comes from a study using positron emission tomography (PET) as 2-month-olds watched faces: the faces elicited more activity than the control visual stimulus in the right inferior temporal gyrus, near the classic fusiform face area of adults, but, unlike in adults, they also elicited more activity in the left auditory cortex and left Broca's area that will later be relatively specialized for language (Tzourio-Mazoyer et al., 2002; see also Huttenlocher, 1984, 1994; Huttenlocher & de Courten, 1987; Huttenlocher & Dabhokar, 1997; Huttenlocher, de Courten, Garey, & Van der Loos, 1982). These findings suggest that there are functional connections among sensory cortical areas during early childhood that are later pruned. These connections may allow the system to easily learn to associate information in different sensory modalities (e.g., mom's face and voice, bananas are yellow, large objects make loud noises) to better understand the environment. Thus, sensory associations not based in learning may be a side effect of these initial connections, some of which may persevere into adulthood. Evidence for such extra connections in synaesthetes was obtained in a recent study using diffusion tensor imaging (DTI) to trace white matter tracts: adults with colored grapheme synaesthesia showed evidence of greater connectivity than did controls between brain regions including the word form area in the inferior temporal cortex that lies contiguous to color form area V4/V8, with the strength of hyperconnectivity correlated with the strength of the projection of the synaesthetic colors onto the inducing black letters (Rouw & Scholte, 2007). The perseverance of some of these cortical connections in non-synaesthetic children and adults may remain to mediate sensory associations without the conscious perception that characterizes synaesthesia. Evidence of consistency in some sensory associations between synaesthetes and non-synaesthetes suggests some similarity in which connections fail to be pruned in these two groups. However, the idiosyncrasy of individual synaesthetic associations for other letters suggest that the mechanism of pruning and perseverance of cortical connections plays out in slightly different ways in synaesthetes versus non-synaesthetes.

The current research does not indicate which neural pathways mediate color-letter associations at any stage of development; however, naturally biased functional connections may be more

likely to occur between contiguous brain areas (e.g., Ramachandran & Hubbard, 2001). This idea is consistent with evidence that synaesthesia involving interactions between dimensions mediated by adjacent brain areas occurs more often than synaesthesia involving dimensions mediated by neural areas more remote from one another. For example, V4 and V8 in the visual extrastriate cortex, which are involved in color processing, lie adjacent to the fusiform gyrus, which is involved in word form processing (Hubbard et al., 2005; Sperling et al., 2006). The adjacency of these brain areas may facilitate interaction, leading to the high incidence of color grapheme synaesthesia as well as the ready association of color to letters in non-synaesthetic adults.

An alternative possibility is that some of the associations involve interactions within or among V4 cells that respond to both color and form (Desimone, Schein, Moran, & Ungerleider, 1985). This alternative is suggested by our finding that the naturally biased mappings for O, X, I, and Z appear to be based on the shape and not the sound of the letter (Experiments 1 and 2; Spector & Maurer, 2008), as is the mapping documented in Experiment 3 between black and white and angular and non-angular shapes. They are also present in toddlers for whom letters are not yet meaningful components of words. Rather than being based on interactions between areas involved in word processing and color processing, these mappings might be mediated by structural connectivity between the color and form pathways within the extrastriate visual cortex itself.

Learning to read may induce a processing shift for color-letter associations from the perceptual level (shape-based) to the cognitive level (letter-based). At that point, the posterior parietal cortex may begin to play a larger role in the associations, given its documented role in the binding of color to shape in typical adults (Donner et al., 2002). Evidence that deactivation of the posterior parietal cortex by TMS interferes with color-grapheme synaesthesia suggests that the same perceptual binding mechanisms underlie synaesthetic and non-synaesthetic percepts (Esterman et al., 2006; Muggleton et al., 2007). This conceptualization is consistent with the idea that synaesthesia stems from an exaggeration of sensory mechanisms that are common to everyone, what Mulvenna & Walsh (2006) term "supernormal integration" (e.g., Esterman et al., 2006; Sagiv & Ward, 2006; Simner et al., 2005; Ward et al., 2006).

Our results add to the growing evidence for sensory associations that do not appear to be learned and are consistent across individuals. Many of them involve color and/or shape, like the associations explored here. Similarly, adults report seeing colors and forms when presented with flickering white light that fills their visual field, with the specific associations consistent across subjects and dependent on the frequency and phase of the flicker (Becker & Elliott, 2006). Moreover, specific colors and forms consistently co-occur with one another (including zig-zags with black), providing additional support for the systematic binding of color to form in adults' perceptual system. Naturally biased sensory associations extend to cross-modal associations. For example, toddlers systematically map lower pitch to darker objects, as do non-synaesthetic adults (Marks, 1996; Mondloch & Maurer, 2004; Ward et al., 2006). This pattern also matches the percepts of adults with colored hearing synaesthesia (Marks, 1975; Marks, 1996; Ward et al., 2006) but is not evident in the statistics of the environment (darker objects do not consistently make lower

pitched sounds). Toddlers, like adults, also map nonsense words with non-rounded and rounded vowels (kiki versus bouba) to jagged and rounded shapes, respectively (Lindauer, 1990; Maurer, Pathman, & Mondloch, 2006; Ramachandran & Hubbard, 2001). Like the current results and our previous findings (Spector & Maurer, 2008), these studies suggest that humans have intrinsic biases to make specific cross-dimensional and cross-modal associations.

An additional way to provide strong support for naturally biased associations between shape and color would be to examine this question in other cultures. If there are natural biases between shape and color, then we would expect to find the same consistent associations in non-English speaking toddlers as we do in English-speaking toddlers. Future studies could ascertain whether the association of the letter C to yellow is based upon the shape of the letter rather than its sound, as is the case for the associations between I, O, X, and Z and achromatic color. It would also be worthwhile to examine whether valence judgments of good/bad are what drives the toddlers' associations of non-angular shapes to white and angular shapes to black. To do this, toddlers could be asked to place a shape on the "good" or "bad" side of a box that is half black and half white. Or toddlers could be presented with one "good" shape and one "bad" shape and be asked to put the good or bad shape in the designated side of a homogeneously colored box. It would also be useful to devise a methodology to test infants for the shape/color associations we have found in toddlers. We have used the term "naturally-biased" to refer to associations that cannot be readily explained by learning because they do not appear to occur consistently in the environment. However, toddlers have had over two years of postnatal visual experience, and it is possible the associations were learned indirectly from the environment in ways that are not immediately obvious (such as black = darkness, which is scary and, therefore, bad). Testing infants (old enough for exuberant connections to have been established but before substantial understanding of language) would add to the evidence on whether or not some sensory associations arise from intrinsic sensory cortical organization.

References

- Bar, M., & Neta, M. (2006). Humans prefer curved visual objects. *Psychological Science, 17*, 645–648.
- Barnett, K. J., Finucane, C., Asher, J. E., Bargary, G., Corvin, A. P., Newell, F. N., & Mitchell, K. J. (2008). Familial patterns and the origins of individual differences in synesthesia. *Cognition, 106*, 871–893.
- Becker, C., & Elliott, M. A. (2006). Flicker-induced colour and form: Interdependencies and relation to stimulation frequency and phase. *Consciousness and Cognition, 15*, 175–196.
- Cytowic, R. E. (2002). *Synesthesia: A union of the senses*. Cambridge, MA: The MIT Press.
- Day, S. (2005). Some demographic and sociocultural aspects of synesthesia. In L. C. Robertson & N. Sagiv (Eds.), *Synaesthesia: Perspective from cognitive neuroscience* (pp. 32–33). Oxford, England: Oxford University Press.
- Dehay, C., Bullier, J., & Kennedy, H. (1984). Transient projections from the fronto-parietal and temporal cortex to areas 17, 18, and 19 in the kitten. *Experimental Brain Research, 57*, 1423–1106.
- Dehay, C., Kennedy, H., & Bullier, J. (1988). Characterization of transient cortical projections from auditory, somatosensory, and motor cortices to visual areas 17, 18, and 19 in the kitten. *The Journal of Comparative Neurology, 272*, 68–89.
- Desimone, R., Schein, S. J., Moran, J., & Ungerleider, L. G. (1985). Contour, colour and shape analysis beyond the striate cortex. *Vision Research, 25*, 441–452.
- Dixon, M. J., Smilek, D., Cudahy, C., & Merikle, P. M. (2000). Five plus two equals yellow. *Nature, 406*, 365.
- Donner, T. H., Kettermann, A., Diesch, E., Ostendorf, F., Villringer, A., & Brandt, S. A. (2002). Visual feature and conjunction searches of equal difficulty engage only partially overlapping frontoparietal networks. *NeuroImage, 15*, 16–25.
- Eagleman, D. M., & Goodale, M. A. (2009). Why color synesthesia involves more than color. *Trends in Cognitive Sciences, 13*, 288–292.
- Esterman, M., Verstynen, T., Ivry, R. B., & Robertson, L. C. (2006). Coming unbound: Disrupting automatic integration of synaesthetic colour and graphemes by transcranial magnetic stimulation of the right parietal lobe. *Journal of Cognitive Neuroscience, 18*, 1570–1576.
- Grossenbacher, P., & Lovelace, G. (2001). Mechanisms of synaesthesia: Cognitive and physiological constraints. *Trends in Cognitive Sciences, 5*, 36–41.
- Hubbard, E. M., Arman, A. C., Ramachandran, V. S., & Boynton, G. M. (2005). Individual differences among grapheme-colour synaesthetes: Brain-behaviour correlations. *Neuron, 45*, 975–985.
- Huttenlocher, P. R. (1984). Synapse elimination and plasticity in developing human cerebral cortex. *American Journal of Mental Deficiency, 88*, 488–496.
- Huttenlocher, P. R. (1994). Synaptogenesis in human cerebral cortex. In G. Dawson and K. Fischer (Eds.), *Human behaviour and the developing brain* (pp. 137–152). New York, NY: Guilford.
- Huttenlocher, P. R., & Dabholkar, A. S. (1997). Regional differences in synaptogenesis in human cerebral cortex. *Journal of Comparative Neurology, 387*, 167–178.
- Huttenlocher, P. R., & de Courten, C. (1987). The development of synapses in striate cortex of man. *Human Neurobiology, 6*, 1–9.
- Huttenlocher, P. R., de Courten, C., Garey, L. J., & Van der Loos, H. (1982). Synaptogenesis in human visual cortex – Evidence for synapse elimination during normal development. *Neuroscience Letters, 13*, 247–252.
- Kennedy, H., Batardiere, A., Dehay, C., & Barone, P. (1997). Synaesthesia: Implications for developmental neurobiology. In S. Baron-Cohen & J. E. Harrison (Eds.), *Synaesthesia: Classic and contemporary readings* (pp. 243–256). Malden, MA: Blackwell Publishers, Inc.
- Lindauer, M. (1990). The effects of the physiognomic stimuli *takeete* and *maluma* on the meanings of neutral stimuli. *Bulletin of the Psychonomic Society, 28*, 151–154.
- Marks, L. E. (1975). On coloured-hearing synaesthesia: Cross-modal translations of sensory dimensions. *Psychological Bulletin, 82*, 303–331.
- Marks, L. E. (1996). On perceptual metaphors. *Metaphor and Symbolic Activity, 11*, 39–66.
- Mattingley, J. B., Payne, J. M., & Rich, A. N. (2006). Attentional load attenuates synaesthetic priming effects in grapheme-color synaesthesia. *Cortex, 42*, 213–221.
- Mattingley, J. B., Rich, A. N., Yelland, G., & Bradshaw, J. L. (2001). Unconscious priming eliminates automatic binding of color and alphanumeric for in synaesthesia. *Nature, 410*, 580–582.
- Maurer, D., & Mondloch, C. (2005). Neonatal synaesthesia: A re-evaluation. In L. Robertson & N. Sagiv (Eds.), *Synaesthesia: Perspective from cognitive neuroscience* (pp. 193–213). Oxford, England: Oxford University Press.
- Maurer, D., Pathman, T., & Mondloch, C. (2006). The shape of boubas: Sound-shape correspondences in toddlers and adults. *Developmental Science, 9*, 316–322.
- Meier, B. P., Robinson, M. D., & Clore, G. L. (2004). Why good guys wear

- white. Automatic inferences about stimulus valence on brightness. *Psychological Science*, 15, 82–87.
- Mondloch, C., & Maurer, D. (2004). Do small white balls squeak? Pitch-object correspondences in young children. *Cognitive, Affective, and Behavioural Neuroscience*, 4, 133–136.
- Muggleton, N., Tsakanikos, E., Walsh, V., & Ward, J. (2007). Disruption of synaesthesia following TMS of the right posterior parietal cortex. *Neuropsychologia*, 45, 1582–1585.
- Mulvenna, C. M., & Walsh, V. (2006). Synaesthesia: Supernormal integration? *Trends in Cognitive Sciences*, 10, 350–352.
- Neville, H. (1995). Developmental specificity in neurocognitive development in humans. In M. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 219–231). Cambridge, MA: Bradford.
- Nikolic, D., Lichti, P., & Singer, W. (2007). Color opponency in synaesthetic experiences. *Psychological Science*, 18, 481–486.
- Ramachandran, V. S., & Hubbard, E. M. (2001). Synesthesia: A window into perception, thought, and language. *Journal of Consciousness Studies*, 12, 3–34.
- Rich, A. N., Bradshaw, J. L., & Mattingley, J. B. (2005). A systematic, large-scale systematic study of synaesthesia: Implications for the role of early experience in lexical-colour associations. *Cognition*, 98, 53–84.
- Rouw, R., & Scholte, H. S. (2007). Increased structural connectivity in grapheme-colour synaesthesia. *Nature Neuroscience*, 10, 792–797.
- Sagiv, N., Heer, J., & Robertson, L. (2006). Does binding of synesthetic color to the evoking grapheme require attention? *Cortex*, 42, 232–242.
- Sagiv, N., & Ward, J. (2006). Crossmodal interactions: Lessons from synesthesia. *Progress in Brain Research*, 155, 259–271.
- Sherman, G. D., & Clore, G. L. (2009). The color of sin: White and black are symbols of moral purity and pollution. *Psychological Science*, 20, 1019–1025.
- Simner, J., Mulvenna, C., Sagiv, N., Tsakanikos, E., Witherby, S., Fraser, C., . . . Ward, J. (2006). Synaesthesia: The prevalence of atypical cross-modal experiences. *Perception*, 35, 1024–1033.
- Simner, J., Ward, J., Lanz, M., Jansari, A., Noonan, K., Glover, L., & Oakley, D. (2005). Non-random associations of graphemes to colours in the synaesthetic and non-synaesthetic populations. *Cognitive Neuropsychology*, 22, 1–17.
- Spector, F., & Maurer, D. (2008). The Colour of Os: Naturally-biased associations between shape and color. *Perception*, 37, 841–847.
- Sperling, J. M., Prvulovic, D., Linden, D. E. J., Singer, W., & Stirn, A. (2006). Neuronal correlates of colour-grapheme synaesthesia: A fMRI study. *Cortex*, 42, 295–303.
- Stabler, J. R., & Johnson, E. E. (1972). The meaning of black and white to children. *International Journal of Symbolology*, 3, 11–21.
- Stabler, J. R., Johnson, E. E., & Jordan, S. E. (1971). The measurement of children's self concept as related to racial membership. *Child Development*, 42, 2094–2097.
- Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, 18, 643–662.
- Tzourio-Mazoyer, N., de Schonen, S., Crivello, F., Reutter, B., Aujard, Y., & Mazoyer, B. (2002). Neural correlates of woman face processing by 2-month-old infants. *NeuroImage*, 15, 454–461.
- Ward, J., Huckstep, B., & Tsakanikos, E. (2006). Sound-colour synaesthesia: To what extent does it use cross-modal mechanisms common to us all? *Cortex*, 42, 264–280.
- Wolff, P. H., Matsumiya, Y., Abrohms, I. F., van Velzer, C., & Lombroso, C. T. (1974). The effect of white noise on the somatosensory evoked responses in sleeping newborn infants. *Electroencephalography and Clinical Neurophysiology*, 37, 269–274.
- Zentner, M. R. (2001). Preferences for colours and colour-emotion combinations in early childhood. *Developmental Science*, 4, 489–398.

Received May 23, 2009

Revision received January 13, 2010

Accepted April 19, 2010 ■