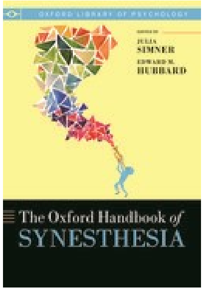

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CHAPTER

3 Synesthesia in Infants and Very Young Children

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Abstract

This chapter provides a review of the hypothesis that synesthetic-like perception is present in infants and toddlers. Infants and very young children exhibit evidence of functional hyperconnectivity between the senses, much of which is reminiscent of the cross-sensory associations observed in synaesthetic adults. As most of these cross-sensory correspondances cannot be easily explained by learning, it is likely that these represent natural associations between the senses. In average adults, these 'natural associations' (e.g., large = loud) are felt only intuitively rather than explicitly. These observations have led to the proposal of the 'neonatal synaesthesia hypothesis', which purports that all individuals are born synaesthetic, with explicit conscious perception of these natural cross-modal associations dissipating over development in typical individuals. This dissipation is likely the result of experience-dependent synaptic pruning and/or inhibition of cross-sensory neural connections. At the same time, cross-modal associations matching those common in the environment might be assumed to be learned. This hypothesis is re-evaluated in light of recent research findings, and is examined in the context of current evolutionary models of neuronal recycling and emerging evidence of longitudinal changes in children with synaesthesia.

Keywords: synaesthesia, development, plasticity, evolution, multimodal processing

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The perceptual validity of synesthesia has been established through behavioral (Asheret al. 2006; Jarick et al. 2009; Novich, Cheng, and Eagleman 2011; Ward, Huckstep, and Tsakanikos 2006; Ward and Mattingley 2006; Ward, Simner, and Auyeung 2005) and neuroimaging (Hubbard et al. 2005; Nunn et al. 2002; Paulesu et al. 1995; Rouw and Scholte 2007; Rouw, Scholte, and Colizoli 2011) evidence; however, its cause and developmental origins remain unclear. Several theories have been proposed as to the origins of synesthesia, such as the neonatal synesthesia theory (Maurer 1993; Maurer and Maurer 1988; Maurer and Mondloch 2004), the cross-activation theory (Hubbard, Brang, and Ramachandran 2011; Ramachandran and Hubbard 2001b), the disinhibited feedback theory (Grossenbacher and Lovelace 2001), and the re-entrant feedback model (Smilek et al. 2001), each generating predictions about normal and atypical cross-sensory development.

The Developmental Origins of Synesthesia

Typical brain development is characterized by two distinct processes: first, the exuberant generation of connections between neurons via the production of synapses, and second, the strengthening of stimulated connections and the pruning away of unused connections—the result being (relatively) distinct sensory areas each specialized to process one type of dominant input (reviewed in Maurer, Gibson, and Spector, 2012). Anatomical tracing, a method in which groups of neurons are labeled with a substance (e.g., a fluorescent dye) such that the pathways connected to, and ultimately structures targeted by, the labeled neurons are visible, has documented this developmental process ↳ in numerous species. Studies using this methodology show that the timing of exuberance and pruning varies across species and sensory modalities (Bourgeois and Rakic 1993; Dehay, Bullier, and Kennedy 1984; Huttenlocher 1984). In humans, this pattern of formation and subsequent pruning of synaptic connections has also been revealed by increases in measurements of glucose utilization over sensory cortical areas during the first 3 to 4 years of life—presumably reflecting the flourishing of exuberant connections in sensory areas—followed by a subsequent decline beginning at about age 9—presumably reflecting experience-dependent pruning (Chugani 1994; Chugani and Phelps 1986; Chugani, Phelps, and Mazziotta 1987). Similarly, studies of resting state metabolism (synchronous increases and decreases in neuronal activity across the brain in the absence of stimulation) and white matter tracks (connections between neurons with axons sheathed in myelin, which speeds neural conduction) indicate that between 7 to 9 years of age and adulthood, the strength of local connectivity diminishes (Fair et al. 2009; Supekar, Musen, and Menon 2009).

The exuberant connections early in development include ones between cortical areas that receive input from different sensory systems (e.g., originating from auditory versus visual versus tactile receptors), and these connections appear to be functional. For example, in newborns, unlike adults, sound amplifies the somatosensory potential evoked by tactile stimulation of the wrist (Wolff et al. 1974). In other words, our early neural response to touch is exaggerated when accompanied by sound. Another example comes from the evoked responses elicited by human speech: in young infants, human speech elicits event-related potentials over both the auditory *and visual* cortices, unlike adults, for whom speech elicits evoked responses only over the auditory cortex (Neville 1995). This pattern of cross-activation by speech diminishes over the first 3 years of life (Neville 1995), suggesting that the connections between auditory and visual cortices are gradually being pruned away. Similarly, at 3 months of age, exposure to speech in comparison to a baseline quiet period causes increases in oxygenated hemoglobin and decreases in deoxygenated hemoglobin not only in the temporal, language-specialized cortex, as is true in adults, but also in the visual cortex (Homae et al. 2011). Neuroimaging (positron emission tomography) data also suggest more widespread activation by visual stimulation during infancy (Tzourio-Mazoyer et al. 2002): when activation evoked by Christmas tree lights is compared to that evoked by a human face, there is differential activity at 2 months of age, not only in areas geographically close to what will become the face area in the fusiform gyrus, but also in a number of other areas, including the right inferior parietal cortex (which is active during many forms of synesthesia; Rouw et al. 2011), the left inferior frontal cortex, and left temporal gyrus, which will later form the core of the language network. Similarly, there is evidence that different pathways in the visual cortex are not initially segregated. For example, adults process color and motion in distinct, parallel ventral and dorsal pathways within the extrastriate visual cortex. This causes motion for adults to be "color-blind," in the sense that adults can discern the direction of moving stripes only if they are of contrasting luminance but not if they vary only in color. Unlike adults, infants 2 to 4 months old can discern the direction of movement of stripes defined by either color or luminance (Dobkins and

p. 48 Anderson 2002). ↳ These results suggest that the motion and color pathways in the visual cortex are not initially as segregated as they will become.

The observation of functional cross-sensory connections in infants, combined with anatomical evidence for increased cross-modal connectivity in synesthetes (Rouw et al. 2011), supports the "neonatal synesthesia hypothesis": that the perception of typical infants is influenced more strongly by cross-modal activation than the perception of non-synesthetic adults, perhaps even to the point that an inducer in one modality can induce a conscious synesthetic percept in another modality or along another dimension (Maurer 1993; Maurer and Maurer 1988; Maurer and Mondloch 2004; Maurer, Gibson, and Spector 2012; Spector and Maurer 2009). Indeed, three recent studies provide empirical evidence for synesthetic-like cross-modal correspondences in young infants (see section entitled "Manifestations of synesthesia-like perception in infants and young children").

The neonatal synesthesia hypothesis proposes that all infants experience a form of synesthesia, but that these cross-sensory percepts are largely eliminated in most people via experience-dependent neural pruning as they develop through childhood into adulthood. This pruning leaves behind remnants that are largely inhibited but nevertheless influence intuitive cross-modal associations (Spector and Maurer 2009). For example, even non-synesthetic adults might sense that higher pitch matches brighter light in some way. The hypothesis suggests that those who experience synesthesia as adults, in contrast, experience less-than-normal synaptic pruning among and between sensory cortices during development, causing some of the functional cross-modal hyper-connectivity observed in infancy to persist into adulthood (Maurer 1993; Maurer and Mondloch 2004; Maurer et al. 2012; Spector and Maurer 2009). In addition, there may be less inhibition of the remaining connections. Consistent with this hypothesis, synesthetes report having experienced their synesthesia "all their lives" and often experience more than one form of synesthesia (Simner et al. 2006), an outcome predicted by less overall pruning and inhibition throughout the brain. Also, consistent with this hypothesis is neuroimaging evidence of activation by black letters and digits in adults with colored grapheme synesthesia of color area V4, which lies contiguous to the visual word form area. Also activated is a network involving other extrastriate visual areas, posterior parietal areas involved in binding color and shape, the insula, the precentral gyrus, and the frontal lobe (Hubbard et al. 2005; Rouw et al. 2011). That these activations result from hyper-connectivity is supported by evidence for increased white and gray matter in much of the same network (Rouw and Scholte 2007, 2010; Weiss and Fink 2009). Although much less extensive, there is similar neuroimaging and anatomical evidence for hyper-connectivity in other forms of synesthesia (Hänggi et al. 2008; reviewed in Hubbard, Brang, and Ramachandran 2011; Rouw et al. 2011).

In the typically developing child, the initial exuberant connections are reshaped by experience so that those that are frequently activated become stronger and those that are rarely used are pruned. The best evidence for this experience-dependent pruning comes from comparisons of typical adults with those who missed auditory ↳ or visual input because of deafness or blindness, respectively. p. 49 In adults who are congenitally blind, unlike adults with normal vision, auditory, tactile, and language input increase activation in the visual cortex. Interference with this activation by transcranial magnetic stimulation (TMS; a method in which magnetic stimulation is applied to the scalp to depolarize neurons in the underlying cortex, effectively disrupting the normal processing of affected cortical structures) degrades accuracy in responding to those inputs (Collignon et al. 2009; Kupers et al. 2007; Lewis, Saenz, and Fine 2010; Pascual-Leone and Hamilton 2001; Pascual-Leone and Torres 1993; Stilla et al. 2008). Indeed, in adult cats whose eyes were removed at birth, neurons in the visual cortex are tuned precisely to auditory rather than visual inputs (other modalities have not been tested) (Yaka, Yinon, and Wollberg 1999). Similarly, in adults who are congenitally deaf, unlike normally hearing adults, visual input increases activation of the auditory cortex (Finney 2003; Finney, Fine, and Dobkins 2001).

Together, these studies suggest that in typical development, dominant input from a single sensory system leads to the specialization of sensory cortical areas through the strengthening and refinement of the synapses it drives. It also leads to the pruning away of other synapses that respond to the less frequent or less coherent input from other sensory modalities. Remnants of the initial cross-sensory connections do remain but they have minimal impact because their influence is dampened by neuronal inhibition. They nevertheless can influence our cross-modal associations (Spector and Maurer 2009). Unlike typical adults, synesthetes appear to have a genetic predisposition for the pruning process to be less complete and for the remaining connections to be uninhibited (Hubbard, Brang, and Ramachandran 2011; Ramachandran and Hubbard 2001a, 2001b). Instead, or in addition, the synesthete may develop less than the normal amount of modulation of the remaining hyper-connectivity by feedback from higher cortical areas (Grossenbacher and Lovelace 2001; Smilek et al. 2001).

Regardless of the origins of synesthesia in adults, the implication is that synesthesia will be a normal phase in typical development, either before experience-dependent pruning is complete, or before inhibition has emerged and been consolidated. Two predictions follow: (1) even in the typical, non-synesthetic adult, functional remnants of cross-sensory and cross-dimensional connections should still exist because of incomplete pruning or inhibition; (2) to the extent that contiguous brain areas are organized systematically by specific stimulus properties (e.g. neurons are contiguous that have the same orientation or color tuning in the visual cortex or the same tuning to auditory frequency in the auditory cortex), there may be similarities in the cross-modal and cross-dimensional associations of typical children and adults and the conscious percepts of synesthetes. In the next section, we present evidence for similarities between the perception of adults with synesthesia and the perception of typical infants and toddlers. We then summarize the two studies documenting changes in the nature of synesthesia during development and in the final section, consider their implications for the neonatal synesthesia hypothesis.

Manifestations of Synesthesia-Like Perception in Infants and Young Children

Evidence of functional hyper-connectivity in early development and of the slow development of inhibitory processes (discussed in the previous section) suggests that young children's perception should resemble that of adults with synesthesia. In this section, we summarize investigations of whether cross-modal and cross-dimensional percepts that are commonly elicited in adults with synesthesia can be observed early in development.

Synesthesia-like perception in infants

Wagner and Dobkins (2011) recently provided the first direct evidence for synesthetic perception in typical infants. They did so by testing for the infant equivalent of colored grapheme synesthesia, which they reasoned would be manifest as the elicitation of a colored percept by basic shapes. Specifically, they presented infants with arrays of triangles on some trials and arrays of circles on other trials, in each case against a background that was half red (or yellow) and half green (or blue). The researchers hypothesized that if either shape evoked a particular color for an infant, that shape would be easier to see against some colors than against others. For example, if an infant perceived red when looking at the triangle, it would be easier for that infant to see the triangle against a green background than against a red background. In this case, the infant should look consistently at the green side when shown triangles, both on trials when the green background was on the right side of the panel and trials when it was on the left side of the panel. Consistent with this hypothesis, infants behaved as though the shapes were colored by exhibiting non-random responses across trials—a result suggesting that synesthetic binding of color and shape is present at 2 months of age for red/green. The same pattern of results was observed in slightly older infants for yellow/blue backgrounds (as expected, given the slower development of yellow/blue channels). This pattern diminished with increasing age, as would be expected if experience-dependent pruning has begun to shape inputs into visual cortical neurons.

Other studies have looked for cross-modal associations in infants that match typical synesthetic percepts in adults with synesthesia. One common form of synesthesia is colored hearing, in which specific pitches evoke specific colors and often shapes as well. Although these pitch to color associations are largely idiosyncratic, higher pitches usually evoke visual percepts of sharp, pointy shapes that are smaller in size and located higher in space, and lower pitches usually evoke percepts of round, amoeboid shapes that are of larger size and located lower in space (Marks 1974, 1975; Melara and O'Brien 1987). To test whether these associations are present early in development, Walker and colleagues (2010) presented 3- to 4-month-old infants with two audiovisual combinations. In one combination, a visual display showed a shape morphing from round and ↳ amoeboid to sharp and pointy, while a whistle changed from low to high pitch (congruent condition) or from high to low pitch (incongruent condition). In a second combination, an orange ball moved up and down the screen while the pitch of the whistle increased and decreased, respectively (congruent condition), or while the whistle first decreased and then increased (incongruent condition). In both experiments, infants looked longer at the congruent displays, a preference that the authors interpreted as a familiarity preference—an interpretation suggesting infants experience common synesthesia-like pitch/shape and pitch/height associations. Even if the authors' assumption of a familiarity preference is unwarranted, the results do indicate that 3- to 4-month-old infants systematically relate pitch and shape, as well as pitch and location. In a separate experiment, Peña and colleagues (Peña, Mehler, and Nespor 2011) found that 4-month-old infants also associate sound with size: when they heard a consonant-vowel pairing with higher pitch vowels such as /i/ (as in feet), they looked longer at the smaller of two geometric shapes, and when they heard the pairing with lower pitch vowels such as /a/ (as in cat), they looked longer at the larger object. These associations may be based on pitch, because the "smaller" sounds had a higher pitch than the "larger" sounds. As it is unlikely that infants have learned these associations from the statistics of the environment (e.g., there is no obvious connection between pointed shapes and higher pitch), these associations may represent natural biases that result from the initial hyper-connectivity of the auditory and visual systems and that persist as conscious percepts in adults with audiovisual synesthesia. Remnants of these associations appear to exert unconscious influences in non-synesthetic adults (Spector and Maurer 2009).

Even when pitch is matched between sound contrasts, infants show systematic associations between sound and shape. Typical adults tend to associate words with rounded vowels (e.g. the phoneme /o/, as in code, or /u/, as in rule) with round, amoeboid shapes, and words with non-rounded vowels (e.g., the phoneme /i/, as in feet) with pointed shapes (Köhler 1929; Lindauer 1990; Ramachandran and Hubbard 2001b). There are additional systematic associations of these shapes to specific consonants (Nielsen and Rendall 2011). Infants just 4 months old make similar sound symbolic matches: when presented with words matched to ameboid shapes (*kiki*) versus jagged shapes (*bubu*) by 98% of English-speaking adults, infants look longer on trials with the incongruent mapping than on trials with the congruent mappings (Orturk, Krehm, and Vouloumanos 2013). Unlike adults, presentation of just the vowel contrast (*kiki* versus *kuku*) or just the consonant contrast (*bubu* versus *kuku*) is insufficient to elicit the congruency effect. By toddlerhood, children explicitly match words with rounded vowels (e.g. go-gaa, maa-boo-maa, go-go, do-do) with round, amoeboid shapes and words with non-rounded vowels (e.g. tee-tay; tuh-kee-tee, gee gee, dee-dee) with sharp, pointy shapes (Maurer, Pathman, and Mondloch, 2006), and do so even when the stimuli contrast only in vowels (*bibi* versus *bobo*) (Spector and Maurer, 2013). It is possible that these associations are based in experience. Having been exposed to language since they were in the womb, it is possible that children become sensitive to the statistical regularities of English semantics, and may have learned that sharp objects often have names with non-rounded vowels (e.g., the last syllable of spiky) and round objects often have names with rounded ↳ vowels (e.g., round, amoeboid). Although that explanation is plausible for the data from toddlers and adults, it seems unlikely to explain the results from 4-month-old infants. Future research could test for the associations at even younger ages and test whether the same relationships hold for synesthetes for whom specific sounds induce specific shapes, as would be predicted if the infants' and toddlers' associations are a consequence of neonatal synesthesia.

Some cross-modal correspondences seen in synesthetic adults can be explained as a manifestation of a common code for magnitude, such that more intense stimuli in one modality induce more intense percepts in another modality. For example, adults with colored hearing synesthesia report that louder sounds induce brighter percepts (Marks 1974, 1975). Similarly, newborn infants habituated to a brighter light exhibit less heart-rate response to the presentation of a louder noise, while those habituated to a darker light show less heart-rate response to a softer noise (Lewkowicz and Turkewitz 1980)—as if they transfer habituation from visual to auditory intensity.

In sum, it is clear that infants experience a number of functional cross-sensory connections, some of which cannot readily be explained by learning and manifest as synesthesia-like perception.

Synesthesia-like perceptions in toddlers

With toddlers, we have investigated a number of other correspondences that are common in synesthetes. According to the neonatal synesthesia hypothesis, the initial hyper-connectivity should be most prominent during infancy, but remnants of it should persist into toddlerhood, and, to a lesser extent, even adulthood. While studies with infants make it easier to sort out the role of experience versus intrinsic wiring, studies of toddlers and older children can be easier to interpret because the child understands verbal instructions.

In addition to the evidence for colored percepts elicited by shapes during infancy (see earlier section entitled “The developmental origins of synesthesia”), there is evidence for color associations to some letters in toddlers that parallel the colored percepts elicited by letters in adults with colored grapheme synesthesia. Thus, both typical toddlers and adults with colored grapheme synesthesia associate X and Z with black, I and O with white, and C with yellow at rates far exceeding chance (Spector and Maurer 2008, 2011). For toddlers, like typical synesthetes with colored graphemes, these associations were observed when they were presented with both the letter shape and sound or just the letter shape, but not when they just heard the sound of the letter. Certain other common associations in colored grapheme synesthesia appear to result from learning to read because there is a ready explanation based on literacy (G is green for English-speaking synesthetes) and because typical toddlers are random while older children who have learned to read make the expected association. This is the developmental pattern for English-speaking children for A/red; G/green; B/blue; and Y/yellow (Spector and Maurer 2008, 2011). Combined, the results suggest that there are some natural ↳ associations between shapes and colors that influence toddlers’ cross-dimensional associations and the actual percepts of adults with colored grapheme synesthesia (Day 2005; Rich, Bradshaw, and Mattingley 2005; Simner et al. 2006). Not surprisingly, remnants of this organization are also evident in the letter/color associations of typical adults without synesthesia (Rich, Bradshaw, and Mattingley 2005; Simner et al. 2006).

Toddlers also associate pitch to surface lightness in the same way as adults with colored hearing synesthesia. Although the exact color elicited by a particular pitch varies among adults with colored hearing, almost universally they report that higher pitches induce percepts of lighter colors: a higher pitched C induces a lighter color than a lower pitched C (Marks 1974, 1975; Ward, Huckstep, and Tsakanikos 2006). A similar pattern is observed in toddlers. This was evident when 2.5- to 3-year-old toddlers observed a display of two balls, one white and one gray, bouncing in synchrony with one another and accompanied by a higher or lower pitched tone (Mondloch and Maurer 2004). When asked which ball was making which tone, the toddlers consistently matched the lighter-colored white ball to the higher pitched tone, and the darker, gray ball to the lower pitched tone. This association is unlikely to have developed through experience with the statistics of the environment, because lighter colored stimuli do not consistently produce higher-pitched sounds than darker stimuli (e.g., white cats do not have higher-pitched meows than black cats). Instead, it is possible that this pairing reflects a natural bias induced by cortical connectivity between neighboring sensory cortices that influences the synesthetic percepts of adults with colored hearing and the cross-modal matches of young children. Remnants of the connections appear to influence the perception of non-synesthetic adults: they also match higher pitches to lighter colors, and are more accurate at judging pitch or lightness when the luminance of a paired distracter is congruent (Marks 1987).

Adults with colored hearing also commonly report that exposure to pitch induces visual images, with higher pitches inducing visual photisms that are smaller in size than those induced by lower pitched sounds (Marks 1975; see section "Synesthesia-like perception in infants"). This association is evident in toddlers: when asked which of two bouncing white balls was making a higher- or lower-pitched sound, 2.5- to 3-year-olds matched the higher pitch with the smaller ball, and the lower pitch with the larger ball (Mondloch and Maurer 2004). It is possible that this association arises with exposure to regularities in the environment because larger organisms tend to produce lower-pitched sounds: the roar of a lion is lower pitched than the squeak of a mouse. However, the association may also reflect a natural bias based in cortical connectivity that is reinforced and strengthened with experience. A role for experience is supported by the fact that children exhibit stronger evidence of making the association at older ages (Marks, Hammeal, and Bornstein 1987).

In sum, in addition to evidence of functional hyper-connectivity in human infants, behavioral evidence lends support to the hypothesis that all infants experience synesthesia-like percepts. The similarity of cross-sensory associations in adults with synesthesia, toddlers, and non-synesthetic adults suggests that remnants of the early hyper-connectivity persist to influence cross-modal and cross-dimensional associations, whether or not it is sufficiently strong to influence conscious perception (as it does in adult synesthetes). Many of these cross-sensory associations cannot be explained by learning, and as such, likely reflect natural biases arising from unpruned and uninhibited exuberant neural connections between contiguous brain areas.

Longitudinal Observations of Developing Synesthetes

One of the most common forms of synesthesia is colored graphemes (Day 2005; Novich, Cheng, and Eagleman 2011; Simner et al. 2006; Ward, Simner, and Auyeung 2005). However, as letters and numbers are culturally-learned stimuli, it is likely that colored-grapheme synesthesia cannot have been present since birth despite the impression of synesthetes that they have had it "all their lives." Instead, it is likely that it was originally manifest as a robust association between color and basic shapes or between color and the sound of words, as suggested by the finding that infants appear to perceive circles versus triangles as differentially colored (Wagner and Dobkins 2011) and the finding that toddlers' associations between letters and colors are driven systematically by the jaggedness of the shape (Spector and Maurer 2008, 2011) (see section "Manifestations of synesthesia-like perception in infants and young children"). Indeed, one adult with colored grapheme synesthesia and colored hearing has preserved pictures she drew as a pre-schooler of the sound of words: it appears that before she learned to read she drew a unique design for each word (Duffy 2001). The sample reproduced in the book resembles a swirling kaleidoscope of three- and four-sided shapes in red, purple, blue, and yellow, overlaid with blue circles and yellow curved lines.

Two longitudinal studies on the development of colored grapheme synesthesia illustrate how the phenomenon changes as children learn to read. Simner and colleagues (Simner et al. 2009) asked a large sample (615) of 6- to 7-year-old British children to choose the best of 13 possible colors for the 26 letters of the English alphabet and the ten numerals from 0 to 9 on an initial test, and on a surprise retest 10 seconds later. Follow-up tests 1 year later with the 46 children who were significantly more consistent than their peers during the first session pointed to eight children who appeared to have colored grapheme synesthesia, or 1.3% of the sample: their color choices were more consistent over 12 months than those of their peers after 10 seconds during the first session. Interestingly, across the 12 months, the putative synesthetes became more consistent, moving from having on average 10.5 stable grapheme-to-color associations (29%) during the first session to16.9 stable associations (43%) during the second session 1 year later. Even so, at age 8, more than half of the graphemes were not consistently colored for these putative synesthetes, a far larger proportion than lack color for adults with colored grapheme synesthesia (Mills et al. 2002).

p. 55 A similar picture emerges from our longitudinal study of three pre-school English-speaking children of mothers with colored grapheme synesthesia (Spector and Maurer, unpublished data). Because synesthesia tends to run in families, we knew that the likelihood that these children would have some form of synesthesia was higher than in the general population. Moreover, all three children were making comments from the start of our observations suggesting that they experienced some colored graphemes. Over 1 to 2 years, beginning at age 3.5, 3.75, or 4.5 years, the three children were asked to choose from among 96 crayons, the best one or ones to color the 26 letters of the alphabet, the digits 0 to 9, and four basic shapes. Once the child had colored all of those stimuli, with no more than one given per day, the cycle was repeated, with a total of six cycles for one child, and three cycles for the other two children. As a baseline against which to evaluate consistency, we tested non-synesthetic control children on two cycles of the same task at the age corresponding to each synesthete's 1st and 2nd cycle, and, for the child with six cycles, between the 5th and 6th cycles, with four controls for each time point and stimulus. Each control child was tested with ten of the stimuli.

From the first test, each putative synesthete reported having very specific color associations to the graphemes. Parents recorded comments like: "This is definitely blue, but not dark blue, this blue"; "The right green is not in this box, but this is as close as I can find"; "This letter is always gray like rain clouds." Such comments are reminiscent of reports of how specific and adamant adult synesthetes are about their synesthetic colors. The three putative synesthetes were far more consistent (55%) than their age-matched controls (0%), but less consistent than adults synesthetes (Baron-Cohen et al. 1996). Moreover, consistency between later cycles (cycles five to six, or for the children with only three cycles, cycles two to three; age 4.5 to 5.5 years: 75%) was much higher than between the first two cycles (age 3.75 to 4.75 years: 40%), perhaps because learning to read altered the neural representation of the letters. Most of the inconsistencies during the first two cycles were small, such as purple changing to red or a letter colored yellow changing to half yellow/half orange. Tests of letter knowledge indicated that children progressed from some basic letter knowledge at the beginning of testing to complete letter and letter-sound knowledge by the end of testing. Like studies of color-shape associations in typical toddlers (Spector and Maurer 2011), these data suggest that there may be intrinsic connections between graphemes and color that are modified as children learn to read and those graphemes take on meaning.

At the initial meeting, all children were tested on immediate and delayed recall for letters, numbers, colors, objects, and shapes. On the immediate test, two of the three synesthetic children showed a much higher rate of recall than age-matched controls (see Table 3.1). After a 5-minute delay, only one synesthetic child showed a much higher rate of recall than controls (see Table 3.1). It is important to note that the synesthetic children who did not perform better on the memory tests appeared bored with the task (perhaps because their procedure was much longer than that for controls), and thus their performance may be more reflective of a lack of attentiveness than a lack of memory. However, the evidence of superior memory in some of the children is consistent with ↳ evidence that adult synesthetes have a better memory for stimuli related to their synesthesia (Yaro and Ward 2007) or, in some cases, more generally (Gross et al. 2011). p. 56

Table 3.1 Correct responses on a memory task consisting of immediate and delayed recall for four each of colors, letters, objects, numbers, and shapes. Memory scores for synesthetic children (GK, BP, and ED) are presented in raw scores (number correct). Memory scores for controls are the mean of correct responses across the three controls for each synesthetic child

Immediate	**Colors**	**Letters**	**Objects**	**Numbers**	**Shapes**	**Overall**
GK	4	2	4	4	2	3.2
Control average	2.75	3.25	4	3	3.25	3.25
BP	4	4	4	2	4	3.6
Control average	0	1.5	2.25	1.5	2.25	1.5
ED	4	3	4	4	4	3.8
Control average	2	1.75	2.5	1.25	2.5	2
Delay	Colors	Letters	Objects	Numbers	Shapes	Overall
GK	3	0	0	0	0	0.6
Control average	2.75	2.25	4	3.5	3.75	3.25
BP	0	4	4	2	4	2.8
Control average	0	0.8	0.8	0.4	0.8	0.56
ED	0	2	0	0	0	0.4
Control average	0.5	0.75	1.25	0.75	1	0.85

In sum, although synesthetes report having their particular forms of synesthesia “all their lives,” longitudinal data on the general population of 6- to 7-year-olds and on pre-school children growing up in synesthetic homes suggests that the nature of synesthesia changes as children enter and progress through school, at least for colored grapheme synesthesia: their color associations to graphemes become more consistent and more graphemes induce consistent choices. It is not clear whether these changes represent the emergence of synesthetic percepts that are greater in number, stronger, or more salient and/or an increase in the stability of the color induced, which may be as strong perceptually at all ages. Children’s comments in our longitudinal study favor the latter hypothesis because they described very specific colors from the start, much like synesthetic adults.

Reconsideration of the Neonatal Synesthesia Hypothesis

Studies of typical infants and young children (see "Manifestations of synesthesia-like perception in infants and p. 57 young children" section) provide support for the neonatal ↳ synesthesia hypothesis: before they learn to read, typical children associate some shapes to specific colors and make systematic cross-modal associations that are not explained easily by mere learning of the statistical regularities in the environment. In at least some cases, these associations match common percepts induced in adults with synesthesia. Studies of emerging colored grapheme synesthesia (see section "Manifestations of synesthesia-like perception in infants and young children") also provide support by showing that its manifestation in pre-literature children has many of its later hallmarks: highly specific induced colors and consistency over time. What seems paradoxical is that the consistency increases with age and learning to read and that, like so many other forms of synesthesia (e.g., ordinal space synesthesia for days of the weeks or months of the year; gustatory synesthesia induced by words), it involves a culturally learned inducer that children learn postnatally.

An evolutionary perspective is useful in thinking about this paradox. Such culturally learned stimuli developed fairly recently, long after the brain had evolved to process color, shape, touch, flavor, etc., processing systems that are well-conserved across mammalian species. Dehaene and Cohen (2011) have hypothesized that the neural representation of such cultural stimuli makes use of existing cortical specialization by recycling neuronal architecture best suited for the types of computations needed. In the case of reading and writing, they speculate that the neural recycling took advantage of brain areas already adept at processing objects and faces. Support for this hypothesis comes from their findings for the visual word form area in the left temporal cortex, which sits next to color area V4, that is active in colored hearing and colored grapheme synesthesia. In typical adults (synesthetes have not been studied), the visual word form area responds more to strings of letters than to line drawings of objects, scrambled words, or scrambled objects. This specialization for letter processing/reading is evident in adults who know how to read, whether they learned as adults or children, but not in illiterate adults (Dehaene et al. 2010). At the same time, the visual word form area responds to other objects—to faces, houses, tools, and patterns of checks—but the response to at least some of these categories is smaller in literate than in illiterate adults, as would be expected if reading is making use of neurons that would otherwise be used to process objects. From this perspective, colored grapheme synesthesia would not be expected to emerge in its adult form before the child has begun to learn to read so that hyper-connectivity between the reshaped visual word form area/fusiform gyrus and color area V4 can be manifest. Before the child learns to read, the same hyper-connectivity could be manifest in other forms, such as colored facial features, shapes, or sounds. Consistent with the neuronal recycling account, graphemes that are encountered most frequently have the strongest representation in the visual word form area (Dehaene and Cohen 2011) and elicit correspondingly brighter synesthetic percepts in adults with colored grapheme synesthesia (Beeli, Esslen, and Jäncke 2007; Cohen Kadosh, Henik, and Walsh 2009; Simner 2007; Smilek et al. 2007). For similar reasons, graphemes learned early (1, 2, 3) or learned in association with specific colors, such as those on fridge magnets (Witthoft and Winawer 2006), may be strongly represented in the visual word form area and elicit especially p. 58 strong or consistent colors in those individuals with the hyper-connectivity leading to ↳ colored grapheme synesthesia. Similarly, culturally based ordinal sequences, such as the days of the week or the months of the year, may be represented in the right parietal cortex because its pre-existing properties make it best suited to represent them by neuronal recycling—and as they become represented there, they easily become linked to other properties represented in the parietal cortex in those with hyper-connectivity, namely, spatial position and/or colored shapes (Hubbard et al. 2005).

Remnants of neonatal synesthesia are evident in typical adults (Spector and Maurer 2009) as intuitive cross-modal associations and subsequent influences on behavior. These remnants may be sufficiently strong to induce synesthetic percepts after the use of drugs that reduce inhibition (e.g., lysergic acid diethylamide (LSD)) or after hypnosis (Cohen Kadosh et al. 2009). Nevertheless, they appear insufficient to support the induction of synesthesia through training without altered states of consciousness. Non-synesthetic adults can learn to associate a specific color to a specific letter through many hours of training or through years of linking numbers to colors in activities such as cross-stitch needlepoint (e.g., one cross-stitching system uses the number 3 to denote red thread and the number 7 to denote yellow etc.; Elias et al. 2003; Meier and Rothen 2009; Rothen, Wantz, and Meier 2011). Nonetheless, these individuals do not experience those colors perceptually, although they may show congruency effects in a Stroop-type task: trainees are slower to name the font color of digits if these colors conflict with their learned associations (i.e., slower to name the font color of digit 3 if this is yellow versus red). This is much like the interference found in genuine synesthetes—who are slower for colors that conflict with their synesthesia—even though the non-synesthetic trainees do not experience synesthetic percepts (Elias et al. 2003; Meier and Rothen 2009).

Recent evidence of unexpected plasticity in the adult brain (reviewed in Bavelier et al. 2010) suggests that there are manipulations that might increase the efficacy of the remnants of the original hyper-connectivity. For example, pharmacological interventions that reduce neural inhibition (e.g., Rösser et al. 2008), engaging in aerobic exercise (e.g., Colcombe and Kramer 2003), and playing action video games (e.g., Li et al. 2011) all appear to induce heightened plasticity in the adult brain. However, it is not clear that doing so would be desirable—after all, the function of experience-dependent pruning is to tune the individual's brain to match the stimuli in his or her environment. It leads to sensory cortices that are relatively specialized and efficient for specific functions. Sudden strengthening of the residual hyper-connectivity—unlike spending years of development learning about a world formed of a combination of "real" and synesthetic percepts—might lead to a loss of sensitivity to the building blocks of perception.

In summary, we have shown that infants and young children exhibit functional hyper-connectivity between the senses, much of which is reminiscent of the cross-modal associations observed in synesthetic adults. The recent research findings reviewed in this chapter lend cogent support to the hypothesis that all individuals experience something like synesthesia as infants, with remnants of these cross-modal associations still observable in adulthood, either explicitly in synesthetes or implicitly in all other people.

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