The Developmental Learning Hypothesis Of Synaesthesia - A Summary

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Introduction

For most of us, the letters on this page all appear black. But other people experience each letter as having its own colour. For others, certain sounds have distinct tastes, odours, or shapes. And still other people experience numbers, days of the week, or months of the year as being arranged on a convoluted path through the space around their body. The term for these and other such experiences is *synaesthesia*.

Synaesthesia has proven difficult to define formally. Psychologists and neuroscientists seem to have settled on a working definition: a condition in which a category of stimuli reliably elicit experiences of some additional properties that are not really "in" the stimuli. In the modern literature, a stimulus that elicits the unusual experiences is called the *inducer*, while the unusual experience itself is called the *concurrent*. Different forms of synaesthesia are usually specified by the formula *inducer-concurrent*. Thus for *grapheme-colour synaesthetes*, the inducers are graphemes (letters and numerals), and the concurrents are the colours the synaesthete associates with them.

Although synaesthesia might sound like a kind of hallucination, it bears little resemblance to the effects of psychosis or psychotropic drugs. Concurrents are reliably triggered only by particular inducers (sensed or sometimes imagined), and their association is automatic, stable, consistent, and not typically accompanied by other perceptual disturbances. Scientific and informal reports have documented all kinds of inducers, perceived or imagined, and all kinds of concurrents, within or outside of the sense modality in which the inducer is perceived, with varying degrees of perceptual vividness. This can range from the mere association of a perceptual quality, e.g. letters reliably cause the synaesthete to think of particular colour categories, to richly sensory experiences such as actually *seeing* the colour at a location in space outside the body (Ward, Li, Salih, & Sagiv, 2007).

Our interest is in how and why synaesthesia develops. In some sense, the developmental question is inseparable from the question of mechanism, the question of what is going on neurologically when an inducer triggers a concurrent in the brain of a synaesthete. After all, trivially, the question of how and why synaesthesia develops is the question of how and why the underlying mechanism comes into existence. Nevertheless, we might be able to understand the mechanism by which synaesthesia occurs without understanding how that mechanism comes into existence, or understand important factors about the development of synaesthesia without knowing exactly how it is manifested in the brain. We propose a *Developmental Learning Hypothesis* of synaesthesia, which states that synaesthesia arises, at least in part, as a strategic response to specific learning challenges faced by children. We believe that this hypothesis is compatible with all existing theories of the neuronal mechanisms of synaesthesia.

In what follows, we briefly review some of the major theories of the general nature, neural basis, and developmental origins of synaesthesia, concentrating on grapheme-colour synaesthesia. We argue that the developmental picture given by these theories is incomplete, and present the Developmental Learning Hypothesis as a potential alternative or addition to the existing theories. Finally, we discuss a specific prediction stemming from the Developmental Learning Hypothesis about the rates of grapheme-colour synaesthesia in different linguistic groups, a prediction that we are currently testing using a large-scale survey of synaesthetic tendencies in the Canadian and Czech populations.

High and low in synaesthesia
Synaesthesia is one of the more bizarre phenomena to have attracted the attention of cognitive scientists. Particularly unusual is the way synaesthesia seems to involve an interplay between “high level” conceptual factors and “low level” perceptual factors. Grapheme-colour synaesthesia involves associations between what many think of as a set of essentially cognitive or linguistic categories (the letters) and purely sensory categories (the colours).

This interplay has proven hard for researchers to characterize theoretically. Some have insisted that synaesthesia is a perceptual phenomenon with essentially no cognitive characteristics (e.g. Cytowic, 1989; Cytowic, 1995). This position has proven hard to maintain in the light of evidence of synaesthetic inducers (e.g. Myles, Dixon, Smilek, & Merikle, 2003; Smilek, Dixon, Cudahy, & Merikle, 2002) and concurrents (Dixon, Smilek, & Merikle, 2004) that, on the face of it have a straightforward conceptual or cognitive aspect to them. One response to such evidence was to propose a taxonomy which segregates “low” from “high” synaesthesia (Hubbard & Ramachandran, 2005; Ramachandran & Hubbard, 2003; Ramachandran, Hubbard, & Butcher, 2004). According to this taxonomy, low synaesthesia has both perceptual inducers and perceptual concurrents, while high synaesthesia has conceptual inducers and conceptual concurrents.

More recent work has found that the varieties of synaesthesia cannot be accurately classified in this way, since many of them involve both "low" and "high" processes (Ward et al., 2007). For instance, a synaesthete might see the number 6 as pink whether it occurs as the written word “six”, a pattern of dots on dice, the numeral “6”, someone holding up six fingers, or simply as a thought. This could be described as a case of conceptually induced synaesthesia, since the pinkness appears to be induced by an abstract concept, i.e. that which is common to all the concrete representations of the number six. It is clearly the number 6, not the numeral “6” that is associated with the colour pink. This same synaesthete, however, might describe her experience in clearly perceptual terms: she sees a patch of pinkness floating at a particular location in physical space, such as a meter in front and thirty centimeters to the left of her head. This apparent tension between the conceptual and perceptual aspects of synaesthesia remains unresolved in the literature to date. We will return to this issue when discussing our own hypothesis of the development of synaesthesia.

The development of synaesthesia - current theories
Whatever else goes on in the brain of a synaesthete, there must be an unusual relationship between the neural activity associated with the inducing stimuli and that associated with the concurrent experiences. Synaesthete brains are different from non-synaesthete brains. All prominent modern theories of the mechanisms underlying synaesthesia assume that these mechanisms are responsible for a “breakdown” or reduction in neural modularity (e.g. Bargary & Mitchell, 2008; Baron-Cohen, Burt, Smith-Laittan, Harrison, & Bolton, 1996; Cohen Kadosh, Henik, & Walsh, 2009; Hubbard & Ramachandran, 2005; Maurer & Mondloch,

2005). These theories typically propose that synaesthesia is caused by extra neural connections between the cortical areas responsible for processing inducers and the areas responsible for processing concurrents (e.g. Bargary & Mitchell, 2008; Hubbard & Ramachandran, 2005), or by the selective *de-inhibition* of signals passing from inducer to concurrent areas due to differences in the levels of neurotransmitters present at the synapses (Cohen Kadosh & Henik, 2007; Cohen Kadosh & Walsh, 2008; Grossenbacher & Lovelace, 2001; Ward, Huckstep, & Tsakanikos, 2006). The de-inhibition theory also predicts increased connectivity between inducer and concurrent areas (consider the classical Hebbian dictum “neurons that fire together, wire together”), but according to this theory the increased connectivity should be seen as a consequence, not the cause, of synaesthesia (Jäncke, Beeli, Eulig, & Hänggi, 2009; Cohen Kadosh & Walsh, 2008). Consistent with both types of theory, imaging studies have shown that grapheme-colour synaesthetes tend to have increased structural connectivity in the fusiform gyrus, sub-regions of which are involved in the processing of letters and colours (Jäncke et al., 2009; Rouw & Scholte, 2007).

Whatever the exact neural basis of synaesthetic experiences, there is a further etiological question: what causes synaesthetes’ brains to develop in this peculiar way? The standard answers invoke a genetic mutation as the significant causal factor. The mutation would make the development of synaesthesia probable (perhaps highly so) against certain background conditions of human neural organization and development (trivially, in the case of grapheme-colour synaesthesia, the individual must learn graphemes). There are a few suggestions for how a genetic mutation might produce the abnormal connectivity of a synaesthetic brain. A popular idea is that synaesthetes have a mutation in a gene affecting neuronal "pruning" (e.g. Bargary & Mitchell, 2008; Ramachandran & Hubbard, 2001; Spector & Maurer, 2009), a process in which connections are hypothesized to decrease among functionally specialized neural structures, making them more modular (Dobkins, 2009). A genetic mutation in synaesthetes, the proposal holds, attenuates this pruning in or between areas of the brain involved in processing the inducers and concurrents, and this accounts for the extra connections (relative to normal brains). Similar proposals have also been made regarding the possibility of decreased inhibition (Cohen Kadosh & Walsh, 2008).

These proposals have the great advantage of simplicity. They posit only one causal force that leads to the development of synaesthesia. Further, they are consistent with the very clear evidence that there is a genetic component to synaesthesia, both from familial studies (e.g. Barnett et al., 2008; Baron-Cohen et al., 1996) and from genetic analysis (Asher et al., 2009). However they are, at the very least, incomplete. Synaesthetic associations are much less stable in children than in adults, and these associations only gradually stabilize over several years (Simner, Harrold, Creed, Monro, & Foulkes, 2009). None of the genetic proposals indicate what might cause this progressive stabilization. Further, it is clear that factors other than genetics will be required to explain why synaesthetes make the *particular* associations they do between inducers and concurrents, e.g. why one synaesthete associate “Y” with a pale yellow while another associates it with lime green (cf. Ramachandran et al., 2004; Spector & Maurer, 2009).

The Developmental Learning Hypothesis of synaesthesia:
According to the Developmental Learning Hypothesis (DLH), synaesthesia develops as an aid to learning, a strategy, albeit not necessarily a conscious one, for solving any of a variety of common conceptual problems in early childhood. The DLH is neutral with respect to the underlying neurological mechanisms and genetic basis of synaesthesia, and so complements existing theories. It predicts that there will be architectural or functional abnormalities in the cortices of synaesthetes, but suggests that these abnormalities do not "just happen", resulting in synaesthesia. Rather, they are in part the *result* of inducer-concurrent associations that are first, in some sense, *made* in early childhood.. And whatever the role of genetics in synaesthesia, the DLH asserts that synaesthesia's utility as a solution to specific learning problems is a key factor in its development.

If the DLH is correct, we can expect synaesthesia to develop as part of, and so concurrently with, the solution to specific learning problems, to have a positive effect on the acquisition of specific knowledge, and to be generalized as a learning strategy to similar domains in some children. There are any number of problems that children find conceptually challenging, but some particularly common ones include understanding sequences and the relations among ordered elements and categorizing physical and abstract properties. This is, we speculate, why the inducers of synaesthetic experiences are most often taken from domains such as the days of the week, the months of the year, numbers, letters, or musical notes (Simner et al., 2006b). These inducers are all learned as members of ordered sequences, and several of them also require difficult perceptual categorizations (such as identifying letters, as discussed below, or the different musical notes). Though the DLH is meant to apply to synaesthesia in general, we continue to concentrate on the specific case of grapheme-colour synaesthesia. The specific hypothesis in this case is that associating letters with colours helps children with the multiple and difficult tasks involved in becoming literate.

Although the implementation of any learning strategy would naturally seem to involve cognitive processes, the concurrents in grapheme-colour synaesthesia — colours — are usually regarded as perceptual. And because colours are perceptual, it seems bizarre that they could be simply “conjured up” in the requisite way. Child synaesthetes, after all, are not taking hallucinogens or using other direct, physical interventions to trigger their concurrents. How, then, could a “high level” strategy affect the development of “low level” sensory systems? As noted above, the puzzle about an interaction between high-level or conceptual factors and low-level or perceptual factors is a puzzle at the heart of grapheme-colour synaesthesia itself. And yet grapheme-colour synaesthesia exists — an apparently low-level, perceptual experience is somehow coupled with the experience of a sign with learned, conventional significance. The solution we offer to this puzzle involves a reconsideration of the nature of colour perception, one which treats colour perception as a learned ability with important “high-level” or cognitive aspects. In the next section we briefly present some of the key elements of this view of colour vision, and in the following sections we sketch some of the difficulties children face when becoming literate, and explain how colours, understood in this new light, might help solve some of these problems.

The nature of colour perception
We naturally assume that from the moment of birth the infant is confronted with a cacophony of sensation, experienced but not yet understood — scarlet red, a mother's voice, a tickle on the sole of a foot, hunger pangs, a dog's bark, kisses on the belly and the like (cf. Maurer & Mondloch, 2005; Maurer & Mondloch, 2006). According to one way of thinking, dating back at least to Locke (Locke, 1690), infants begin to conceptualize experiences when they learn to organize these basic percepts into similarity sets. For example, a sensation of focal green is identified as paradigmatically "green", and then new colour percepts are added or rejected as members of the category "green" on the basis of similarity. As more colour categories emerge, similarity relations between the colour categories can then be recognized (e.g. the category "red" is more similar to "orange" than it is to "green"). This is still the predominant view of view of colour conceptualization in colour development research, even among the most sophisticated of researchers (e.g. Pitchford & Mullen, 2003).

According to this view, then, learning to categorize colours is merely a matter of comparing "raw" colour sensations and recognizing their inherent similarities or differences. Intuitively, this does not seem like a very difficult task. Given this view, it is puzzling that children acquire colour terms relatively late. Most children learn colour names between the ages of 4-7, long after they have acquired the names for common household objects, exotic and domestic animals, persons, machines and other concrete objects. Moreover, while children may know many colour terms from age 2 or even younger, colour names are first applied at random and often without regard for property type (Baldwin, 1989; Cruse, 1977; Darwin, 1877, cited in Bornstein, 1985; Modreski & Goss, 1969; Nagel, 1906;). This is so despite the fact that by 4 months of age, infants may have some basic colour categorization abilities, as determined by a preferential looking task (Bornstein, Kessen, & Weiskopf, 1976), and by 3 years of age, children can sort coloured papers and group objects according to colour (Baldwin, 1989; Brian & Goodenough, 1929; Itskowitz, Strauss, & Gross, 1987; Melkman, Koriat, & Pardo, 1976; Suchman & Trabasso, 1966). Thus at a time when a number of colour categorization skills appear to be well in place, the acquisition of colour terms still poses a challenge for children.

An alternative way of understanding colour vision can account for this difficulty, and may illuminate the puzzling interaction in synaesthesia between "high level" processes such as letter categorization and "low level" ones such as colour perception. On this view, the human visual system uses spectral or wavelength information for a wide variety of visual tasks, only one of which is "colour vision", the perception of colour, e.g. seeing grass as green, the sky as blue, etc.

As is well-known, light behaves in some respects like a wave. Considered as such, it has, among other properties, amplitude (the "height" of the waveform, corresponding to the light's intensity) and wavelength (the distance between identical points on two consecutive waves). Almost any light source emits light of many different wavelengths, each at a particular amplitude/intensity. Such a pattern of different intensities of different wavelengths is known as a *spectral power distribution* (SPD) of a light source. The principal source of light on earth is sunlight which, as it reaches the earth, contains wavelengths through and beyond the range visible to humans. When sunlight interacts with the various media of the world, e.g. by being reflected, refracted or absorbed, its SPD and direction are affected in law-like ways. The amplitude and wavelength of light, then, both carry information about the media that have interacted with this light, that is, information about the distal world (Aaron et al 2005). Thus any visual system that can independently register amplitude and wavelength has two distinct sources of information about the furniture of the world.

There is now a great deal of evidence that the human visual system distinguishes luminance (intensity/amplitude) from spectral (wavelength) information (for a review, see Merigan & Maunsell, 1993). There is also increasing evidence that human vision uses spectral information, in conjunction with luminance information, for the vast majority of visual tasks. Some of these visual tasks include the processing of: linear apparent motion (Cavanagh, Tyler, & Favreau, 1984; Gegenfurtner & Hawken, 1995; Willis & Anderson, 1998); depth from parallax motion (Cavanagh, Saida, & Rivest, 1995); depth from stereopsis (Kingdom & Simmons, 1996; Simmons & Kingdom, 1997); texture segregation (Gorea & Papathomas, 1991; Martini, Girard, Morrone, & Burr, 1996; Wang & Dana, 2006); object coherence (Gegenfurtner, 1998; Kooi, De Valois, Switkes, & Grosof, 1992); scene segmentation (Kingdom, Beauce, & Hunter, 2004; Kingdom & Kasrai, 2006; Kingdom, Rangwala, & Hammamji, 2005); object shape (Davis & Driver, 1997; Gheorghiu & Kingdom, 2007; Kingdom et al., 2005; Kingdom, Wong, Yoonessi, & Malkoc, 2006; Mullen & Beaudot, 2002; Zaidi & Li, 2006), and object recognition (Wurm, Legge, Isenberg, & Luebker, 1993). What remains controversial is how dependent human vision in general is upon spectral processing, relative to luminance processing.

We can now begin to see why the late development of colour-naming abilities might not be as puzzling as it seemed on the standard view of colour vision. On a Lockean view of human vision, the job (or at least *a* job) of the colour system is to present colour sensations to the mind. The task of categorizing the colours is hardly more than a matter of noting the inherent similarities of these sensations and then “projecting” them upon the world’s furnishings. On the broader understanding of “colour” vision that we have outlined above, human vision has two sources of information about the world, intensity and wavelength, and two parallel systems for processing these types of information, the luminance and spectral systems. Both the luminance and spectral systems have the same overall function: *to see the world and its many properties.*

In vision research, it is widely accepted that human luminance vision requires a long period of post-natal development. We acquire the capacities for scene segmentation, depth processing, shape recognition, object identification, texture segregation, motion processing, the organization of objective visual space, and a myriad of other functions over a period of many years. One among the many tasks that the infant must learn is that of lightness constancy, or the ability to judge the objective lightness or darkness of an object independently of illumination. This is a computationally complex process that begins to appear, in rudimentary form, around 4 months of age (Chien, Bronson-Castain, Palmer, & Teller, 2006).

Analogously, spectral vision must also develop, with new uses for spectral information learned over time. Here, there is good initial evidence that the capacities of spectral vision accrue on their own timetable, a month or so behind luminance vision (Dobkins, Anderson, & Kelly, 2001; Dobkins, Anderson, & Lia, 1999; Dobkins, Lia, & Teller, 1997; Dobkins et al., 1999). Just as the luminance system eventually establishes the capacity for lightness constancy, a child will learn to use both spectral and luminance information for colour constancy, that is, for judging the objective colour of an object independently of illumination.

It is important to realize that on this broader view, our ability to see colour in the world — e.g. to see a kiwi as green or a traffic light as red — is not a low level visual process. It is not a matter of receiving colour sensations, organized according to their mutual similarity and projected upon the world. What our visual system receives is a retinal image, a spatial pattern of light reflected from the distal object. However, there is no neat relationship between the spectral properties of this retinal image ("image colour") and the inherent tendency of every object to reflect light as a function of wavelength ("object colour"). The kiwi on the table may well be green, but the *image* of the kiwi is quite another matter. This is because numerous other factors, in addtion to the colour of the kiwi itself, affect the spectral composition of its image: the angle, direction and SPD of the light source, the kiwi's shape and texture, the inter-reflection of light between the kiwi and nearby objects, the distance from the kiwi to the viewer, the intervening atmosphere and any number of other properties. Colour constancy, learning to recognize the colours of the distal world, is as computationally complex as the problem of lightness constancy, and with a host of additional confounds.

Where does this leave the development of colour perception? Intuitions and conventional wisdom notwithstanding, colour experiences are probably not paradigmatic examples of basic "sense data" given from birth. Hence colour conceptualization is probably not a simple matter of dividing our colour sensations into similarity sets and projecting them upon the world. Learning to wield spectral information is just like learning to use luminance information. And beginning to see objects as having surface colour is a far more complex process than learning to see objects as being light or dark. In other words, colour perception is probably a slowly acquired cognitive capacity. This suggestion is corroborated by Pitchford and Mullen's (Pitchford & Mullen, 2001; Pitchford & Mullen, 2002) finding that the acquisition of colour terms is not delayed if compared to the acquisition of terms for general properties of objects (big, small, round, square, slow, fast), as opposed to terms for object categories (e.g. dog, cat, couch, spoon). In retrospect, this makes a good deal of sense. Colours are *properties* of objects, not *types* of objects (at least if we set aside talk of colour sensations). In any event, it is clear that the acquisition of colour names is a significant event, both cognitively and physiologically[1], for young children.

So on this new way of thinking about colour the idea that colour-grapheme

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1. Recently, Franklin et al (Franklin et al., 2008a; Franklin et al., 2008b) have shown that while adults have lateralized colour categorization effects for the left hemisphere, seven month old toddlers are right lateralized for colour categorization. Once colour terms are used correctly and consistently, colour categorization undergoes a shift to the left hemisphere, consistent with adult physiology.

synaesthesia might be *learned* should not be quite as mysterious. Learning to see that particular objects have particular colours is on par with learning to see that particular unintelligible squiggles have particular shapes. Both letter recognition and colour perception are complex, cognitive tasks.

The challenges of literacy

There are a great number of different learning challenges involved in becoming literate, three of which we will consider in relation to the DLH. First, children often find it difficult to learn their letters. This is partly because there are a lot of letters, many of which look quite similar (e.g. "P" and "F"), and learning large category structures is not easy. However it is also because letter recognition presents a unique set of problems for the visual system. As this unusual nature of letter shapes is not often mentioned, we discuss it in some detail below. Second, as well as recognizing letters, children must learn to recognize the connection between each letter and the phoneme(s) it represents. Third, children must become masters of the ordered sequences of letters that constitute written words. This involves both being able to keep track of the position of each letter in a sequence and being able to generate a corresponding sequence of phonemes with appropriate stress patterns.

It is usually not noted how unique the task of letter recognition is. Letter recognition is not, and could not be, a mere sub-class of the normal process of recognizing shapes, that is, shapes *of objects* – either physical objects or (two-dimensional) images of physical objects. Unlike the identities of physical objects, the identities of letters are not invariant on rotation. A teacup, rotated around any axis, presents a different form to the eye, but the perceiver implicitly understands that the shape of the teacup itself remains constant from whatever angle it is seen. Whatever the specific form of human visual shape recognition, children have learned to recognize this type of invariance from infancy onwards. In contrast, grapheme identity is *perspective-relative*, from the point of view of the reader. The letter 'b', on left-right rotation, becomes the letter 'd'; the letter 'w', rotated downwards, becomes the letter 'm'. In other words, it is not possible to identify letters if one treats them as physical objects in space, subject to the conventions of standard shape recognition. Learning to see letters, then, involves relearning many of the perceptual rules by which one identifies virtually any other shape in the world.

A large part of this relearning involves overriding one's natural tendencies to understand the shape of objects as perspective-invariant, and learning to "hold in place," relative to one's own viewpoint, each grapheme in order to identify it. This is supported by several pieces of evidence. Consider the ability of most children in the initial stages of literacy to read and write the mirror images of letters, which is then lost in adulthood but may reappear following brain damage (Balfour, Borthwick, Cubelli, & Della Sala, 2007; Cornell, 1985; Cubelli & Della Sala, 2009; Della Sala & Cubelli, 2007; Schott, 2007). Further, Dehaene et al. (Dehaene et al., 2009) have recently shown that for French and Japanese adults, the mirror images of pictures of objects have a robust priming effect on the timing of object identification, whereas the mirror images of words, in either language, do not prime word identification. The effect of mirror invariance was localized, using fMRI, to the *visual word form area*, an area of cortex that is specialized for the perception of written words and letters (Cohen & Dehaene, 2004). Thus written stimuli are treated like any other objects by pre-literates, but learning to read and write involves learning a new, perspective-relative form of shape identification.

Grapheme-colour synaesthesia as a learning strategy

There are many ways in which grapheme-colour synaesthesia could help with the various challenges faced by a child developing literacy. Here we offer a few suggestions relating to the three challenges discussed in the previous section. Without a great deal of further research, it is of course impossible to know which of these, if any, actually play a role in the development of synaesthesia. The idea is simply to allow the reader to see the richness of the of possibilities that associations between letters and colours could open up to the child.

One potential use of colour is as a simple mnemonic for letters. Several studies on adult synaesthetes have shown that synaesthetic colours can be powerful memory aids (Mills, Innis, Westendorf, Owsianiecki, & McDonald, 2006; Smilek et al., 2002; Yaro & Ward, 2007). Children learning their letters might take advantage of the colour categories they have recently mastered by connecting these now familiar categories to the still meaningless squiggles that are letters. Of course this association is arbitrary, but so are many proven mnemonic strategies. One common example is the so-called *method of loci*, in which individuals remember items by associating them with particular locations in a familiar area or building. This has been shown to allow astonishing feats of memory (Raz et al., 2009), yet it is just as arbitrary as associating letters with colours.

If colour can be used as a long-term memory aid for letters, it might also be useful in the short term, when the child is trying to read an unfamiliar word by sounding it out. One of the difficulties here is keeping the letters in precise order in short term memory. This is critical in languages such as English, where the phoneme associated with a letter changes depending on the sequence of letters surrounding it (e.g. consider the way that changes in the order of the surrounding letters change the sound of “a” in “rats”, “rates”, “rattles”, “later” and “latter”). Remembering a sequence of colours may be easier than a sequence of monochrome squiggles. If this is the case, then translating a written word into the correct sequence of phonemes ought to be easier for a young grapheme-colour synaesthete than for someone who lacks the benefit of letter colours.

Another way synaesthetic colours could be used is to indicate relationships *between* letters. We perceive some colours (e.g. two different shades of red) as similar, and others (e.g. red and green) as dissimilar. Colour gives us a *similarity space* in which every coloured object is positioned relative to every other coloured object, and these relationships can be used as indicators of relationships in other domains. It is known, for example, that numerals representing larger magnitude numbers tend to be associated with brighter colours by grapheme-colour synaesthetes (Cohen Kadosh et al., 2009), and that for music colour synaesthetes there is a correspondence between distances among elements in a tonal space (notes) and distances among their coloured concurrents (Head, 2006). Thus the space of synaesthetic colour concurrents encodes information about the relationships among the elements in the inducer domain. (This appears to be a manifestation of a general tendency in human analogy-making and association-forming to preserve similarity relationships in domain-to-domain mappings - e.g. the common tendency to think of notes as “high” or “low” preserves acoustic similarity relationships in a spatial domain.)

As children become colour "experts", abstract relationships among elements in a inducer domain might be easier to process when encoded in a colour space. In the case of grapheme-colour synaesthesia, similar shapes could be associated with dissimilar colours, to make them easier to tell apart. Alternatively, letters which are rotational variants of each other (such as b and d) could be encoded as different shades of the same hue. Here, the same category of colour, say, green, serves to point out the set of letters which are easily confused and to act as a warning flag to provoke extra attention. Further, if both shape and phonemic information were included in the colour space, this might allow for the relationships between letters and phonemes to be characterized in terms of colour, which could also be of great assistance to the child. We are currently investigating this issue in the laboratory.

Grapheme-colour synaesthetes not only perceive individual letters as having colours, but also tend to see each word as having its own unique colour. In some instances, the colour associated with a particular word appears to be random; nevertheless, statistical analyses of multiple synaesthetes have revealed a number of factors that influence the colour concurrents of words. For example, colour words such as “blue” are associated with the colour they name far more often than by chance (Gray et al., 2002), which provides a simple clue to the word’s meaning for a beginning reader. Perhaps more interestingly, one of the strongest influences on word colour is the colours of the letters that make it up (Simner, Glover, & Mowat, 2006; Ward, Simner, & Auyeung, 2005). Often, the colour of the word is the same as the colour of the stressed vowel or consonant in the word (so the noun CON-vict might be the colour of the letter “o”, while the verb con-VICT might be the colour of the letter “i”, Simner et al., 2006). This means that the synaesthetic colour of these words represents an interaction between their orthography, phonology and prosody, which has the potential to be a powerful tool for someone learning to read.

Finally, an intriguing possibility is that grapheme-colour synaesthesia might aid with the recognition and categorization of individual letters. As noted above, this is a difficult task that requires developing a new mode of shape perception. But this raises an obvious paradox: if the child needs to first recognize a letter in order to “assign” its synaesthetic colour, the colour concurrent cannot be an aid to shape recognition. An interesting way out of this paradox is to recall that spectral information is used to discern multiple visual properties — e.g. object shape, depth, motion, and colour — and that these properties are mutually constraining. For example, information about shadows or shading can help lead to conclusions about shape; information about depth can contribute to the determination of surface colour. The proposal here is that synaesthetic colour might influence a hypothesis-testing procedure for determining letter shape.

According to hypothesis-testing models of perception, the processes leading to perception of an object involve repeatedly and rapidly testing and revising hypotheses on the basis of sensory input and further processing, with the “best-supported” hypothesis “winning out” and becoming the dominant perception (e.g.

Gregory, 1966). In synaesthesia, it could be that a tentative hypothesis about letter colour is used to constrain the formation of hypotheses about letter shape and identity, and the interactions between these hypothesized colours, shapes, and identities refine and revise themselves until a particular letter is actually perceived and the appropriate colour is actually experienced. This might allow for more rapid letter recognition. We know that spectral information is used by human vision "all the way up", from very low to high level visual processes, and it is possible that synaesthetic colours generated by a "high-level" strategy have an effect "all the way down" to low-level shape recognition processes.

As noted above, these potential uses of synaesthesia are not intended to be an exhaustive list of the possibilities. There are likely many more, and only careful experimentation would be able to determine which are actually used. But they do make clear just how wide the field of potential uses of synaesthetic colours is for children developing literacy. We postulate that a similar set of possible uses can be found for many other varieties of synaesthesia, which is why we offer the Developmental Learning Hypothesis as an account of synaesthesia in general, and not just grapheme-colour synaesthesia.

A specific prediction: testing the hypothesis

Synaesthesia, according to the Developmental Learning Hypothesis, develops as a strategic response to specific learning challenges that children are faced with in the course of their development. The various types of learning problems that children encounter may be one explanation for the various kinds of synaesthesia. Other factors, notably a genetic predisposition, may also play important roles in determining whether some variety of synaesthesia develops, but the DLH denies that a complete explanation need refer only to normal learning and an abnormal gene.

Becoming literate, as we have noted, is a difficult challenge for any young mind. However it is not equally difficult for learners in every linguistic environment – it is easier to learn to read and write some languages than others. This fact suggests a way to test our hypothesis. If grapheme-colour synaesthesia develops in response to the challenges faced by children as they become literate, it ought to be more common in cases where these challenges are greater. Thus we predict that grapheme-colour synaesthesia will be most prevalent among people who grew up speaking languages that are especially difficult to read and write, and will be least prevalent among speakers of languages in whcih the task of becoming literate is easier.

One factor that influences how easy a language is to learn is its degree of *orthographic transparency*. *Orthography* roughly means "spelling", though more accurately it refers to the correct way to write a language given all its elements (graphemes, diacritics, and other symbols). A perfectly transparent (or shallow) orthography pairs each grapheme with just one phoneme (a basic sound of the spoken language) – the same symbol always indicates the same sound. Departures from one-to-one pairing make a language more orthographically opaque (or deep). Some languages with highly transparent orthographies include Greek, German, Finnish, Welsh, Italian, Turkish, Spanish, and Czech. English, on the other hand, is one of the most orthographically opaque languages: it is both *polyphonic* (most of its graphemes can indicate more than one phoneme) and *polygraphic* (phonemes are indicated by more than one grapheme, e.g. the *schwa* in unstressed syllables is spelled with different vowels in different words). Other things being equal, an opaque orthography makes reading more difficult for children learning to read (e.g. Ellis et al., 2004; Seymour et al., 2003), and it may also have an influence on learning letters outside the context of words.

When Anglophone children learn letters, they must learn both to recognize each letter (a meaningless squiggle) and to memorize its name. These letter names are not entirely arbitrary with respect to their phonemic contributions (many letter names, such "bee" for B or "dee" for D, begin with phonemes commonly indicated by these graphemes). However, the opacity of English orthography means this is always a matter of degree, depending in any given case on just how consistently a grapheme indicates the relevant phoneme(s) throughout the language. Moreover there are cases (e.g. H, W, and Y) where the letter's name bears no relationship to its sound. And finally, the opaque orthography of English means that English letter names cannot simply be the sound they indicate, since there is no single sound that any letter indicates. In a nearly transparent orthography such as Czech, however, almost all letters indicate unique sounds, so these sounds can naturally serve as the letters' names – each letter has a ready-made label which is already meaningful to the child who has have mastered their spoken language. We suggest that the non-arbitrary nature of letter names in languages such as Czech may make the task of learning individual letters, prior to learning to read, easier.[2] Thus Czech children may have a double advantage in the development of literacy, as both learning to categorize letters and learning to recognize ordered strings of these letters (words) should be easier for them.

If grapheme-colour synaesthesia is more likely to arise when children are learning a particularly difficult written language, then we should expect a direct correlation between the opacity of orthographies and the frequency of grapheme-colour synaesthesia among native speakers of their language. We are beginning to test this hypothesis with a survey of native Czech and English speakers, followed by a computerized verification procedure, to determine the incidence of colour-grapheme synaesthetes among the two linguistic groups. If the Developmental Learning Hypothesis of synaesthesia is correct, we should find a higher incidence of grapheme-colour synaesthesia in the English than in the Czech population, but roughly the same amount of other forms of synaesthesia. Such a difference would be tantalizing evidence in favor of the hypothesis.

2. Unfortunately a literature search did not turn up any studies which test this claim.

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