THE COLOURS AND SHAPES OF THE WORLD: TESTING PREDICTIONS FROM SYNESTHESIA ABOUT THE DEVELOPMENT OF SENSORY ASSOCIATIONS

By

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Abstract

The present collection of studies examines how sensory information is interrelated, and how that changes with age and experience. The hypotheses motivating the research were based on the sensory associations of adults who experience concrete inter/intra-sensory linkage, known as synesthesia. Adult synesthesia can inform the study of perceptual development, and even of language, because it appears to represent one way in which normal developmental mechanisms can play out. Using insights gained from adults with synesthesia, we derived novel hypotheses about cross-modal and cross-dimensional links likely to be present in early childhood and to persist in muted form in non-synesthetic adults.

The research reported in Chapters 2 and 3 was an examination of the learned and naturally biased influences on the development of one type of intermodal sensory association. Specifically, it investigated whether colour-letter associations found in adults reflect learned versus naturally-biased influences between shape and colour. Results from these two studies suggest that pre-literate children (2.5-3 years old) show natural biases to associate certain shapes to certain colours, which can be manifest as colour associations to letters. Naturally-biased associations between shape and colour appear to be based, in part, on the angularity of the shape. In addition to the same naturally biased colour letter associations found in toddlers, older children (7-9 years old) and adults showed colour letter associations that appear to be based in literacy, since they were not present in pre-literate toddlers. The research reported in Chapter 4 was an examination of cross-modal associations between sound and shape. Specifically, it investigated the influences of consonant and vowel sound on the mapping of words to shape in toddlers. Results from this study suggest that the vowel sound of a nonsense word can reliably predict its association to a shape with specific characteristics (rounded versus jagged). Such natural biases may help bootstrap language learning. The research reported in Chapter 5 was an examination of cross-modal associations to odour. Specifically, it investigated whether there any consistent cross-modal associations between odour and either colour or texture. Results from this study suggest that there are consistent colour and texture associations to odours, some of which do not appear to be based in experience. Across studies, pre-literate toddlers, older children, and/or adults provide evidence that stimulus characteristics reliably relate to one another cross-dimensionally and cross-modally. Further, sensory associations in adulthood appear to result from an interplay of learning and natural biases, and non-synesthetic adults and toddlers show consistent, naturally-biased sensory associations similar to those seen in synesthesia.

The work presented in this thesis reveals the value of deriving hypotheses from the phenomenon of adult synesthesia about the interplay of learning and natural biases in the formation of sensory associations.

Preface

Each of the experimental chapters in this thesis are manuscripts authored by myself and Daphne Maurer. Chapter 2 has been published in the journal of *Perception.* The following documents my contribution to each of the manuscripts contained in this thesis (Chapters 2-5).

Chapter 2: The Colour of Os: Naturally biased associations between shape and colour, is a manuscript that has been published in the journal *Perception* (issue 37, pages 841-847). This paper includes 3 experiments. I did the background research and designed each of these experiments under the guidance of Daphne Maurer. I then created the experimental materials by hand. I was directly responsible for testing the 60 toddlers, 60 older children and 30 adults who participated in Experiments 1, 2 and 3, and coded the data from all participants. I then analyzed the data, interpreted it, and drafted the manuscript, which was subsequently edited by Daphne Maurer.

Chapter 3: The colours of the alphabet: Naturally-biased associations between shape and colour, is a manuscript in preparation for submission to a scientific journal. This chapter includes 6 experiments. The rationale for these experiments were largely based upon the results from the experiments in Chapter 2. I designed all 6 experiments under the guidance of Daphne Maurer, and created the experimental materials by hand. I was directly responsible for testing the 140 toddlers, 60 older children, and 40 adults who participated in all 6 experiments, and coded the data from all participants. I then analyzed the data, interpreted it, and drafted the manuscript, which was subsequently edited by Daphne Maurer.

Chapter 4: Early sound symbolism for vowel but not consonant sounds, is a manuscript in preparation for submission to a scientific journal. This chapter includes 2 experiments. I did the background research and designed both experiments under the guidance of Daphne Maurer. I then created the experimental materials by hand. I was directly responsible for testing the 60 toddlers who participated in both experiments, and coded their data. I then analyzed the data, interpreted it, and drafted the manuscript, which was subsequently edited by Daphne Maurer.

Chapter 5: Making sense of scents: The colour and texture of odours, is a manuscript in preparation for submission to scientific journal. This chapter includes 1 experiment. I did the background research and designed the experiment under the guidance of Daphne Maurer. I then gathered the materials from various sources. I tested the 80 adults who participated in this experiment, and coded their data. I then analyzed the data, interpreted it, and drafted the manuscript, which was subsequently edited by Daphne Maurer.

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Chapter 1: Introduction

The purpose of this program of research was to examine how sensory information is interrelated, and how that changes during development with maturation and experience. At birth, babies can already recognize their mothers' voices (DeCasper & Fifer, 1980; Ockleford, Vince, Layton & Reader, 1988), but they must learn to associate that voice to the correct face. During development, we learn many sensory associations between related stimuli, like the sound "ay" with the written letter "A", and a perfumey smell with the sight of roses. Yet there are additional sensory associations that do not seem to be learned from the environment, such as the association that young children as well as adults make between higher pitch and lighter colours (Marks, 1996; Mondloch & Maurer, 2004; Ward, Huckstep & Tsakanikos, 2006). How is information linked together between sensory dimensions, and how does this change as we gain more experience during development? Studying these questions may provide insights into the organization of the sensory systems as well as an understanding of how natural biases and learning can influence the sensory associations that colour our perceptual world.

It is often the case that one of the best ways to understand normal development is to examine what happens in cases that deviate from the norm. By studying individuals who experience concrete inter/intra-sensory linkages, known as synaesthesia, we can gain a great deal of knowledge about perceptual organization. For a synaesthete the sound of a trumpet may not only be heard but also perceived in red, or the letter J may always be perceived as the colour green. Adult synaesthesia can inform the study of perceptual development, and even of language, because it appears to represent one way in which normal developmental mechanisms can play out. Synaesthesia appears to magnify connections present in early life, that are pruned and/or inhibited during development, and that persist in muted form in all adults. Thus, the cross-modal connections that can be documented in adult synaesthetes can be used to derive novel hypotheses about cross-modal links likely to be present in early childhood as well as to provide unique insights into how the brain organizes incoming sensory information. That is the approach I took in the empirical work reported in this thesis.

Synaesthesia

There are at least 54 types of synaesthesia, the majority of which involve extra visual percepts of colour (Day, 2007). For example, individuals with coloured-hearing synaesthesia might see bright patches of different brilliant reds when hearing lively classical music, or if they have coloured-word synaesthesia, might perceive blue when hearing their name spoken. For a person with coloured-grapheme synaesthesia, the number 8 might be the same shade of blue as the letter N. For individuals with time-space synaesthesia, units of time such as days of the week or months of the year have specific and enduring spatial locations, and, in some cases, colour as well. For an individual with olfactory synaesthesia, smelling her favourite perfume might elicit the percept of green.

Synaesthetes report having had the extra percepts all their lives and many experience more than one type of synaesthesia. Some synaesthetes indicate that the extra percepts are projected into specific locations in space, where they may be superimposed on real world stimuli ("projectors") while others report that the extra percepts are "in the mind's eye" ("associators") (Dixon, Smilek, & Merikle, 2004; see also Ward & Sagiv, 2007). Although the specific mappings vary among synaesthetes, there is nevertheless some consistency across individuals and between the extra cross-modal percepts of synaesthetes and the cross-modal associations of non-synaesthetic adults. It is from those consistencies that we hope to derive predictions about sensory associations present in early development.

Prevalence and perceptual reality. Synaesthesia was traditionally dismissed as a rare phenomena arising from overly vivid imagination—mainly in women. However, recent studies of the general population suggest that it occurs in 4-5% of adults and is as common in men as in women (Simner et al., 2006). Recent studies have also used a variety of techniques to establish its perceptual reality. One method has been to study the specificity and consistency of synaesthetic percepts over time, compared to the cross-modal associations of the typical population. An early study of 9 synaesthetes with coloured word hearing, established consistency as a hallmark of synaesthesia: the synaesthetes chose the same colour 92% of the time when given a surprise retest after 1 year compared to 38% consistency in a control group given a retest that they had been told to expect after 1 week (Baron-Cohen, Harrison, Goldstein, & Wyke, 1993). Similarly high rates of consistency have been shown in later studies of coloured-hearing synaesthetes who perceive colour in response to sounds, coloured-grapheme synaesthesia in which letters and digits are perceived in colour, time-space synaesthesia in which units of time have specific spatial locations, and word-taste synaesthesia in which words induce the perception of taste, with no overlap between the worst synaesthetic score and the best control score (coloured-hearing: Asher, Aitken, Farooqui, Kurmani, & Baron-Cohen, 2006; de Thornley Head, 2006; Ward, Huckstep, & Tsakanikos, 2006; coloured-grapheme: Dixon, Smilek, Cudahy, & Merikle, 2000; Eagleman, Kagan, Nelson, Sagaram & Sarma, 2007; Edquist, Rich, Brinkman, & Mattingley, 2006; Mattingley, Rich, Yelland, & Bradshaw, 2001; time-space: Smilek, Callejas, Dixon, & Merikle, 2007; word-taste: Ward & Simner, 2003).

Additional evidence for the perceptual reality of synaesthesia comes from studies showing that synaesthetic percepts interact with the perception of real-world stimuli as would be expected if they are perceptual phenomena—interfering with typical percepts if they are inconsistent and facilitating typical percepts if they are consistent. The most prominent example is Stroop interference (Stroop, 1935). Much as a colour word ("green") interferes with naming an incompatible colour of ink (red), individuals with colour-grapheme synaesthesia have difficulty naming the colour of ink of a letter or digit if it induces an incompatible synaesthetic colour (Dixon et al., 2000; Mattingley et al., 2001; Mattingley, Payne, & Rich, 2006; Ward et al., 2006). The incongruency causes longer reaction times and induces pupillary dilation (Paulsen & Laeng, 2006). For example, a synaesthete who reports that the digit "1" induces the colour green will be slower to name the colour of a red "1" than a black or green "1". In fact, subjects report an inability to suppress the incompatible synaesthetic colour, much as we cannot prevent ourselves from automatically processing the meaning of the word when it is irrelevant to the task of naming the colour of ink (Mattingley et al., 2001). Stroop-like interference is largest when the real-world and synaesthetic colours are opponent colours (red/green or blue/yellow), an effect suggesting that synaesthetic colour arises from the same opponent colour mechanisms which mediate normal colour vision in the primary visual cortex and/or extrastriate visual area V4 (Nikolié, Lichti, & Singer, 2007).

Stroop-like interference also occurs for coloured hearing: synaesthetes for whom auditory tones induce colours are slower to name the colour of a visual patch when listening to an irrelevant tone that induces an incongruent rather than congruent colour (Ward, et al., 2006). These results suggest that the synaesthetic percepts are automatic and not easily suppressed. Synaesthetic colours can act like real colours in inducing a number of other perceptual phenomena as well: apparent motion, grouping during binocular rivalry, figure-ground segmentation, visual search, and attentional priming, in some cases inducing effects as strong as the interactions among real colors and in others, effects that are similar but less strong (e.g., Hubbard, Arman, Ramachandran, & Boyton, 2005; Hubbard, Manohar, & Ramachandran, 2006; Kim, Blake, & Palmieri, 2006; Laeng, Svartdal, & Oelmann, 2004; Mattingley et al., 2001; Mattingley et al., 2006; Palmieri, Blake, Marois, Flanery, & Whetsell, 2002; Ramachandran & Azoulai, 2006; Smilek et al., 2007; Smilek, Dixon, Cudahy, & Merikle, 2001; Smilek, Dixon, & Merikle, 2003; Ward et al., 2006; but see Edquist et al., 2006; Sagiv, Heer, Robertson, 2006). Like the data on consistency over time, the behavioral findings that synaesthetic percepts behave like typical percepts in perceptual tasks have established their perceptual reality.

Neural basis of synaesthesia. Recent studies using functional magnetic resonance imaging (fMRI) reveal neural activations in response to synaesthesia-inducing stimuli are found in both the typical brain area for the physical stimulus (e.g., areas normally activated by the inducing stimulus), and the area responsible for coding the induced synaesthetic percept (i.e., as if the percept was an external stimulus). An example comes from an fMRI study of a synaesthete (JIW) who tastes words: specific words evoke highly specific tastes (*Philip* evokes the taste of "oranges not quite ripe"). When JIW listened to words, the fMRI showed that in addition to the expected activation in the brain areas involved in listening to words, there was additional activation in the primary gustatory cortex (Brodman's area 43) that did not occur when he listened to tones, or when non-synaesthetes listen to words or tones (Ward & Simner, 2003). Similarly, when synaesthetes with coloured hearing listen to inducers (e.g., the sound of the letter 'l' or of a trumpet that induces a specific colour), there is activity in the brain areas responsible for processing the actual stimulus, but also activation in visual cortical area V4/ V8, which plays a key role in the processing of colour and form in typical perception (Aleman, Rutten, Sitskoorn, Dautzenberg & Ramsey, 2001; Gray, Parslow, Brammner, Chopping, Vythelingum, & Ffytche, 2006; Hubbard et al., 2005; Nunn et al., 2002; Paulesu et al., 1995; Steven, Hansen & Blakemore, 2006; Winawer & Witthoft, 2004). In addition, in some studies, there was activation of the primary visual cortex, of a number of higher visual association areas, and of areas in the parietal cortex in the angular gyrus that bind colour to shape. All of these activations were observed in the absence of any physical visual stimulation.

Similarly, in synaesthetes for whom black letters evoke coloured percepts (i.e, who have coloured-grapheme synaesthesia), viewing letters during fMRI causes activation in visual cortical area V4/V8, with some reports of additional activation in lower visual areas (above that observed in non-synaesthetes), including primary visual cortex V1, and in a number of higher cortical areas, including the intraparietal cortex (Hubbard et al., 2005; Rouw & Scholte, 2007; Sperling, Prvulovic, Linden, Singer, & Stirn, 2006; but see Rich et al., 2006; Weiss, Zilles, & Fink, 2005). A role for the parietal cortex was confirmed by two studies using transcranial magnetic stimulation (TMS) to induce extraneous noise in specific areas of the parietal cortex in synaesthetes with coloured graphemes: interfering with the right parietal-occipital area and, in some subjects, the right parietal area or the left parietal-occipital area, reduced the Stroop interference between synestheically-induced and real colours (Esterman, Verstnen, Ivry, & Robertson, 2006; Muggleton, Tsakanikos, Walsh, & Ward, 2007; see Rouw & Scholte, 2007, for converging evidence of increased parietal connections in the left parietal cortex of grapheme-colour synaesthetes). Like the fMRI results, these findings suggest a role for the areas of the parietal cortex that are involved in binding colour to shape in typical perception. Overall, the neuroimaging results suggest that the brain connections mediating synaesthesia are similar to those mediating typical perception.

Developmental origins of synaesthesia. There are two predominant theories about the development of synaesthesia, both of which are rooted in normal developmental processes. In the case of the cross-activation theory, synaesthesia arises when the pruning of synapses is not completed between some contiguous brain areas (e.g., Maurer & Maurer, 1988; Ramachandran & Hubbard, 2001). In the case of the disinhibited feedback theory, synaesthesia arises when the re-entrant feedback that develops post-natally from higher cortical areas onto lower sensory cortical areas is not strong enough to inhibit effects from connections among primary sensory cortical areas (Grossenbacher & Lovelace, 2001). By either account, cross-modal effects similar to those seen in adult synaesthesia are expected to occur during early childhood and to persist in muted form even in typical adults.

Cross-activation. In adults, each sensory cortical area is specialized for the processing of information from one sensory modality: neurons in the visual cortex respond primarily to input from the eyes; neurons in the auditory cortex respond primarily to input from the ears, etc. The cross-activation theory is based on evidence that, across a number of species, sensory cortical areas are initially not as specialized as they will become. Instead, there are transient connections among sensory cortical areas that are pruned during childhood in an experience-dependent manner. For example, in the kitten, there are transient connections among the visual, auditory, tactile, and motor cortices (Dehay, Bullier & Kennedy, 1984; Dehay, Kennedy & Bullier, 1988), and, although such ubiquitous overwiring does not appear to occur in the infant monkey brain, there are transient connections from auditory cortex to visual area V4 (Kennedy, Batardiere, Dehay & Barone, 1997), which is homologous to the colour area that is active when adult synaesthetes with coloured-hearing listen to an inducing sound. There is indirect evidence that the same phenomenon—a superabundance of connections among sensory cortical areas followed by experience-dependent pruning—occurs in humans, and that the extra connections are functional during early childhood. 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, Matsumiya, Abrohms, van Velzer & Lombroso, 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 specialized exclusively for language (Tzourio-Mazoyer, de Schonen, Crivello, Reutter, Aujard, Mazoyer, 2002; see also Huttenlocher, 1984, 1994; Huttenlocher & Dabhokar, 1997; Huttenlocher & de Courten, 1987; Huttenlocher, de Courten, Garey & Van der Loos, 1982). Combined with the animal data, these findings suggest that there are functional connections among sensory cortical areas during early childhood that are later pruned.

According to the cross-activation account, synaesthesia occurs when some of the connections between sensory cortical areas (usually ones that are contiguous) are not pruned (Ramachandran & Hubbard, 2001). Thus, synaesthetic colour is evoked because connections between area V4/V8 and areas mediating the perception of sound, words, graphemes, or taste were not pruned. Evidence for such extra connections was obtained in a recent study using diffusion tensor imaging (DTI) to trace white matter tracts. In adults with coloured grapheme synaesthesia, there was evidence of greater connectivity than in controls in three brain regions, including the word-form area in the inferior temporal cortex that lies contiguous to V4/V8. Further, the strength of hyperconnectivity correlated with the strength of projecting the synaesthetic colours onto the inducing black letters (Rouw & Scholte, 2007). Even in typical adults, some of those connections may not be pruned—leading to synaesthetic-like cross-modal effects that do not reach conscious perception (see below).

Although the reason for the reduced pruning in synaesthetes is not known, a genetic factor is suggested by its tendency to run in families (e.g., Ward & Simner, 2005). In addition, studies of sensory deprivation suggest indirectly that the pruning of connections among sensory cortical areas is shaped by experience: when the normal input is missing because a child is blind or deaf, the primary sensory cortex missing its normal input does not develop normal specialization, but instead responds to input from other sensory modalities (reviewed in Maurer, Lewis, & Mondloch, 2005). In adults blind from an early age, Braille reading (Sadato et al., 1996), as well as the untrained tactile tasks of discriminating between vibrotactile gratings (Burton, Sinclair & McLaren, 2004) and between embossed roman letters (Burton, McClaren & Sinclair, 2006), recruit the visual cortex, including both extrastriate and primary visual cortices (for reviews, see Amedi, Merabet, Bermpohl & Pascual-Leone, 2005; Maurer et al., 2005). The ability of the blind group to discriminate Braille and embossed roman letters is impaired when visual cortical activity is interfered with by applying TMS over the medial occipital cortex or from an occipital stroke (Cohen at al, 1997; Cohen, Weeks, Sadato, Celnik, Ishii & Hallett, 1999; Hamilton, Keenan, Catala & Pascual-Leone, 2000), whereas sighted individuals' ability to discriminate embossed Roman letters is impaired by TMS applied only over the sensorimotor cortex. In adults with congenital blindness, the visual cortex also responds to auditory stimuli and perhaps even language (e.g., Burton, Snyder, Diamond & Raichle, 2002; Röder, Rösler, Hennighausen & Nacker, 1996; Röder, Stock, Bien, Neville & Rösler, 2002; Sadato, Pascual-Leone, Grafman, Deiber, Ibanez & Hallett, 1998; Sadato et al., 2002). Thus, it appears as if the visual cortex is recruited after early blindness for tactile and auditory perception. Similarly, in kittens whose eyes were removed at birth, neurons in the visual cortex give well-tuned responses to sound (Yaka, Yinon & Wollberg, 1999). These data converge in indicating that the specialization of sensory cortical areas is tuned by experience from the expected sensory modality, which may be favored because its input is stronger, faster, or more coherent over space and time than input from other sensory modalities. In the absence of the expected input—and, perhaps to a lesser extent when there is a genetic predisposition to synaesthesia, connections from the "wrong" sensory modality remain and influence perception.

Disinhibited feedback. The alternative explanation of the development of synaesthesia is that it arises from altered feedback from higher cortical areas onto lower sensory cortices (Grossenbacher & Lovelace, 2001). In the typical adult, the feedback strengthens firing of neurons consistent with the expected stimulus (e.g., neurons tuned to horizontal and vertical orientations when a square is expected or begins to be perceived) and inhibits inconsistent firing (e.g., neurons tuned to diagonal orientations or responding to input from an unexpected modality such as audition). What happens in synaesthesia, according to this account, is that some of the inhibitory feedback is disinhibited, allowing primary sensory cortical areas to be activated by unexpected input from the "wrong" sense. This account rests on the premise that connections among sensory cortices are not all eliminated by pruning; instead some remain but are normally functionally inhibited. Evidence for this idea has emerged in recent animal studies: sensory cortical areas that were traditionally thought to be unimodal have been shown to receive direct input from other sensory areas. Thus, in the adult marmoset, there is evidence that the primary auditory cortex receives inputs from a number of visual cortical areas and from the somatosensory cortex, and in the monkey, the response of neurons in the primary auditory cortex is modulated by simultaneous visual input (reviewed in Bulkin & Groh, 2006). Also in monkeys, there is evidence that neurons in the primary visual cortex with receptive fields in the periphery receive direct input from the primary auditory cortex (Falchier, Clavagnier, Barone, & Kennedy, 2002; see also Cappe & Barone, 2005; Rockland & Ojima, 2003), and that neurons in the monkey's primary visual cortex fire faster when a sound accompanies a peripheral visual stimulus (Wang, Celebrini, Trotter, & Barone, 2008).

Indirect evidence for connections among sensory cortical areas in human comes from studies of the visual cortex of typical sighted adults after a period of visual deprivation (blindfolding) (Pascual-Leone & Hamilton, 2001). Over the course of five days of blindfolding, sighted individuals were taught to discriminate tactile patterns. From Day 2 onward, the visual cortex was increasingly active during these tactile tasks and the somatosensory cortex was increasingly less active (Pascual-Leone & Hamilton, 2001). TMS over the visual cortex disrupted the tactile discrimination as much as it does in subjects blind from an early age. A similar pattern of activation over the visual cortex occurred when the blindfolded adults discriminated between auditory tones, a task unlikely to be mediated by visual imagery. A half-day after the blindfold was removed—after normal visual input was restored, auditory and tactile stimulation no longer caused activation of the visual cortex and TMS over the visual cortex no longer interfered with discrimination, even if the blindfold was temporarily restored. In a more recent study, adults were blindfolded only briefly while they performed tactile discriminations in an fMRI scanner (Merabet et al., 2007). The tactile stimuli produced significant activation in the primary visual cortex and significant deactivation in higher levels of the visual pathway—as would be expected if the activation of the primary visual cortex by touch is evident only if higher level responses are suppressed.

Collectively, these data suggest that the visual cortex of the typical adult favors visual input because it is stronger, faster, and/or more coherent and because neural responses to other inputs that are not pruned during development are normally inhibited. If the visual input is missing, the visual cortex readily responds to those other inputs. The evidence for short-term, reversible changes in cortical activation patterns after blindfolding suggest that functional connections between primary sensory cortical areas persist into adulthood but are typically inhibited. Those connections can be disinhibited in the case of sensory deprivation and perhaps synaesthesia. As would be expected, chemicals likely to modulate the level of inhibition (alcohol, caffeine) affect the reported intensity of synaesthetic percepts, with alcohol enhancing the intensity, and caffeine reducing its intensity (e.g., Ward & Simner, 2003).

Implications. The theories of synaesthesia have implications for understanding the development of the typical child. By both explanatory accounts, development involves the proliferation of connections among sensory cortical areas and then the specialization of each sensory cortex for a particular sensory modality. The specialization is driven by experience (see Greenaugh, Black & Wallace, 1987), which influences which connections are pruned and shapes re-entrant feedback. The inhibitory aspects of that feedback are likely to be especially slow to develop (see Burkhalter, 1993, for evidence for the visual cortex). Moreover, some of the extra, "wrong" connections appear to persist into adulthood, as conscious percepts in synaesthetes and as influences on perception in the typical adult (see next sections). These explanations imply that such cross-modal influences will be even stronger during early childhood, before pruning of many of the excess connections among sensory cortices and before the development of inhibitory reentrant feedback. They also imply that synaesthesia is an exaggeration of processes common to us all (e.g., Marks, 1975, 1982; Mulvenna & Walsh, 2006; Ramachandran & Hubbard, 2001; Sagiv & Ward, 2006; Ward et al., 2006). That exaggeration makes explicit the connections in the typical adult brain that might otherwise not be suspected and the connections that are likely to have influenced the perception of the developing child. These developmental processes—of experience-dependent pruning and re-entrant feedback—have clear adaptive value and an unexpected side-effect: cross-modal and cross-dimensional correspondences that are not readily explained by learning. In other words, connections between sensory areas that are not pruned and/or selectively disinhibited may lead to associations between sensory modalities (e.g., audition and vision), or between different dimensions within the same modality (e.g., shape and colour) that cannot be explained by learning from correspondences present in the environment. Because neurons with similar response properties tend to cluster together within each sensory cortical area, these connections between sensory areas are likely to be systematic and similar from individual to individual.

Clues to the associations that may be present in early development come from the consistencies in the relationship between specific inducers (e.g., the pitch of a middle C) and specific synaesthetic percepts (e.g., red) among individual synaesthetes and in the cross-modal associations of typical adults (e.g., common colour associates to middle C). Particularly compelling are cases where there is evidence for the same connection in the percepts of synaesthetes and the cross-modal associations of typical adults (e.g., is middle C red for both?), especially when the cross-modal or cross-dimensional correspondence is not obvious because it is not predominant in the environment. The consistencies among synaesthetic and nonsynaesthetic adults suggest that some associations may arise from the intrinsic wiring of the nervous system and hence influence the perception of young children. This is not to say that adults' cross-modal perception arises only from the effects of pruning and inhibition on intrinsic connections among sensory cortical areas. Learning also leads to new connections as the child learns face-voice associations, the colour of familiar foods, the noise that trains make, etc., but the influences described here may also constrain that learning, facilitating the learning of some associations and interfering with the learning of others.

The following sections include discussion of cross and intramodal associations that may result from the physiological mechanisms discussed in this section, including the background and rationale for the studies presented in this thesis.

Cross-modal Associations

In this section I describe some of the cross and intra-modal associations found in non-synaesthetic adults and/or synaesthetic adults and in children that appear not to be based entirely on learning the statistics of the environment. I begin with examples that have already been explored developmentally to some extent: influences of pitch and timbre on colour perception. I then discuss other sensory associations that remain to be explored, discussing first those that may represent a common code for magnitude, followed by a description of other associations that cannot be explained by magnitude. I conclude with a discussion of the specific associations I investigated in this thesis.

Influences of pitch and timbre on vision. Synaesthetic adults with coloured hearing report that the timbre of a musical note (the quality of a pitch that differs when it is played, for example, by different instruments) affects the saturation of the induced colour such that a note played from a piano induces a more saturated colour percept than a pure tone of the same pitch, with mid-range notes (e.g., C) reported as inducing the most colourful percepts (Ward et al., 2006). Non-synaesthetic adults asked to associate pitch to colour show the same relation between timbre and chroma and choose similar chromas for each note to some extent, although they are less consistent in their choices from an initial to a repeat test 2-3 months later. There is no obvious environmental basis for the associations: there is no systematic relation between the chroma and saturation of animals and the pitch of their vocalizations. The common patterns among synaesthetes and between synaesthetic and non-synaesthetic adults suggest that there are natural correspondences between timbre and colour. Those patterns might be present early in development and influence the child's learning of music.

Synaesthetic adults also report that higher pitched sounds induce more angular percepts than do lower pitched sounds (Marks, 1974). Likewise, non-synaesthetic adults are faster at responding to angular/rounded shapes when simultaneously presented with high-pitched/low pitched tones, respectively (Marks, 1987). Cross-modal associations between pitch and shape may influence cross-modal perception and the ease of language mapping (words with higher pitched vowels will be more easily associated to angular shapes; metaphors consistent with the mappings will be easier to learn).

Synaesthetic adults with coloured hearing also experience brighter percepts in response to sounds of higher pitch, and darker percepts in response to sounds of lower pitch (e.g., a higher pitched C elicits a brighter red) (Marks, 1974, Ward et al., 2006). Likewise, non-synaesthetic adults match tones of higher pitch to lighter colours, and tones of lower pitch to darker colours (Marks, 1974; Ward et al., 2006). Moreover, the pitch of a distracting noise affects their accuracy and speed in making a two-choice luminance discrimination: non-synaesthetic adults are faster and more accurate if the distractor has a higher auditory frequency when the correct answer is the lighter of the two visual stimuli (Marks, 1987). Similarly, the luminance of a distracting light affects their performance when discriminating auditory frequency: they are faster and more accurate on trials when the distractor is lighter if the correct answer is the higher auditory frequency (Marks, 1987). These consistencies among synaesthetic and typical adults suggest that there are natural mappings between pitch and lightness.

Toddlers (2.5 – 3 yrs of age) demonstrate the same pitch-lightness correspondence as do adults. This was shown in a study in which toddlers observed two simultaneously bouncing balls, one light and one dark, accompanied by a lower pitched or higher pitched sound. When asked which ball was making the noise, toddlers consistently matched the lower pitched sound to the darker ball and the higher pitched sound to the lighter ball (Mondloch & Maurer, 2004). This correspondence between pitch and lightness is unlikely to arise from experience with the association in the environment, as lighter objects do not consistently make higher pitched sounds in the world (e.g., a brown mouse has a high-pitched squeak the same as a white mouse). Thus, pitch and lightness are associated sensory dimensions that could be naturally-biased by cortical connectivity.

This body of research illustrates my overall research strategy, which begins with observing consistencies in sensory associations in adults. If those consistent associations cannot be explained easily by learning, then very young children may show the same consistencies. Specifically, I explored toddlers' associations for dimensions previously documented to be consistently related in adults (sound/shape; letter/color) and adults' associations for dimensions not previously measured (odor/colour and texture).

Cross-modal associations: A common code for magnitude:

Some cross-modal matching seems to be the manifestation of a multisensory code for magnitude: more in one modality translates into more in another modality. For example, synaesthetic adults with coloured hearing report that louder sounds (more sound) induce brighter percepts (more light) (Marks, 1974), just as non-synaesthetic adults match louder noises to brighter lights (Marks, 1987).

A common code for magnitude can influence the overt matching of stimuli across modalities, but it can also influence perception in a more covert way: concurrent multisensory stimulation can affect the perceived magnitude of a stimulus. For example, adults perceive white noise presented with light as being louder than when presented alone (Odgaard, Arieh, & Marks, 2004). Similarly, adults rate near-threshold light flashes as brighter when accompanied with a burst of white noise (Stein, London, Wilkinson, & Price, 1996). In the realm of the chemical senses, adding red to a solution that smells like strawberry increases adults' perception of the intensity and pleasantness of the odours (Zellner & Kautz, 1990), just as increasing the amount of red colour increases the perceived sweetness of a sucrose solution (Johnson & Clysesdale, 1983). Although some of these effects may be based on learned expectancy, or modulation of attention, they occur even when the colour and odours/flavour are mismatched: red lemon smells stronger than pink lemon, which in turn smells stronger than colourless lemon (Zellner & Kautz, 1990).

The correspondence in magnitude across different modalities could be learned from the statistics of the environment: larger objects do tend to make louder sounds, for example. However, this cross-modal magnitude translation extends to examples not readily explained by learning (e.g., pink lemon) and there is evidence for a form of it at birth. After habituation to a brighter or darker light, newborns respond less to an intense or soft sound, respectively, a result suggesting that they had habituated to the intensity of the light and translated it into the auditory domain (Lewkowicz & Turkewitz, 1980). Such crossmodal translation at birth suggests that it is possible that a cross-modal magnitude code represents a natural bias in the associations between sensory modalities without specific learning. Such a code may prime the system to learn cross-modal correspondences that are present in the environment. From this perspective, humans are born equipped with the cortical connections necessary to make sense of correspondences they can expect to find in the world, thus leaving more energy for learning correspondences that are important but idiosyncratic, such as mom's voice and her face.

Cross-modal associations: Not obviously based in magnitude:

In addition to associations suggesting a common intersensory code for magnitude, there are other consistent associations found in adults that provide clues about the nature of early intersensory perception.

Influences on vision from auditory and tactile events. One of the best examples of multisensory modification of the perception of unimodal stimuli is the 'illusory flash effect' in which the perception of a visual stimulus is induced by sound (Shams, Kamitani & Shimojo, 2002). Specifically, when a single flash is presented concurrently with multiple short beeps, adults often perceive the single flash as multiple flashes. Likewise, when a single flash is presented along with tactile stimulation in the form of two concurrent taps, adults often report seeing two flashes (Violentyev, Shimojo & Shams, 2005). The timing of the auditory 'illusory flash effect' and the evoked related potentials (ERPs) associated with it suggest that it results from direct connections from the auditory to visual cortex, rather than feedback from higher multimodal cortex (Mishra, Martinez, Sejnowski & Hillyard, 2007)—the same connections that appear to be functional in early infancy and to be only partially pruned and/or inhibited during development (see above).

Influences of sound on shape matching. It is possible that intrinsic cross-modal associations may influence the development not only of perception but also of language. The foundations for this idea lie in evidence that typical adults have biases to associate specific shapes and properties of stimuli to particular sounds (Kohler, 1929; Lindauer, 1990; Marks, 1996; Ramachandran & Hubbard, 2001). For example, sharp visual shapes go with words that produce a small, constricted and non-rounded movement of the tongue and mouth (e.g. spike, needle). This idea is supported by an experiment in which adults were asked to make a forced choice between a rounded and jagged shape as the referent for a nonsense word. When asked to match the nonsense words 'takete' and 'maluma' to the shapes, most adults answered that 'takete' was the jagged shape and 'maluma' was the rounded shape (Kohler, 1929; Lindauer, 1990). This effect has been replicated with modified shapes and words (e.g., kiki and bouba) in English-speaking adults and in 8 to 14-year-old children who spoke Swahili and the Bantu dialect of Kitongwe, but not English (Davis, 1961; Holland & Wertheimer, 1964; Ramachandran & Hubbard, 2001). Likewise, English-speaking toddlers also associate the nonsense words 'takete' and 'kiki' to jagged shapes and nonsense words such as 'mabuma' and 'bouba' to rounded shapes (Maurer, Pathman &

Mondloch, 2006). Ramachandran and Hubbard (2001) speculate that these phenomena arise from connections among contiguous cortical areas mediating decoding of the visual percept of the nonsense shape (round or angular), the appearance of the speaker's lips (open and round or wide and narrow), and the feeling of saying the same words oneself. They argue that these connections lead to natural mappings between sound and shape that sometimes lead to synaesthesia but which are present in some form in everyone. These associations may influence the evolution of our own language such that we can easily figure out the meaning of words in an unknown language (see Day, 2004; Koriat & Levy, 1977; Nuckolls, 1999; and Tanz, 1971 for supporting cross-language evidence). Additionally, these naturally biased associations may influence the language development of an individual child by contributing to the ease with which the child learns semantic mappings.

The sound characteristic that appears predictive of the association to round versus jagged shape in adults and toddlers is the vowel sound (Maurer, Pathman & Mondloch, 2004; Ramachandran & Hubbard, 2001), though there is evidence that a written consonant can have some effect in adults (Westbury, 2005). However, the influence of the consonant *sound* on shape matching has never been tested systematically in children or adults. Even the results for vowel sound may not be definitive because previous studies did not control for phonemic variation. Some of the stimulus words contained repeating syllables with no vowel or consonant variety (e.g., kiki) and some did not (e.g., maluma). If vowel variety or consonant variety influence sound/shape matching, then the previous studies may have mistakenly concluded that it is roundness of vowel that matters. Toddlers are an appropriate age group to examine this question because they are in the midst of a vocabulary explosion and sound symbolism must be effective in this period if it is to influence language learning as postulated. In addition, although they have had ample exposure to language, toddlers have little knowledge of metaphor, and have less understanding than adults of the overall statistics of the vocabulary in their own language that would generalize to nonsense words and shapes. In the research reported in Chapter 4, I examine the influence of the consonant and of vowel sound on shape mapping in toddlers, while controlling for vowel and consonant variety.

Intramodal visual influences: Shape-colour. While each individual grapheme-colour synaesthete has a unique coloured alphabet, there are some letters of the alphabet that tend to be associated to the same colours across synaesthetes (e.g., ~ 40% of English-speaking synaesthetes say that A is red) (Day, 2004; Rich et al., 2005; Simner et al., 2005). Likewise, non-synaesthetic adults do not typically associate letters to colours, but when asked to do so, they tend to agree on the choice for some letters of the alphabet, largely the same ones for which synaesthetes with coloured graphemes show consistency (Rich et al., 2005; Simner et al., 2005). Some of the consistent letter-colour associations appear to be based upon literacy: for example, English-speaking subjects commonly associate G to green. However, some of the consistent colour-letter associations cannot be explained easily by literacy. For example, at levels far exceeding chance, English-speaking adults, whether synaesthetic or non-synaesthetic, associate X and Z to black; O and I to white, and C to yellow (Day, 2004; Rich et al., 2005; Simner et al., 2005). Although more cross-linguistic studies are needed, an initial study of German-speaking adults suggests that at least some colour-letter associations are consistent among English-speaking synaesthetes and English and German-speaking non-synaesthetic adults (Simner et al., 2005).

The common colour-letter mappings seen in adults may in part reflect common neural cortical connections that facilitate links between the senses and between sensory dimensions such as shape and colour (see the section on *Developmental origins of synaesthesia*). If systematic mapping of colour to shape is determined by intrinsic sensory cortical organization, then the same consistent associations should exist in young children as in adults. If, on the other hand, they reflect language-based colour associations that develop after a child learns to read (i.e., after the child realizes, for example, that G is the first letter of green), then pre-literate children should not show consistent colour-letter associations. Although toddlers may recognize the letter G and the colour green, they would be unlikely to associate G to green based on knowledge of the written language. Testing for colour associations to letters in toddlers is an excellent way to differentiate between these two hypotheses. In the research reported in Chapters 2 and 3, I examined the colour-letter associations of toddlers, and compared their responses to those of older children and adults, as well as examined the characteristics of the letters that lead to consistent colour mappings.

Influences between vision and the chemical senses. Smell intensity and colour lightness are associated, as non-synaesthetic adults associate more intense (concentrated) smells to darker colours, and less concentrated smells to lighter colours (Kemp & Gilbert, 1997). Non-synaesthetic adults also match certain smells to specific colours in a non-random fashion (Gilbert, Martin & Kemp, 1996). For example, adults associate the smell of bergamot to yellow, and the smell of caramels to brown. Some of these matches can easily be explained by learning. For example, the smell of a lemon is likely to be associated to the colour yellow. Not surprisingly, an appropriately coloured solution (e.g., light yellow) can facilitate adults' identification of an odour (e.g., lemon) (Zellner, Bartoli & Eckard, 1991). However, the association between more intense smells and darker colours cannot be entirely based upon learning, since ammonia, bleach and garlic (for example) possess intense smells, but have light colours, and eggplant, tree bark and cola (for example) have mild odours, but dark colours. Additionally, dark coloured paint or dark coloured animals (for example) are not likely to have more intense smells than light paint or light coloured animals. Nor is there an obvious learning explanation for some of the specific colour associates reported by Gilbert et al. (1996) (e.g., grey/black for tarragon, brown for patchouli). Some of these associations could instead be caused by perseverant cortical connections that link sensory cortical areas, in which case we predict that these associations will be present and stronger in adults with olfactory synaesthesia and in young children, in whom they may influence food preferences (e.g., more apprehension about tasting novel brown foods because they are expected to have stronger flavors).

The findings that non-synaesthetic adults associate specific colours to odours is intriguing; however, the odours used in the two previous studies of non-synaesthetic adults were ones used commonly in fragrances. Thus, it is possible that the consistency reflects learned associations, a possibility that is difficult to assess because there was no measure of odour recognition in either study. In the research reported in Chapter 5, I examined consistent colour associations to odours in non-synaesthetic adults and looked at the possible influences of odour recognition on colour associations.

There may also be associations between texture and odour. Non-synaesthetic adults rate swatches of fabric as softer when accompanied by a pleasant odours (e.g., lavender) compared to an unpleasant (animal) odour (Damatte, Sanabria, Sugarman & Spence, 2006). This occurs whether the odour emanates from the fabric itself or from another source. Further, in many individuals with gustatory or olfactory synaesthesia, odour induces felt texture (Day, 2007). In the research reported in Chapter 5, I examined texture associations to odours in non-synaesthetic adults and the influence of odor recognition on texture associations.

To sum up, the research in this thesis examined how information is related across and within sensory modalities, how those associations develop, and how they change with experience. In Chapters 2 and 3, I examined the learned and naturally biased influences on the development of one type of intermodal sensory association. Specifically, I examined whether colour-letter associations found in adults reflect learned versus naturally-biased influences between shape and colour. In Chapter 4, I examined cross-modal sensory associations between sound and shape. Specifically, I examined the influences of consonant and vowel sound on the mapping of words to shapes in toddlers. In Chapter 5, I examined cross-modal associations to odour. Specifically, I examined whether there any consistent cross-modal associations between odour and either colour or texture. I will show that sensory associations in adulthood appear to result from an interplay of learning and naturally biases, and that non-synaesthetic adults and toddlers show consistent, naturally-biased sensory associations similar to those seen in synaesthesia.

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Introduction to Chapters 2 & 3

There is evidence of consistent associations between some letters and specific colours in synaesthetic and non-synaesthetic adults (Marks, 1975; Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005). Some of these associations appear to reflect literacy-based associations (e.g., G is for green) while others cannot be easily explained by literacy learning (e.g., X is black). In the research described in Chapters 2 and 3, we tested pre-literate toddlers on color associations to the letters that are consistently mapped in adults and compared their results to literate children and adults. We then examined whether consistent associations found in toddlers are based upon the sound or shape of the letter.

We found that some colour-letter associations appear to be based in literacy, as they are mapped in the literate groups only. Other colour letter associations appear to be naturally biased, as they are consistently mapped in pre-literate toddlers as well as older children and adults and not related to the learning of specific associations from the environment. Further, consistent associations in toddlers are based upon the shape of letter. The crucial characteristic that appears to influence consistent mapping in toddlers, older children and adults is the angularity/smoothness of the contours of the letter shape. Finally, natural biases to associate letters to colours is not limited to black and white. Overall, the research presented in Chapters 2 and 3 suggests that some colour letter associations in adults result from naturally-biased influences that are present before children learn to read while others develop as letters take on meaning. This pattern suggests that sensory associations in adulthood result from the joint influence of naturally-biased sensory cortical organization and of the experience of specific associations.

The Colour of Os: Naturally-biased Associations between Shape and Colour

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Abstract

Many letters of the alphabet are consistently mapped to specific colours in English-speaking adults, both in the general population and in individuals with grapheme-colour synaesthesia who perceive letters in colour. Such associations may be naturally-biased by intrinsic sensory cortical organization, or may be based in literacy (e.g., "A" is for "apple", apples are red, therefore, A is red). To distinguish these two hypotheses, we tested pre-literate children in three experiments and compared their results to those of literate children (aged 7-9) and adults. The results indicate that some colour/letter mappings (O, X to white, black) are naturally-biased by the shape of the letter, whereas others (A, G to red, green) may be based in literacy. They suggest that sensory cortical organization initially binds colour to some shapes and that learning to read can induce additional associations, likely through the influence of higher order networks as letters take on meaning.

Introduction

Adults do not generally have strong colour associations to letters. However, when asked to make a choice, they consistently map some letters to specific colours (Marks, 1975; Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005). Interestingly, adults with grapheme-colour synaesthesia, who actually perceive black-and-white letters in colour, show the same consistent colour/letter associations for those specific letters, (e.g., A tends to be red, G tends to be green, Z tends to be black, etc) despite the variability between synaesthetic individuals in the mapping of other letters. 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 experience in that sense *and in* another sense, or on a different dimension of the same sense, as in the most common form, grapheme-colour synaesthesia (Cytowic, 2002). These synaesthetic colours sometimes behave similarly to real colours in influencing perception. For example, when asked to search for a group of black numbers (e.g., twos) among black numbers of a similar shape (e.g., fives), grapheme-colour synaesthetes who report different induced colours for the two numbers (e.g, red twos and green fives) are much faster than controls at finding the target numbers, much like controls asked to search among numbers painted in two different colours (Ramachandran & Hubbard, 2001). When such grapheme-colour synaesthetes view black-and-white letters, there is activation in the colour processing areas of the brain (V4/V8) (Hubbard, Arman, Ramachandran, & Boynton, 2005; Sperling, Prvulovic, Linden, Singer, & Stirn, 2006).

The common colour-letter mappings seen in adults may in part reflect common neural cortical connections that facilitate links between the senses and between sensory dimensions such as shape and colour. These links may be most likely to occur when the relevant sensory dimensions involve processing by contiguous brain areas. This hypothesis has been used to explain why grapheme-colour synaesthesia is more common than other forms of synaesthesia (e.g., coloured odors) (Ramachandran & Hubbard, 2001). For example, 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 colour (Hubbard et al., 2005; Sperling et al., 2006). If systematic mapping of colour to shape is determined by intrinsic sensory cortical organization, then the same consistent associations should exist in young children as in adults. If, on the other hand, they reflect language-based colour associations that develop after a child learns to read (i.e., after the child realizes, for example, that G is the first letter of green), then pre-literate children should not show consistent colour-letter associations.

In order to differentiate between these two hypotheses, we tested toddlers for colour associations to letters. Letters necessarily have to be learned, and while toddlers may recognize the letter A and may know that apples are red, they do not know that the word apple begins with the letter A. From the letters that are consistently mapped in adults, we chose two colour/letter pairs, each with one rounded and one angular letter (A/G, O/X) that are mapped to opposing colours (red/green, white/black). Crucially, we included one pair with potentially language-based colour associations (A for red, G for green), and one pair without an obvious language basis for the colour mappings (O for white, X for black). We developed a novel way to test for colour/letter associations in pre-literate children in which children are asked to find a letter in a box with two slots, each covered by one of the opposing colours. Experiment 2 served as a replication with the experimenter blind to the location of the colour choices. In Experiments 1 and 2, we also tested older literate children, aged 7 to 9, and adults on the same measures. Experiment 3 evaluated the contribution of the sound of the name of the letter (e.g., the sound of A is "ay", not "ah") versus its shape to the colour-letter mappings in toddlers. We provide the first evidence of naturally-biased colour/letter mapping in pre-literate children. Furthermore, we provide evidence that the mapping is based on the shape of the letter and not its sound.

Method

The experiment consisted of a training session followed by alternating validity and experimental trials. We designed the training session to introduce the game and the validity trials to test for understanding of the task. The experimental trials were designed to test for letter/colour associations.

Participants

Toddlers and children were recruited from a file of parents who volunteered their children for testing during hospital visits shortly after birth. Adults were recruited when in the lab for another experiment. The final sample for Experiment 1 included 20 toddlers (mean age=32.4 months, range= 30-36 months, 12 male), 20 older children (mean age=7.55 yrs, range= 7-9 years, 11 male), and 10 adults (mean age=22.1, range = 18-25 years, 6 male). The final sample for Experiment 2 included 20 toddlers (mean age=34.1 months, 13 male), 20 older children (mean age=7.55 yrs, 8 male), and 10 adults (mean age=20.5, 4 male). The final sample for Experiment 3 included 40 toddlers (mean age=31.3 months, 20 male). An additional 8 toddlers from Experiment 1, and 6 each from Experiments 2 and 3 were excluded because they failed to pass the criterion of three out of four correct validity trials. No older children or adults failed the validity criterion. None of the toddlers correctly identified all four presented letters (OTBG or XCAY) on a test of alphabet knowledge (see procedure).

Materials

Cardboard boxes (16 cm. x 31cm. x 18 cm.) were covered with different colours of fabric on each half (red versus green, or black versus white) and contained an interior cardboard divider. On the front of the box were two slots through which participants could reach to remove stimuli from one side of the box. In Experiments 2 and 3, the boxes had a cardboard occluder (41 cm. x 61 cm.) on the back to prevent the experimenter from seeing the colours.

The experimental stimuli consisted of transparent plastic letters approximately 10.5 cm. wide and 12 cm. long (Experiments 1 & 2: A, G, O, X; Experiment 3: O, X). Validity stimuli were made of the same plastic material and represented objects with known colours (e.g., tree for green, snowflake for white) (see Table 1).

Insert Table 1 about here

Procedure

This study 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 coloured 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 (one for each colour in the experiment). In the first training level, the experimenter explained the game by asking the toddler to look for certain colour-specific objects in the appropriately coloured 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 colour 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 colour 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 colour is a firetruck? OK, so do you think the firetruck is hiding in this side or this side?" The experimenter would point to the red side, then the green side.). Older children and adults were given an explanation of the task in lieu of the training session.

After training on both colour pairs, each participant received a test sequence of four trials in which validity and experimental trials alternated within the first colour pair (e.g., red/green)(see Table 1 for specific stimuli). They were then tested on the other colour pair. The order of colour pairs and stimulus presentation was counterbalanced across participants.

Each validity stimulus was placed in the appropriately coloured side of the box. For example, the tree was placed on the green side of the box and the child was asked "I am looking for my friend the tree, what side of the box do you think the tree is hiding in?" To be included in the analysis, participants needed to respond correctly on at least three out of the four validity trials.

For each experimental trial, two letter stimuli were placed in the box, one on either side. In Experiments 1 and 2, participants were shown the letter as it was spoken out loud. In Experiment 3, half of the participants were shown the letter with no verbal label (e.g., "I am looking for my friend who looks like this..."), and half of the participants were given a verbal label and not shown the letter (e.g., "I am looking for my friend A (ay)...").

In Experiment 1, stimuli were placed in the boxes by the experimenter at the beginning of every trial. In Experiments 2 and 3, stimuli were placed in the boxes prior to testing by a second experimenter to ensure that the experimenter was unaware of the side with the expected answer.

To assess knowledge of the alphabet, toddlers were shown a card with four letters on it (either OTBG or XCAY) and asked to identify each letter on the card (e.g., "Can you show me the letter O?"). No toddlers correctly identified all four letters.

Results

Data analysis

Each participant was given a score based on the proportion of associations made in the expected direction for each pair of letters. For each colour pair, a one sample t-test (one-tailed; alpha = .05) was performed to see if the proportions were significantly higher than a chance value of .5.

Experiment 1

For the O/X colour pair, participants chose in the expected direction (X/black, O/white) at all ages [toddlers: M = .75, t (19) = 3.25, p <. 01; older children: M = .75, t (19) = 3.68, p < .01; adults: M =.85, t (9) = 4.58, p =.001] (Figure 1). For the A/G colour pair, older children and adults chose the expected colours (red/green) significantly more often than chance [children, M = .80, t (19) = 4.49, p < .001; adults, M = 1.0, t (19) = n/a]. However, toddlers chose colours randomly [M = .53, t (=19)= .27, p = .789] (Figure 2).

Insert Figures 1 and 2 about here

Experiment 2: Replication with blind observer

The findings were replicated. For the O/X colour pair, participants chose in the expected direction (X/black, O/white) at all ages [toddlers: M = .85, t (19) = 4.95, p < .001; older children: M = .80, t (19) = 3.94, p = .001; adults: M = .90, t (9) = 6.0, p < .001] (Figure 1). For the A/G colour pair, older children and adults consistently chose the expected colours (red/green) [older children M = .80, t (19) = 3.94, p = .001; adults, M = .90, t (9) = 6.0, p < .001]. However, toddlers chose colours randomly (M= .55, t (19) = .57 p = .577) (Figure 2).

Experiment 3: Sound vs. Shape for O/X in toddlers

Toddlers chose in the expected direction (X/black, O/white) when presented with the letter's shapes alone (M = .70, *t* (19) = 2.63 *p* < .05), but not when presented with the letter's sound alone (M= .50, *t* (19) = .000, *ns*) (Figure 3).

Insert Figure 3 about here

Discussion

The findings indicate that there are natural biases to associate certain shapes to specific colours: in all three experiments, toddlers searched for the X in the black side of the box, and the O in the white side. There is no obvious literary basis for this mapping and, even if there were, it is unlikely to influence the associations of children who have not yet learned to read. In contrast, the results for A/G suggest that literacy associations may induce additional colour-letter associations. Toddlers did not consistently map A to red and G to green, whereas literate children and adults did. These results suggest that cross-and intra-modal sensory associations in adulthood result from the joint influence of naturally-biased sensory cortical organization and of the experience of specific associations.

Our findings for X and O are consistent with evidence of other sensory associations that do not appear to be learned. A classic example is Benham's disc with a black and white pattern that induces the perception of colour when rotated (e.g., Campenhausen & Schramme, 1995). Similarly, adults report seeing colours and forms when their visual field is filled with flickering light, with the specific associations consistent across subjects and dependent on the frequency and phase of the flicker (Becker & Elliott, 2006). Moreover, specific colours and forms are consistently reported to co-occur with one another, providing additional support for the systematic binding of colour to form in adults' perceptual system. Toddlers systematically map lower pitch to darker objects (Mondloch & Maurer, 2004), a pattern matching cross-modal influences on adults' reactions and the percepts of synaesthetic adults (Marks, 1975; Marks, 1996) but 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)[1]. Like the current results for X and O, these recent findings suggest that humans have intrinsic biases to make specific cross-dimensional and cross-modal associations.

Although the current research does not indicate which pathways mediate colour-letter associations at any stage of development, the results of Experiment 3 indicating that toddler's associations for X and O are based on shape and not sound suggest that the colour-letter associations may be based initially on interactions between the colour and form pathways within the extrastriate visual cortex. This interaction could involve interactions within or among V4 cells that respond to both colour and form (Desimone, Schein, Moran, & Ungerleider, 1985) or it could be mediated by the posterior parietal cortex, given its documented role in the binding of colour to shape (Donner et al., 2002). Learning to read may induce a processing shift for colour-letter associations from the perceptual level (shape-based) to the cognitive level (letter-based). In synaesthetes with coloured graphemes, some aspects of colour-letter associations may remain at the perceptual level, which is consistent with imaging evidence of visual cortical activation of V4/V8 in synaesthetes when perceiving black-and-white graphemes in colour (Hubbard et al., 2005; Sperling et al., 2006). Evidence that deactiavation of the posterior parietal cortex by TMS interferes with grapheme colour synaesthesia suggests that the same perceptual binding mechanisms underlie synaesthetic percepts and non-synaesthetic percepts (Esterman, Verstynen, Ivry, & Robertson, 2006). 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., Simner et al., 2005; Esterman et al., 2006; Ward, Huckstep, & Tsakanikos, 2006).

Further research will help to elucidate the influence of different physical characteristics of shapes and letters on colour associations. For example, the letters O and X may be associated with white and black, respectively, because they contain mostly empty space versus a solid middle. Alternatively, they might be associated with shapes with continous versus jagged contours, respectively. Testing letters that have different shapes but are associated to the same colours (e.g., I/white, Z/black) will address this question, as will testing colour mapping to contrasting shapes that are not letters (e.g., rounded versus angular; with and without a solid middle). Finally, red and green lie on opposing sides of the colour wheel, whereas black and white lie at the extreme ends of a unidimensional colour axis. This fundamental difference between black and white versus other colours may result in naturally-biased associations of shape to black and white only. Thus it is important to clarify whether black and white hold a special distinction in initial sensory organization. To do this, we will test toddlers on letters that have consistent non-literacy based mapping in adults to colours other than black and white (e.g., C for yellow). Regardless of the various influences of shape and colour, our results provide intriguing evidence that sensory cortical organization may initially determine the binding of colour to shape in a systematic manner that changes with the development of literacy.

Footnote: [1] Although most researchers characterize the crucial distinction as between rounded and non-rounded vowels, some have identified instead a distinction between stop and continuous consonants (Westbury, 2005). Whichever interpretation is correct, the results indicate that there are sensory associations between sound and shape that do not appear to be learned.

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Table 1

Stimuli used for each colour on each kind of trial.

Trials	Green	Red	Black	White
Training level 1	leaf	cherry	crow	polar bear

level 2	frog	firetruck	bat	cloud
Validity	tree	heart	spider	snowflake
Letters	G	A	X	O

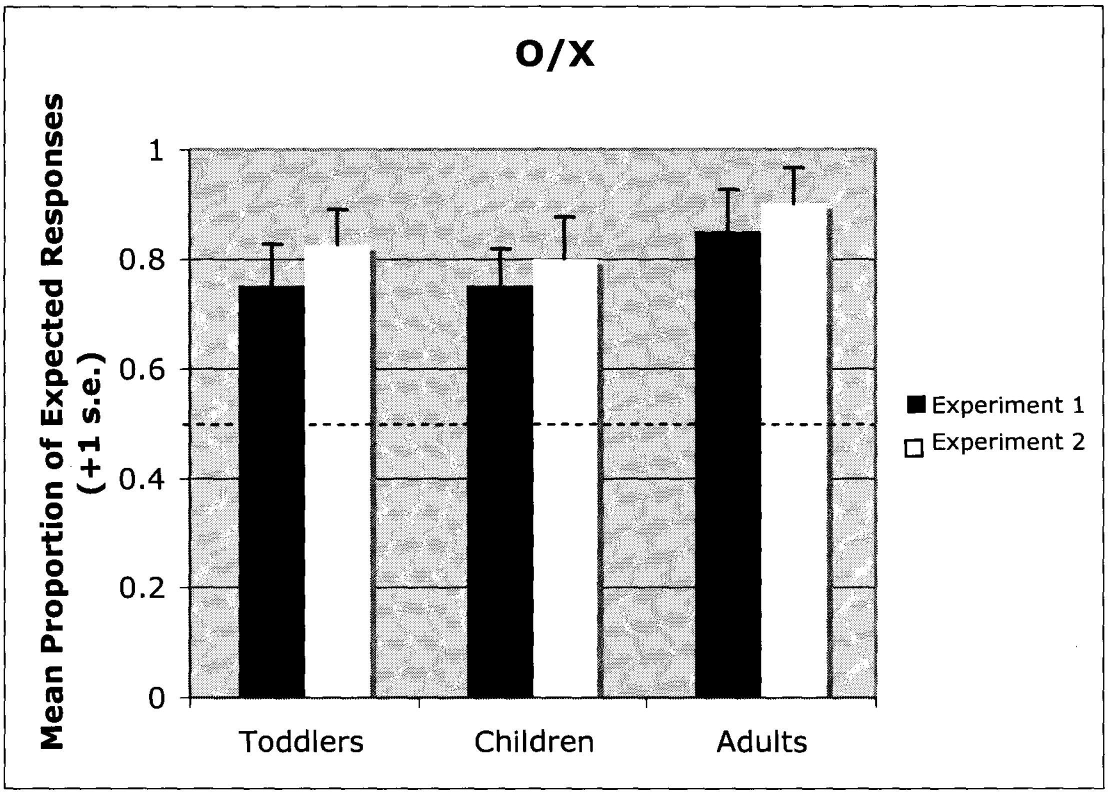
Figure Captions

Figure 1: Proportion of responses in the expected direction for the O/X colour pair (O-white, X-black) in Experiments 1 and 2. All three age groups made colour choices in the expected direction in both experiments. The dotted line indicates the level expected by chance.

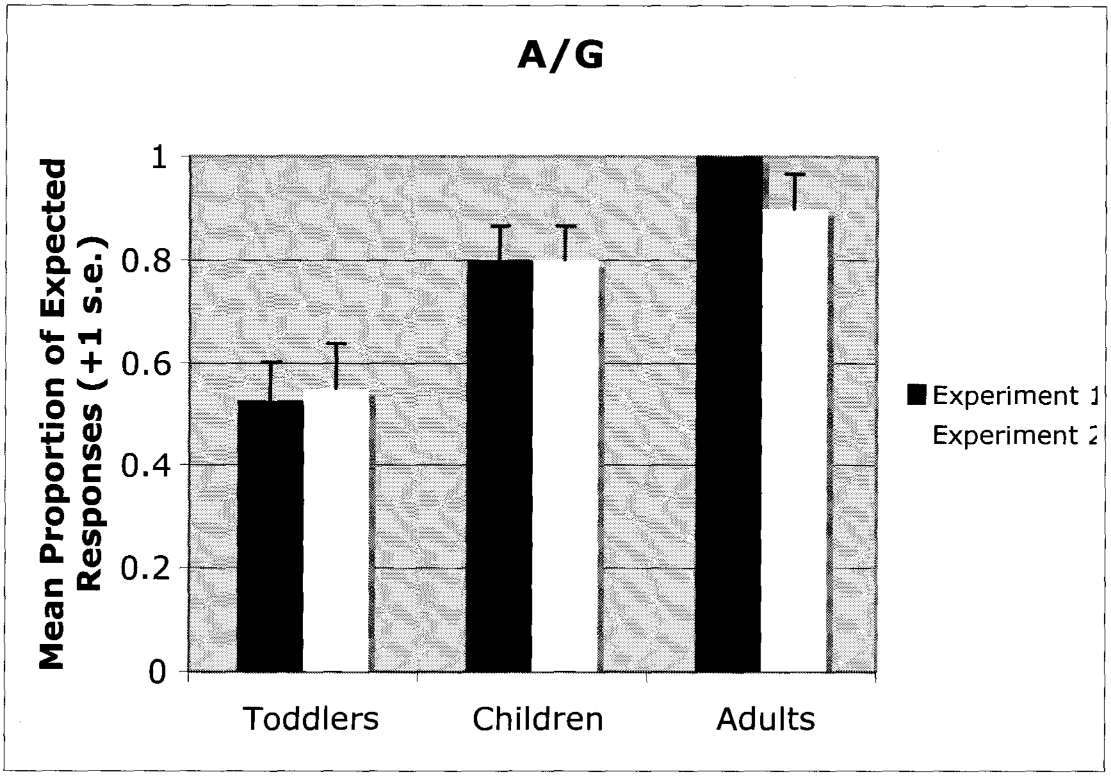
Figure 2; Proportion of responses in the expected direction for the A/G colour pair (A-red, G-green) in Experiments 1 and 2. In both experiments, older children and adults made colour choices in the expected direction, while toddlers did not. The dotted line indicates the level expected by chance.

Figure 3: Proportion of toddlers' choices in the expected direction (O-white, X-black) for the shape only and sound only conditions in Experiment 3. 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 dotted line indicates the level expected by chance.

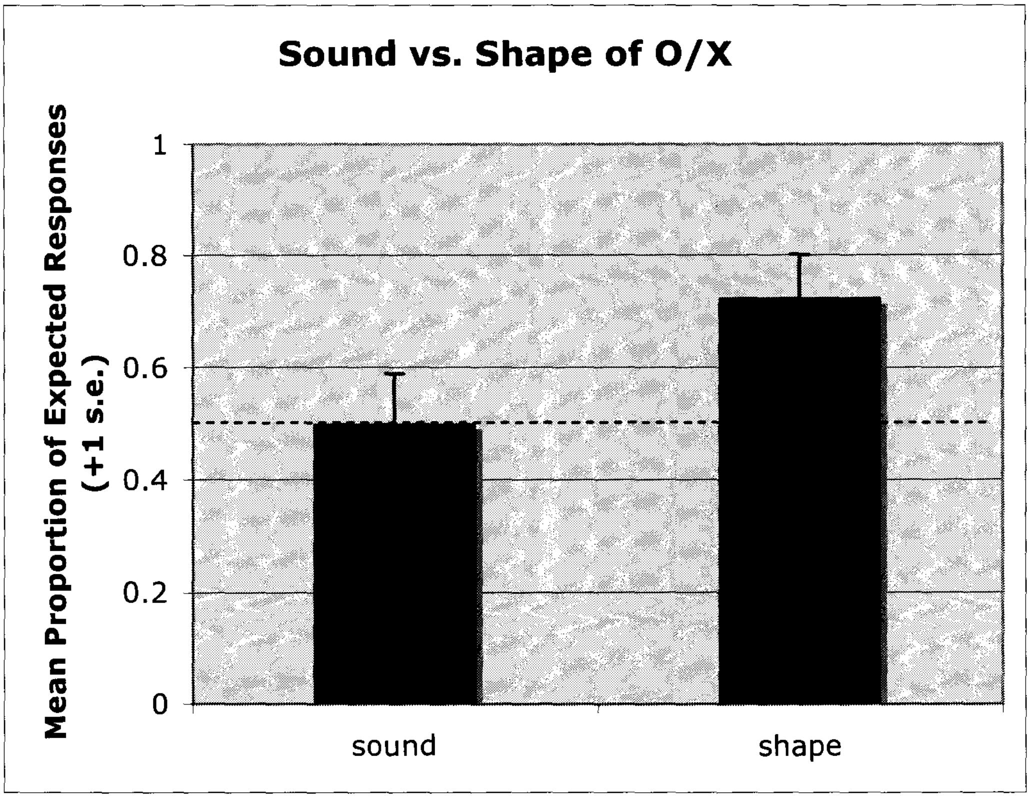
Spector & Maurer Figure 1



Spector & Maurer Figure 2



Spector & Maurer Figure 3



The Colours of the Alphabet: Naturally-biased Associations between Shape and Colour

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Abstract

Many letters of the alphabet are consistently mapped to specific colours in English-speaking adults, both in the general population and in individuals with grapheme-colour synaesthesia who perceive letters in colour. Previously we demonstrated some of these associations in pre-literate children. Here, across six experiments, we tested the ubiquitousness of the colour/letter associations with typically developing toddlers, literate children, and adults. We replicated our earlier finding 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 colour to some shapes and that learning to read can induce additional associations, likely through the influence of higher order networks as letters take on meaning.

Introduction

People 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 colour 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 colour (Marks, 1996, Ward, Huckstep & Tsakanikos, 2006). Interestingly, this association between pitch and lightness also occurs in individuals with coloured hearing synaesthesia, who actually perceive colour 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 → colour), or in a different dimension of the same sense (e.g., shape → colour). 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, Huckstep & Tsakanikos, 2006). Combined with the evidence of similar mechanisms underlying synaesthesia and typical perception (e.g., Esterman, Verstnen, Ivry, & Robertson, 2006; Hubbard et al., 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 colour-grapheme synaesthesia. For an individual with colour-grapheme synaesthesia, letters and/or digits printed in black evoke specific idiosyncratic coloured percepts that are consistent over time (e.g., Cytowic, 2002). These percepts may appear in external space, as if superimposed over the letter/digit, or may be seen in the 'mind's eye' (Dixon, Smilek, Cudahy, & Merikle, 2000; Eagleman, Kagan, Nelson, Sagaram & Sarma, 2007; Edquist, Rich, Brinkman, & Mattingley, 2006; Mattingley, Rich, Yelland, & Bradshaw, 2001). Evidence for the perceptual reality of the synaesthetic colours comes from studies showing that the synaesthetic colours 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 et al., 2000; Mattingley et al., 2001; Mattingley, Payne, & Rich, 2006; Ward et al., 2006). For example, a synaesthete who reports that the digit "1" induces the color green will be slower to name the color of a red "1" than a black or green "1". 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 (Nikolié, Lichti, & Singer, 2007).

In synaesthetes for whom black letters evoke colored percepts (i.e., who have colored grapheme synaesthesia), there is evidence of enhanced connectivity between area V4/V8 and contiguous areas involved in the decoding of word form (Rouw & Scholte, 2007). When such synethetes view black letters during functional magnetic resonance imaging (fMRI), there is indeed activation in visual cortical areas V4/V8, with some reports of activation as well in lower visual areas (Hubbard & Ramachandran, 2005). This is the same pathway that is active during the processing of shape and colour in typical perception. In addition, there is fMRI activation while individuals with coloured graphme synaesthesia view black letters in a number of higher cortical areas, including the intraparietal cortex (Hubbard et al., 2005; Rouw & Scholte, 2007; Sperling et al., 2006; but see Rich et al., 2006; Weiss, Zilles, & Fink, 2005). 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 grapheme color synaesthetes). Consistent with the fMRI results, these findings suggest a role for areas of the parietal cortex in colour-grapheme synaesthesia (Donner et al., 2002). Combined with the evidence of fMRI activation in V4/V8, 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 colours, large-scale studies do show some consistency among adults with colour-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, Bradshaw, & Mattingley, 2005; Simner et al., 2005). Interestingly, when non-synaesthetic adults are asked to make colour associations to that subset of letters, they frequently choose the same letter/colour combinations as those reported by synaesthetic adults (Marks, 1975; Rich, Bradshaw, & Mattingley, 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 colour-letter associations can be explained by literacy: O is consistently associated to white 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 colour/letter associations of non-synaesthetic adults and the colour percepts of adults with colour-grapheme synaesthesia. That hypothesis is consistent with emerging evidence that synaesthesia represents an exaggeration of mechanisms common in typical perception (e.g., Esterman et al., 2006; Mulvenna & Walsh, 2006; Simner et al., 2005; Ward, Huckstep, & Tsakanikos, 2006).

The consistent colour 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, 2006; 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: tactile stimulation of the wrist of a newborn evokes activity over the somatosensory cortex that is enhanced if accompanied by the sound of white noise (Wolff, Matsumiya, Abrohms, van Velzer & Lombroso, 1974). In addition, when hearing spoken language, young human infants show activity not only over the auditory cortex but also over the visual cortex, 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, most 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 colour (Hubbard et al., 2005; Sperling et al., 2006). 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 colours. This explanation helps to explain why colour-grapheme synaesthesia is more common than forms of synaesthesia involving non-contiguous areas (e.g., colored odors) (Ramachandran & Hubbard, 2001)

Thus some colour/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 colour/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 colour 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 colour is naturally-biased (Spector & Maurer, 2008). Specifically, we tested toddlers, older children and adults on letters that are consistently mapped in adults (e.g., A/G, O/X, which are mapped to the opponent colours red/green, white/black, respectively). We included one pair with potentially language-based colour associations (A for red, G for green), and one pair without an obvious language basis for the colour mappings (O for white, X for black). Using a child-friendly hiding game, we found that pre-literate toddlers, literate children, and adults all consistently mapped O to white and X to black (Spector & Maurer, 2008). Further, the consistent association in toddlers was based upon the shape of the letter, and not its sound, a result suggesting a natural bias between the visual attributes of form and colour rather than a connection between the acoustic label and colour. Literate children and adults also consistently mapped A to red and G to green, whereas toddlers did not. These latter associations appear to be language-based because they develop after a child learns to read (i.e., after the child realizes, for example, that G is the first letter of green). This study was the first to suggest that colour/letter associations in adulthood result from the joint influence of naturally-biased sensory cortical organization, evident in pre-literate children, and of the experience of specific associations, as learned through the development of literacy. Thus, sensory cortical organization may initially determine the binding of colour to letter shape in a systematic manner that changes with learning during development.

In the present study we explored the generality of our earlier findings about colour/letter associations. In the first experiment, we investigated whether the results were dependent on having used a forced choice between opponent colours, or whether the same pattern would emerge with non-opponent colour choices. 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 colour pairs. In Experiment 2, we examined whether consistent letter/colour mapping in toddlers extends to other letters which are consistently mapped to specific colours 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 colours other than black and white, by using letters that synaesthetic and non-synaesthetic adults map consistently to chromatic colours without an apparent literary basis (E/green, M/red, T/blue, C/yellow). The results provide additional evidence for shape-colour 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 experiment trials to test for shape/colour associations. In each experiment, training trials were followed by alternating validity and experimental trials. All trials involved a forced choice between two colour alternatives, and, unless otherwise noted, each experiment included 8 training trials, two experimental and two validity trials with one colour pair, and two experimental and two validity trials with a different colour 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. 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.

Insert Table 1 about here

General Materials

The test used opaque plastic boxes (16 cm deep x 31cm wide x 18 cm tall) with an interior wooden divider and each half of the box painted a different colour (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 x 61 cm wide) on the back to prevent the experimenter from seeing the colours.

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 and represented objects with known colours 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 coloured 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 colour 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 colour-specific objects in the appropriately coloured 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 colour 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 colour 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 colour 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 colour pairs to be included in the test, each participant received a test sequence of four trials in which validity and experimental trials alternated within the first colour pair (e.g., red/green)(see Table 2 for validity stimuli), and then four trials with the second colour pair. The order of colour 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 colour pairs was also counterbalanced across participants in each age group such that if one child received the A first for the red/green colour pair (for example), the next would receive the G first. In addition, the side on which each colour 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 asked "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 colour 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 on it and asked to point to each letter on the card as it was named (e.g., "Can you show me the letter O?"). Each letter card had two letters that were present in the experiment, and two that were not. There were two letter cards per experiment, together including all four letters in each experiment, and the letter card used alternated between toddlers. No toddlers correctly identified all four letters.

Insert Table 2 about here

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 colour 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 colours, 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 colours because they are maximally distinctive and because Stroop interference in adults with coloured grapheme synaesthesia is maximal for opponent colours (Nikolié, Lichti, & Singer, 2007), which is a result suggesting that any natural biases might be most likely to be apparent if participants are forced to choose between opponent colours. However, the use of only two choices can lead to what look like strong associations that reflect the colour the letter is clearly *not* associated with rather than the colour it is perceived to match. For that reason, in Experiment 1, we tested whether our initial results could be replicated when the colour pairings were mixed. Specifically, we mixed the red/green opponent colour pair with the white/black opponent colour pair so that red and green could appear with either black or white, but neither opponent colour pair appeared together.

Procedure: We used the same letters (A, G, O, X), and the same colours (red, green, white, black) as Spector & Maurer (2008) but manipulated the colour choices so that they were not opponent colours. 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 colour choices alternated between toddlers such that if one child looked for O in the red/white box, 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 colours randomly (A/red, G/green), [M = 0.45, t(19) = -0.81, p = .21] (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., 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 colour 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) colour 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 colour choices because they provide the strongest test of whether toddlers make any such associations.

Insert Figure 1 about here

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 colour percepts. Specifically, we tested toddlers, older children and adults on colour associations to the letters B, Y, I and Z (Marks, 1975; Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005).

Procedure: We tested for the expected associations of one colour pair with a literacy explanation, B/blue and Y/yellow, and one colour pair with no obvious literacy basis: I/white (with serifs), Z/black (Canadian pronunciation "zed") in toddlers, older children and adults. Each participant received 2 experimental trials with I and Z and the black/white box and 2 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 = .8, 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 = .000; adults, M = .95, t(9) = 9.0, $p < .001$], whereas toddlers chose randomly, [M = 0.43, t(19) = -0.900, p = .19] (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 colours (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 and Experiment 1: toddlers consistently mapped the two letters without an obvious literacy bases to their expected colours (O/white, X/black) but responded randomly for the two letters with an easy literacy basis for their mapped colours (A/red, G/green) (Spector & Maurer, 2008). Combined, the data suggest that those letters that do not appear to have a literacy basis for their mapped colours in adults are consistently mapped regardless of literacy level, and may thus be naturally-biased, whereas colour letter pairs with a possible literacy basis are mapped to the expected colours in the literate groups only, suggesting an influence of literacy learning. Learned associations may override an initial natural bias and/or cause a novel association to form between two previously unconnected attributes. Thus, B may be naturally associated to no colour or to a colour 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. However, if no such learning occurs for a particular stimulus, then the naturally biased association may remain into adulthood, as we see in the perseverance of the association of I, O to white and Z, X to black in adults. In adults with coloured grapheme synaesthesia, the extra percepts duplicate the adult associations reported here and in our previous work: O/white, X/black, I/white, Z/black. That similarity 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).

Insert Figure 2 about here

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 2 experimental trials intermixed with 4 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 colours (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 (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 4 of the letters on the alphabet test (see general design), it is possible that they processed the letters as basic shapes, rather than graphemes. 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. Thus, toddlers may use continuity versus angularity/jaggedness of shape contours, at least in part, as the basis of the mapping of shapes to black or white. In Experiment 4, we used nonsense shapes to test that hypothesis.

Insert Figure 3 about here

Experiment 4

The consistent mappings that we have found in toddlers between shape and colour (O and I to white and X and Z to black) persist in older groups and might be determined by angularity of shape. The purpose of this experiment was to examine the influence of angularity of shape on colour 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.

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 4 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]] (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 colour mapping to black and white. This association between non-angular rounded shapes and white and angular shapes and black could reflect valence judgments in which sharp and black equals bad, while rounded and white equals good. Adults make seemingly automatic valence judgments between shape contour and colour lightness (e.g., Bar & Neta, 2006; Meier, Robinson & Clore, 2004). These judgments could affect the way that parents teach children about objects with these characteristic shapes or lightness, and such teaching could lead young children to make valence judgments to black and white (Stabler & Johnson, 1972; Stabler, Johnson & Jordan, 1971; Zentner, 2001). It is also possible that the associations of black to jagged and white to rounded contours reflect natural biases between shape and colour lightness, associations which help to bootstrap the later learning of valence judgments for these object characteristics (see General Discussion for elaboration).

Insert Figure 5 about here

Experiment 5:

In the results so far, all of the colour/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 colours. To do so, we re-examined the corpus of letters with common colour percepts in adults with colour-grapheme synaesthesia and the letters for which non-synaesthetic adults make consistent colour associations both in English and German (Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005). We restricted the choices to letter associations with no obvious literary basis. Specifically, we tested, E/green, M/red; C/yellow, T/blue, in toddlers, older children and adults. In addition, because the results from Experiment 4 suggest that shape angularity influences colour 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 and 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 2 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 coloured boxes alternated within each age group such that one participant was tested on E/M black/white and C/T blue/yellow, 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 2 training trials and there were 2 additional validity trials at the end with non-opponent colours (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 4 of the 6 validity trials.

Results/Discussion: For the C/T blue/yellow colour 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, $p = .007$]. For all other pairs, choices were random in each of the three age groups: [E/M red/green: (toddlers: M = .5, t (19) = .83, $p = .42$; older children: M = .58, t (19) = 1.0, $p = .33$; adults: M = .67, t (9) = 1.0, $p = .5$) (Figure 6); 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, $p = .095$); 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 =1.0, t (9) = n/a], 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 = .5, t (9) = 1.17, $p = .133$]. 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 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 colours (Experiments 1-3). Our finding that C is mapped to yellow is unlikely to be based on the brightness of the colour yellow (in contrast to the dullness of the colour blue) or a general matching of non-angular contours to lighter colours because the toddlers did not match the C to white when given a choice between black and white. Rather it is likely to be based on some other aspect of the chroma.

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 (C, T, E and M) 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 for non-synaesthetic and/or synaesthetic adults (Rich, Bradshaw, & Mattingley, 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 colour letter pairs were chosen based upon reports of consistent associations among English and German- speaking non-synaesthetic adults as well as reports of consistent percepts among synaesthetic adults (Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005). However, in those previous reports about non-synaesthetic adults, the colour associations to the letters E, M and T were not as consistent as the colour associations to the letters tested in Experiments 1-4 (A, G, O, X, B, Y, I, Z). Perhaps the consistency among non-synaesthetic adults for E, M, and T is too weak to be apparent in a sample of ten adults, unlike the stronger associations for A, G, O, X, B, Y, I, Z, and C examined in the other experiments.

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 4 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 colours (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 colour 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 colours extends beyond black and white to include at least one pairing to a chromatic colour. The association of C to yellow is unlikely to be based on literary associations because it was evident in toddlers who do not yet know how to read and there is no obvious orthographic basis for it. 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 colour yellow (in contrast to the dullness of the colour blue) or a general matching of continuous contours to lighter colours. 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. These results indicate that there appears to be a natural bias to associate at least one letter to a chromatic colour.

Insert figure 6 about here

General Discussion

The findings suggest that there are natural biases to associate certain shapes to specific colours. 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 colour 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 mapping 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 colour is not limited to achromatic colour: 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 colour.

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 colour-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/colour 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 colour lightness is 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: when presented white or black words on a light grey background, they are slower and less accurate in assessing the valence of the word (e.g., happiness, bully) presented in the wrong colour (e.g., happiness presented in black) versus the right colour (e.g., bully presented in black) (Meier, Robinson & Clore, 2004). There appears to be a similar association between curved contours and valence: when shown similarly shaped nonsense objects differing only in whether the contour changes smoothly or abruptly, adults rate smoothly contoured objects higher on a likeability scale, and pointed objects lower, compared to a control object with both smooth and pointed contours (Bar & Neta, 2006). Adults even rate a harmless object (e.g., a watch) lower on likeability if it has sharp versus smooth contours. This could result from associations between sharp visual angles and potentially harmful or threatening objects (Bar & Neta, 2006). Whatever the origin of the effect, adults associate both smooth non-angular contours and white to positive valence and both angular, sharp contours and black to negative valence.

Valence judgments to black and white as well as to sharp versus smooth contours likely affect the way parents use language around children, use which in turn will come to affect how children treat objects with these characteristics. Children as young as 3 years old associate bright colours like yellow and red with happy facial expressions, and dark colours like dark blue with sadness (Zentner, 2001). Likewise, regardless of race, preschool children guess that white boxes hold good objects and black boxes hold bad objects (Stable & Johnson, 1972), and that positive statements (e.g., "I am smart") come from a white speaker while negative statements (e.g., "I am scared") come from a black speaker (Stabler, Johnson & Jordan, 1971). Thus it is possible that 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. There are clear experiential and cultural cues for learning these valences — sharp objects hurt, dark rooms are scary. Nevertheless, it is possible that associations between contour and colour lightness may in part reflect some natural biases that help bootstrap later environmental learning to keep children safe as they maneuver through a world of sharp objects and dark rooms.

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 colour lightness. Rather, it seems as if there are also 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 colour (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, Matsumiya, Abrohms, van Velzer & Lombroso, 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 specialized exclusively for language (Tzourio-Mazoyer, de Schonen, Crivello, Reutter, Aujard, Mazoyer, 2002; see also Huttenlocher, 1984, 1994; Huttenlocher & de Courten, 1987; Huttenlocher, de Courten, Garey & Van der Loos, 1982; Huttenlocher & Dabhokar, 1997). 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 coloured 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 colour form area V4/V8, with the strength of hyperconnectivity correlated with the strength of the projection of the synaesthetic colours 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 similairity in which connections fail to be pruned in these two groups. However, the idiosyncracy 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 colour-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 colour 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 colour grapheme synaesthesia as well as the ready association of colour 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 colour 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 colour processing, these mappings might be mediated by structural connectivity between the colour and form pathways within the extrastriate visual cortex itself.

Learning to read may induce a processing shift for colour-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 colour-grapheme synaesthesia suggests that the same perceptual binding mechanisms underlie synaesthetic and non-synaesthetic percepts (Esterman, Verstynen, Ivry, & Robertson, 2006, Muggleton, Tsakanikos, Walsh & Ward, 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; Simner et al., 2005; Ward, Huckstep, & Tsakanikos, 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 colour and/or shape, like the associations explored here. For example, looking at a rotating disk that has a black and white pattern on it ("Benham's disk") induces the perception of colour (e.g., Campenhausen & Schramme, 1995). Similarly, adults report seeing colours 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 colours and forms consistently co-occur with one another (including zig-zags with black), providing additional support for the systematic binding of colour 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, Huckstep & Tsakanikos, 2006). This pattern also matches the percepts of adults with coloured 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.

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 colour. 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 homogenously coloured box. It would also be useful to devise a methodology to test infants for the shape/colour associations we have found in toddlers. We have used the term "naturally-biased" to refer to associations which 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.

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Table 1

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	
	12 adults	22.3 years	18-28 years	5	
6	20 toddlers	33.4 months	30-36 months	9	11

***Table 1**: Details on participants for all experiments. All excluded toddlers failed to pass validity criterion, and were replaced in the final sample.*

Table 2

Training Level	Colour							
	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

***Table 2:** Training and validity stimuli for each of the colours used in the experiments.*

Figure Captions

Figure 1: Proportion of responses in the expected direction in Experiment 1, in which toddlers were presented with non-opponent colour pairs. The left panel is the overall proportion of responses for each colour pair. The dotted line indicates the level expected by chance; the asterisk indicates the significant colour letter pair. Toddlers made colour 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.

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

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.

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.

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.

Figure 6: Proportion of responses in the expected direction for the E/M and C/T colour 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 colour pair. All four groups made choices in the expected direction on the C/T colour pair (C-yellow, B-blue), but not the E/M colour pair (E-green, M-red). The right panel is the proportion of responses for each individual letter in each group.

Figure 1:

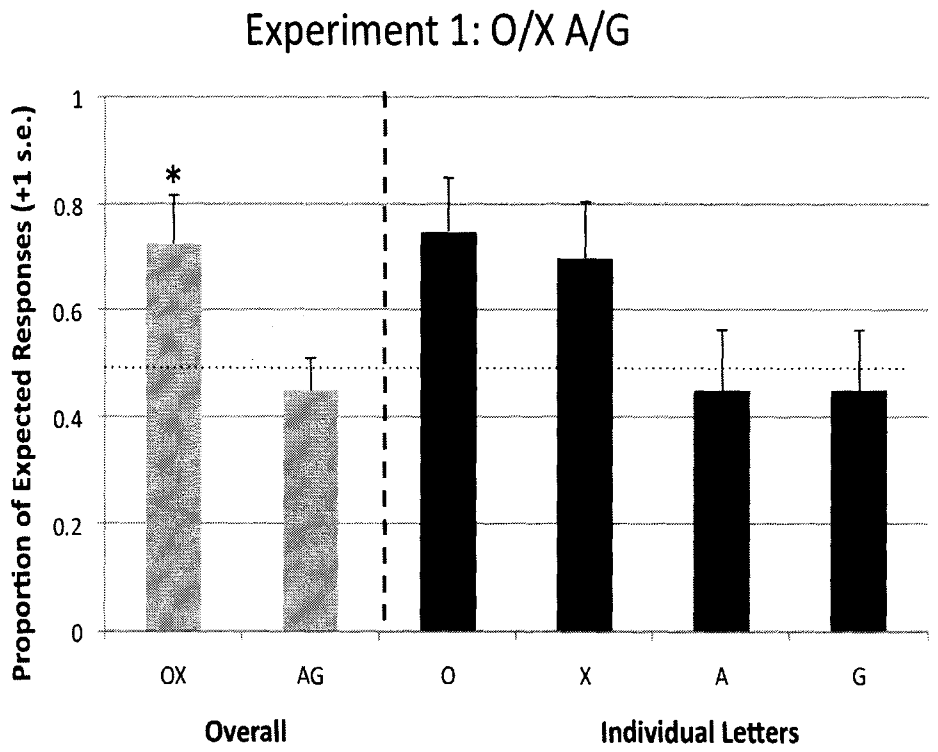


Figure 2:

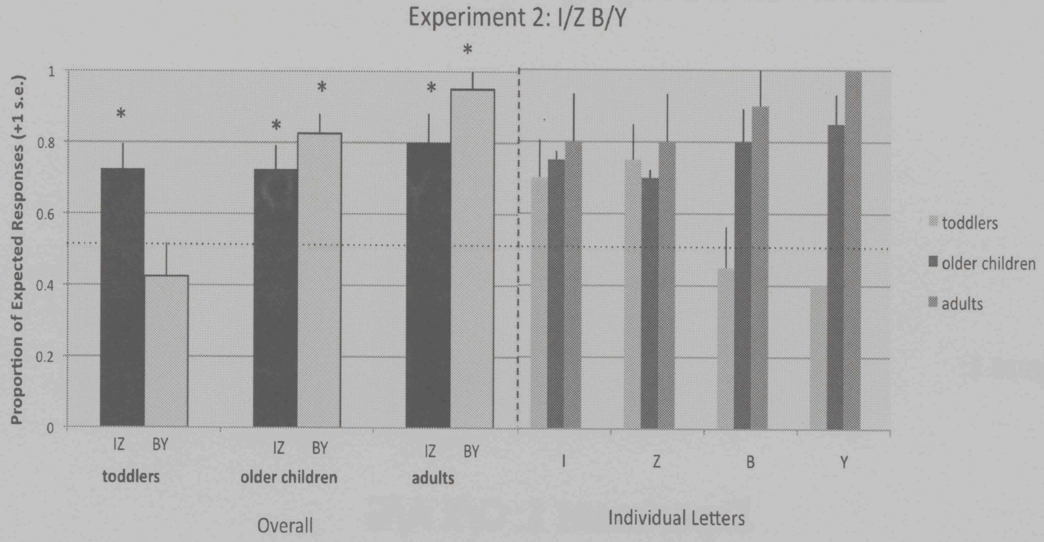

Experiment 2: I/Z B/Y
Proportion of Expected Responses (+1 s.e.)
1
0.8
0.6
0.4
0.2
0
*
IZ
BY
toddlers
older children
adults
Overall
I
Z
B
Y
Individual Letters
toddlers
older children
adults

Figure 3:

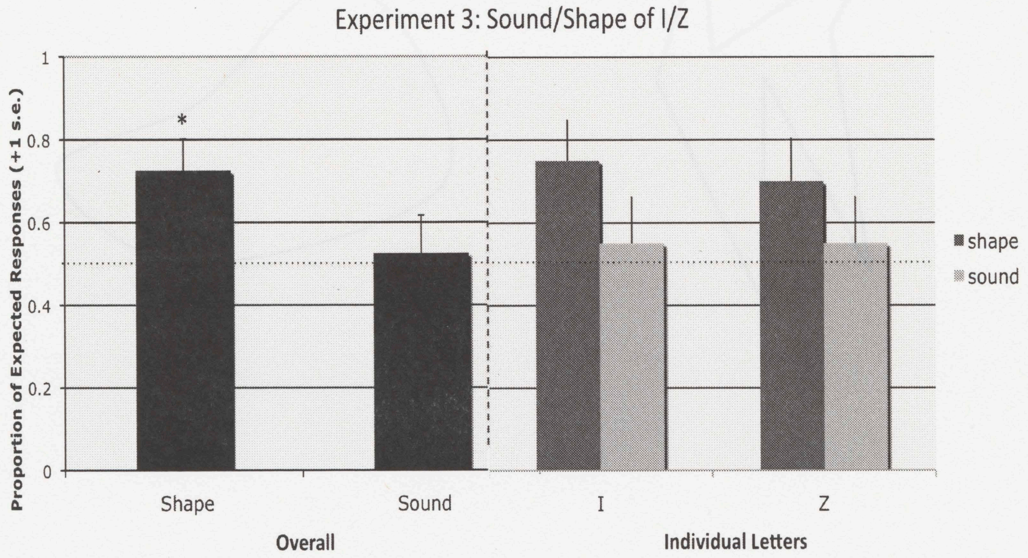

Experiment 3: Sound/Shape of I/Z
Proportion of Expected Responses (+1 s.e.)
1
0.8
0.6
0.4
0.2
0
*
Shape
Sound
Overall
I
Z
Individual Letters
shape
sound

Figure 4:

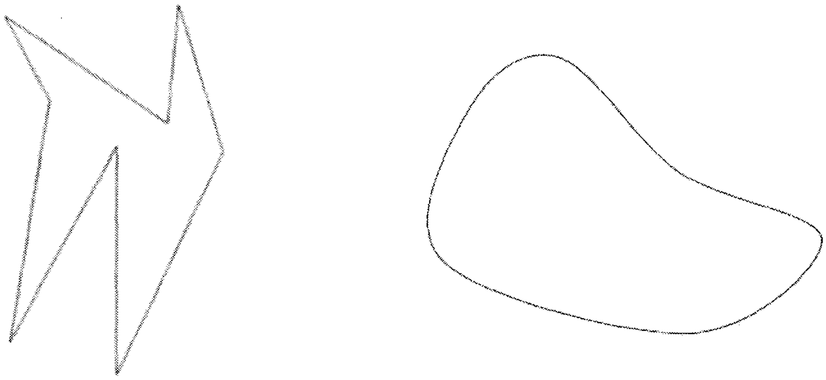


Figure 5:

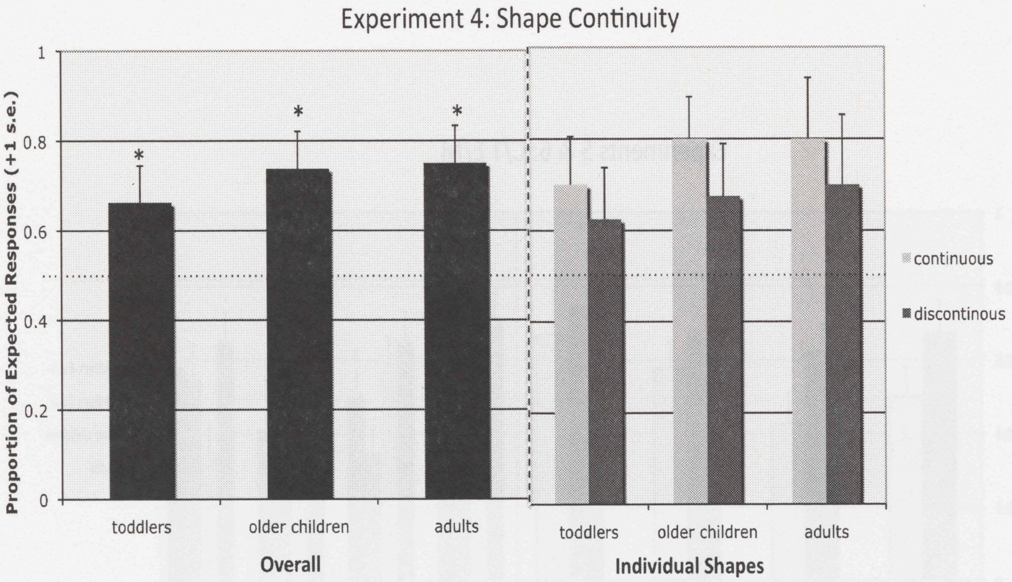
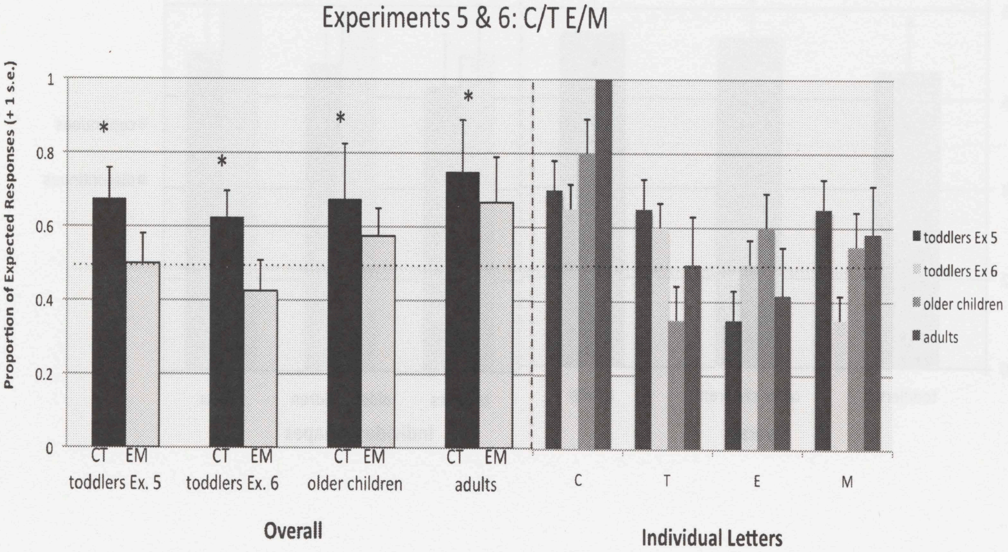

Experiment 4: Shape Continuity
Proportion of Expected Responses (+1 s.e.)
1
0.8
0.6
0.4
0.2
0
*
*
*
toddlers
older children
adults
Overall
toddlers
older children
adults
Individual Shapes
continuous
discontinous

Figure 6:


Experiments 5 & 6: C/T E/M
Proportion of Expected Responses (+ 1 s.e.)
1
0.8
0.6
0.4
0.2
0
*
*
*
*
CT EM
toddlers Ex. 5
CT EM
toddlers Ex. 6
CT EM
older children
CT EM
adults
C
T
E
M
Overall
Individual Letters
■ toddlers Ex 5
■ toddlers Ex 6
■ older children
■ adults

Introduction to Chapter 4:

There is evidence that adults and pre-literate toddlers match words with rounded vowels (e.g., maluma) to a rounded shape and words with non-rounded vowels (e.g., kiki) to a jagged shape (Kohler, 1929; Lindauer, 1990; Marks, 1996; Ramachandran & Hubbard, 2001; Maurer, Pathman & Mondloch, 2006). Previous studies suggest that the effect is based on the roundness of the vowel. In Chapter 4, I extended previous findings by examining the influence of the spoken consonant on shape matching in toddlers and replicated the effects for vowels, while systematically controlling for the influence of consonant and vowel variation by presenting only repeating syllables. Specifically, I examined whether toddlers associate approximant consonants (e.g., w, l) or rounded vowels (i.e., o) to rounded shapes and stop consonants (e.g., g, d) or non-rounded vowels (i.e., i) to jagged shapes.

There was no effect of the consonant sound on toddlers' shape choices. However, toddlers did match words with rounded vowels to rounded shapes and words with non-rounded vowels to jagged shapes. Our findings are the first to suggest that the consonant has no influence on mapping of sound to shape in toddlers. Thus, the crucial characteristic of a nonsense word that determines its mapping to shape in toddlers seems to be the vowel roundedness. Toddlers' consistent associations of rounded vowels to rounded shapes and non-rounded vowels to jagged shapes may influence the ease with which they learn vocabulary.

Early sound symbolism for vowel but not consonant sounds

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Abstract

Young children and adults consistently match nonsense words with non-rounded vowels (e.g., kiki) to jagged shapes and words with rounded vowels (e.g., bouba) to rounded shapes (e.g., Maurer, Pathman & Mondloch, 2006; Ramachandran & Hubbard, 2001), providing evidence for non-arbitrary sound-shape mapping. Such correspondences are typically attributed to the vowel sound. Here we investigated the influence of the consonant sound on sound-shape matching in toddlers (30-36 months, n = 40), using four contrasting pairs of nonsense words differing in stop versus approximant consonants (e.g., bibi vs. lili) and four pairs of rounded versus pointed shapes. Toddlers matched consonant sounds to shape randomly (p = ns). In a second experiment we used the same procedure to verify the effect of vowel roundness on toddlers' matches to rounded and pointed shapes, and unlike previous studies, used only reduplicated syllables (e.g., kiki versus koko) rather than confounding vowel roundness with variability (e.g., kiki vs. bouba). Toddlers (n= 20) consistently matched rounded vowels to rounded shapes and non-rounded vowels to jagged shapes ($p < .001$). This is the first study to systematically examine the influence of the consonant sound on children's matching of sound to shape, The results confirm that there are naturally biased correspondences between vowel sound and shape and failed to provide evidence of a comparable influence of the consonant sound.

Introduction

Learning language is a monumental task requiring the learning of a large number of arbitrary sound sequences that represent different objects and events in the environment. Yet young children are able to learn an incredible amount of vocabulary in a very short period of time. Certainly the young brain has evolved to be ready to learn language, but studies of sound symbolism suggest that language itself may help to bootstrap its learning.

According to the notion of sound symbolism, there are sound-meaning relationships that are non-arbitrary in nature. These relationships are understood universally, regardless of the language the individual has learned (e.g., Berlin, 1994, Imai, Kita, Nagumo & Okada, 2008; reviewed in Nuckols, 1999). Such easily understood sound symbolism may have influenced the evolution of languages, so that words consistent with the sound symbolism were more likely to be added to the language than those with a strictly arbitrary sound-meaning correspondence (Ramachandran & Hubbard, 2001). For example, if it easier to relate sharp visual shapes to sounds produced using a constricted movement of the tongue and mouth than to words produced with an open vocal cavity, then words like *spike* and *point* may have been added to the language more often than words like *barb* or *prong*. Consistent with this prediction, there are consistencies across languages in using words containing the vowel *i*, which involves narrowing the vocal tract and lips, for objects that are smaller, brighter, closer and/or associated with higher pitch (e.g., tiny, mini) (e.g. Day, 2004; Nuckolls, 1999; Tanz, 1971). Likewise, words containing the vowels *a* and *o*, which involve keeping the vocal tract and lips wide, often represent objects that are larger, darker, farther away and/or associated with lower pitch (e.g., large, whopping) (e.g. Day, 2004; Nuckolls, 1999; Tanz, 1971). To the extent that sound symbolism is used in a language, the mapping between sound and meaning may be easier for the young child to learn.

Consistent with the predictions of sound symbolism, adults can guess some of the meanings of words in a foreign language. For example, when tested with Huambisan (a Jivaroan language from north central Peru), naive English-speaking adults sorted words they heard in Huambisan into those naming birds and those naming fish at accuracy levels exceeding chance, and did so without feedback (Berlin, 1994). This may occur because in Huambisan, bird names tend to contain non-rounded (e.g., *i*) vowels and fish names tend to contain rounded (e.g., *o*) vowels, an interesting pattern considering that birds tend to have angular contours while fish contours are more rounded. A vowel is labeled as rounded or non-rounded based upon the shape of the mouth and the lips when pronouncing it. For example, for the non-rounded vowel *i* (pronounced as in b*ee*t), the corners of the mouth are drawn back into a narrow elliptical shape, whereas for the rounded vowel *o* (pronounced as in c*o*de), the lips are rounded and slightly protruded

(Justice, 2001). Findings such as those with Huambisan support the idea that some sound-symbolism is universal across languages. Thus, it may be easy for the human brain to associate non-rounded vowel sounds to objects with angular contours (like a bird) and rounded vowel sounds to objects with rounded contours (like a fish). These natural associations between non-rounded vowels and angular contours may in turn have influenced the evolution of Huambisan so that birds are more likely to be named by words containing rounded rather than non-rounded vowels. Such natural associations may make it possible to figure out whether a word in a foreign language refers to a category of rounded versus pointed objects.

Sound symbolism is also evident when adults are asked to associate objects to nonsense words (Kohler, 1929; Lindauer, 1990; Marks, 1996; Ramachandran & Hubbard, 2001). In the best known example, which was reported by Kohler in 1929, adults chose whether a rounded or jagged shape was the referent for a nonsense word. When the nonsense words were *takete* and *maluma*, most adults answered that *takete* was the jagged shape and *maluma* was the rounded shape (Kohler, 1929). This effect has been replicated in adults with other pointed versus ameboid shapes and other words contrasting rounded and non-rounded vowels (e.g., kiki and bouba) (Hubbard & Ramachandran, 2001; Lindauer, 1990). It has also been found in 8 to 14-year-old non-English speaking children fluent in Swahili and the Bantu dialect of Kitongwe, but not English, (Davis, 1961), and in English speaking toddlers (30-36 months) (Maurer, Pathman & Mondloch, 2004). Ramachandran and Hubbard (2001) speculate that these phenomena arise from connections among contiguous cortical areas mediating decoding of the visual percept of the nonsense shape (round or angular) as well as the areas decoding the sound, the appearance of the speaker's lips (open and round or wide and narrow), and the feeling of the action of saying the same words oneself. They argue that these connections lead to natural mappings between sound and shape that may influence the language development of an individual child. The relationship between the natural mappings and the meaning of words will be one of mutual influence: as the child acquires the vocabulary of the language, some of the natural correspondences between shape and sound will be reinforced and others will be altered because they are not common in the child's language (see Nuckolls, 1999; Smith & Sera, 1992).

Recent evidence suggests that sound symbolism does help to bootstrap language learning. Japanese- and English-speaking adults consistently matched a set of novel Japanese sound-symbolic action words (mimetics) to their corresponding actions (Imai et al., 2008). Two- and three-year-old Japanese children also correctly matched the novel mimetic words to the appropriate action when presented with two videos, one of the matching action, and one of a different action. Although verb generalization tends to be difficult for young children, Japanese-speaking three-year olds were able to generalize the novel mimetics to other objects performing the same action, but failed to generalize for non sound-symbolic mimetic verbs, or mismatching verb/action pairs, a pattern suggesting that the mimetics helped with verb generalization (Imai et al., 2008). The finding that English-speaking adults and young Japanese children match novel Japanese mimetics to appropriate actions adds to the evidence that some sound-symbolism may be universal and naturally-biased. The evidence on verb generalization provides the first empirical evidence that sound symbolism facilitates language learning in children.

The sound characteristic that appears predictive of the association to round versus jagged shape in adults and toddlers is the roundness of the vowel (Maurer, Pathman & Mondloch, 2004; Ramachandran & Hubbard, 2001), though there is evidence that the consonant sound can have some effect in adults (Westbury, 2005). In an implicit interference task, adults showed interference when different single consonants were presented as printed letters in rounded versus jagged shapes (Westbury, 2005). However, the influence of the consonant *sound* in spoken language*s* on shape matching has never been tested systematically in children or adults. Toddlers are an appropriate age group to examine this question because they are in the midst of a vocabulary explosion and sound symbolism must be effective in this period if it is to influence language learning as postulated. In addition, although they have had ample exposure to language, toddlers have little knowledge of metaphor, and have less understanding than adults of the overall statistics of the vocabulary in their own language (e.g., fish are named with rounded vowels) that would generalize to nonsense words and shapes. The purpose of Experiment 1 was to examine the influence of consonant sound on shape matching in toddlers. We maximized the differences between the consonants by contrasting stop consonants, in which the flow of air is cut off completely during production (e.g., *t*, *g*), with approximant consonants in which the articulatory tract is relatively unobstructed, making them more vowel-like (e.g., *w*, *r*) (Justice, 2001). Because of the possible influence of mouth shape on sound-shape matching (e.g., Ramachandran & Hubbard, 2001), we chose consonant contrasts with the largest proprioceptive difference between consonant categories when producing them oneself and the largest visual differences when watching someone else produce them (closed mouth versus partially open mouth). Thus, although it is possible that there may be an influence of other consonant sounds on shape matching, we reasoned that the contrast between stop consonants and approximants maximized the likelihood of finding a difference. Specifically, we examined whether toddlers associate approximant consonants to rounded shapes and stop consonants to jagged shapes.

A limitation in previous studies on sound/shape matching is that they did not control for vowel or consonant variety within words and between word pairings: some of the stimulus words contained repeating syllables (e.g., kiki) and some did not (e.g., maluma). If vowel variety or consonant variety influence sound/shape matching, then the previous studies may have mistakenly concluded that it is roundness of vowel that matters. The purpose of Experiment 2 was to ensure that vowel roundedness has a systematic effect when not confounded with other variations. Specifically, we examined whether toddlers match rounded vowels to rounded shapes and non-rounded vowels to jagged shapes when the presented words contain no vowel or consonant variation (i.e., when they contain repeating syllables).

We played a game with English-speaking toddlers in which we contrasted four pairings of nonsense words and asked the child to choose to which of two unfamiliar shapes, one round and one angular, the nonsense words corresponded. The two nonsense words presented on each trial differed in whether the reduplicated consonant was a stop consonant or an approximant (Experiment 1) or whether the reduplicated vowel was rounded or non-rounded (Experiment 2). The members of each pair with contrasting consonants both had reduplicated rounded vowels or reduplicated non-rounded vowels. The members of each pair with contrasting vowels had identical reduplicated stop consonants. Shape stimuli were based upon the shapes used in previous studies on mapping between nonsense words and shape (e.g., Kohler, 1929; Ramachandran & Hubbard, 2001).

Methods

Design. The experiment consists of 8 forced choice trials: 4 validity and 4 experimental trials, intermingled with each other. Experimental trials tested the hypotheses of the study while validity trials evaluated whether the participant understood the instructions. On experimental trials, the child was shown jagged and rounded shapes, was told two nonsense words and asked to find the object corresponding to one of the words. On validity trials, the child was shown recognizable objects, told two familiar words, and asked to find one object following the same format of instructions as on experimental trials.

Participants. Children were recruited from a file of parents who had volunteers during hospital visits shortly after birth. Participants for Experiment 1were 40 toddlers (18 male; mean age = 32.4 months, range 30-36 months). Participants for Experiment 2 were 20 toddlers (11 male; mean age = 34 months, range 30-36 months).

Materials. Visual stimuli for experimental trials in both experiments were three pairs of shapes molded out of clay (and subsequently hardened), and a cardboard box with a pair of shapes cut out of one side to create two differently shaped holes. All four shape pairs consisted of a shape with rounded contours and one with jagged contours (for an example, see Figure 1).

Sounds for experimental trials were four pairs of nonsense words spoken aloud, each consisting of two repeating syllables. In Experiment 1, the two words within each pair differed only in consonant sound, with one containing a stop consonant (e.g., bibi) and the other word containing an approximant consonant (e.g., yiyi) (see Table 2). Half of the toddlers (n = 20) were tested on word pairs containing rounded vowels (e.g., bobo vs. yoyo), and half (n=20) were tested on words pairs containing non-rounded vowels (e.g., bibi vs. yiyi). In Experiment 2, the two words within each pair differed only on the vowel sound, with one word having a rounded vowel (*o* pronounced as in c*o*de), and the other having a non-rounded vowel (*i*, pronounced as in b*ee*t) (see Table 3); both words within a pair had the same reduplicated stop consonant (i.e., *b*, *g*, *k*, *d*). The presentation of word pairs in each experiment was counterbalanced such that each word pair was presented with each shape pair an equivalent number of times.

The stimuli for the validity trials were four pairs of objects that toddlers would know the difference between. Specifically, a picture of a green rabbit with polka dots and a yellow rabbit with no polka dots; a picture of a blue dog with polka dots and a red dog with none; a picture of a dog dish and a bird cage; and 3-D models of a miniature rooster and a horse.

Procedure. The protocol and procedures were approved by the McMaster Research Ethics Board. Once the procedures were explained and parents gave written consent, the child and experimenter engaged in pre-play in which the child assumed the role of one stuffed animal and the experimenter assumed the role of another (Mr. Mouse or Mr. Bear). During pre-play, the experimenter asked the child to find objects and retrieve them. Once the child consistently brought the requested objects, the experiment began.

"Well, you are such a good helper, but I'm a little sad because I can't find some of my friends. Do you think you could help me? You can, yay!"

On the first validity trial, the experimenter said "I am looking for my friend the green rabbit, he has polka dots. Can you see him? Which one is the green rabbit?" The experimenter showed the child pictures of a green rabbit and of a yellow rabbit. If the child picked the green rabbit, the experimenter said, "Yay, you found the green rabbit, you are such a good helper." If the child picked the incorrect picture, the experimenter said, "Is that the green rabbit? He looks kind of funny to me." Similar dialogue was used for the other three validity trials. To be included in the analysis, participants had to be correct on at least 3 out of the 4 validity trials, a criterion met by all 60 toddlers.

Each experimental trial consisted of the simultaneous presentation of a word pair and two shapes, and a forced choice to match one of the words to one of the shapes. On the first experimental trial, the experimenter presented a box containing two openings, one rounded and one jagged and continued the storyline, "I am looking for my friend Kiki. She is hiding in this box with Wiwi, can you bring me Kiki?" The child reached into the box and retrieved one of the shapes from the box. Similar dialogue was used for the remaining experimental trials in both experiments.

All children were praised on the experimental trials regardless of response and all children received a prize from a treasure box at the end of the session.

Results

Experiment 1. Children were correct on three (n = 4) or four (n = 36) of the four validity trials. For the experimental trials, we calculated a matching score for each subject based on choosing the rounded shape for the words with approximant consonants and the angular shape for the words with stop consonants, such that a score of 4 indicates choosing in the expected direction on every trial and a score of 2 represents random choices. When the data for the *o* and *i* lists were combined, scores were not significantly greater than chance based upon an 1-tailed independent samples t-test against a chance value of 2; children chose in the expected direction on a mean of 2.25 trials out of 4 (t (39) = .83 *p* = .21) (see Figure 2). Further, participants matched stop consonants randomly to shapes whether the contrasting words both contained a rounded vowel (M = .55 in expected direction), or both contained a non-rounded vowel (M = .5 in expected direction). Likewise, participants randomly matched continuant consonants to shape whether the two contrasting words both contained a rounded vowel (M = .45 in expected direction) or non-rounded vowels (M = .55 in expected direction).

Experiment 2. Children were correct on three (n = 5) or four (n = 15) of the four validity trials. For the experimental trials, we calculated a matching score for each subject based on choosing the rounded shape for the words with rounded vowels and the angular shape for the words with non-rounded vowels, such that a score of 4 indicates choosing in the expected direction on every trial and a score of 2 represents random choices. The scores were significantly greater than chance based upon an independent samples 1-tailed t-test against a chance value of 2: children chose in the expected direction on a mean of 2.6 trials out of 4 (t (19) = 3.11 *p* = .006) (see Figure 3). This effect was true on trials with rounded vowels (M = .68 in expected direction) and on trials with non-rounded vowels (M = .63 in expected direction). This effect was generally consistent across consonant contexts (Figure 3) except for the context of the consonant *k*.

Discussion

Children as young as 2.5 years old match rounded shapes to words with rounded vowels, and jagged shapes to words with non-rounded vowels, but do not systematically match shapes to words with stop versus approximant consonants. Thus, the crucial characteristic of a nonsense word that determines its mapping to shape in toddlers seems to be the vowel sound. These results extend previous findings (Maurer et al., 2004) and show that they hold even when the consonant context and sound variability is held constant across the word pairings. Thus, vowel roundness has a robust effect on toddlers' mapping between sound and shape and may aid the learning of the meaning of words, as postulated by Ramachandran & Hubbard (2001).

We found no effect of the consonant sound on toddler's shape associations, despite using maximally contrasting consonants (stop versus approximant) and shapes (round versus jagged). The only previous study investigating sound symbolism for consonant sounds examined the interference for adults between rounded/jagged shape and printed stop (e.g., *t*) versus continuant consonants (e.g., *s*). English speaking adults viewed letter strings containing stop or continuant consonants presented in the middle of either a jagged or a rounded frame, and had to decide whether the letters formed a word (Westbury, 2005). In an additional task, single characters were presented in rounded or jagged frames and adults had to decide whether they were letters. Adults were slower to respond when continuant consonants were presented in a jagged frame or stop consonants were presented in a rounded frame. The author suggests that this interference points to a relationship between visual form and the phonology of consonant sounds. It is difficult to relate these findings to those presented here because of the difference in methodology: printed letters versus spoken consonants; implicit task versus explicit choice of matching shape; and adults versus toddlers. One possibility is that an influence of consonants is acquired with learning because there might be, for example, more words with stop consonants in English used to represent objects with jagged shapes (e.g., spike, point) than objects with rounded shape. Since adults have a larger vocabulary and greater inductive reasoning skills with which to extract the statistics of language than toddlers, they may have learned a correspondence between consonant category and shape that implicitly influences their behaviour. Toddlers may have yet to learn this correspondence to such an extent that it influences their behaviour. Alternatively, the effect may be exclusively between the shape of the printed consonant (curved/continuous *s* versus discontinuous *k*) and rounded versus jagged frames with no effect from the consonant sound itself.

The results found here for rounded and non-rounded vowels might be related to a bias in the referents for the corpus of English nouns with rounded versus non-rounded vowels: It is possible that words that have non-rounded vowels tend to represent objects that are sharp and that words that have rounded vowels tend to represent objects with curved contours. Perhaps these regularities occur often enough in common words for toddlers to pick them up. However, it is also possible that this effect represents a naturally-biased association between shape and the sound of the phoneme, between shape and the sight of the shape of the mouth when producing the sound, and/or between shape and the feeling (amount of oral roundedness) needed to produce the same sound oneself, and that these natural associations influenced the evolution of languages (Ramachandran & Hubbard, 2001). Within this framework, words used to represent sharper objects would tend to have phonemes that do not round the mouth, taking advantage of natural biases. By the time a child is 2 ½ years old, the combination of the natural bias and sensitivity to statistical regularities in sound-meaning mappings that evolved from it, would jointly influence the continued acquisition of vocabulary. Whatever the origins, our results indicate that sound symbolism for vowels influences toddler's mapping of words to objects, and that there is no evidence for a similar effect for consonants.

Future studies examining sound symbolism in infants would clarify the origin of such mappings. Similar studies with young children learning different languages would also be helpful, because languages appear to differ in the extent to which they make use of the sound symbolism (Day, 2004; Nuckolls, 1999). It would also be interesting to explore the characteristics of the stimuli that influence toddlers' mapping of nonsense words to nonsense shape. In this study, toddlers were exposed to both the sound of the word and the shape of the speaker's mouth while saying the words, so we cannot determine which aspect of the spoken word influenced shape mapping. Future studies could present only the visual stimulus (the speaker mouthing the word), only the auditory stimulus (a tape recording of the word), or both to evaluate their separate and interactive influences. They could also vary proprioceptive cues by asking the child to mimic the word or by putting something in the child's mouth to prevent him/her from repeating it. Such studies would separate visual, auditory and proprioceptive aspects of spoken nonsense words in order to allow better understanding of how natural biases can influence language learning.

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Approximates	O list		I list	
R	roro	Bobo	Riri	Bibi
L	Lolo	Gogo	Lili	Gigi
W	Wowo	Koko	Wiwi	Kiki
Y	Yoyo	Dodo	Yiyi	didi

Table 1: The two word lists used in Experiment 1. Each child was tested with either the O or the I list. Each word in a pair had the same vowel sound as its partner, with one word in the pair having a stop consonant and the other having a continuant.

Stop Consonants	Word list	
G	Gigi	Gogo
B	Bibi	Bobo
K	Kiki	Koko
D	Didi	Dodo

Table 2: The word list used in Experiment 2. Each word in a pair had the same consonant sound as its partner, with one word in the pair having a rounded vowel and the other having a non-rounded vowel.

Figure Captions

Figure 1: Example of a shape pair, with the jagged shape on the left and the rounded shape on the right.

Figure 2: Proportion of toddlers' choices in the expected direction (stop consonant – jagged shape, continuant consonant – rounded shape) in Experiment 1. The dotted line indicates the level expected by chance. Toddlers matched consonant sound to shapes randomly.

Figure 3: Proportion of toddlers' choices in the expected direction (rounded vowel – rounded shape, non-rounded vowel – jagged shape) in Experiment 2. Bars to the left of the grey dotted line indicate the overall influence of vowel sound on shape choice. The black dotted line indicates the level expected by chance. Toddlers matched vowel sounds to shapes in the expected direction more than can be expected by chance, as indicated by the asterisks. Bars to the right of the grey dotted line indicate the influence of vowel sound on shape choice across the different consonant contexts. The effect was consistent across consonant contexts, with the exception of the consonant k.

Figure 1

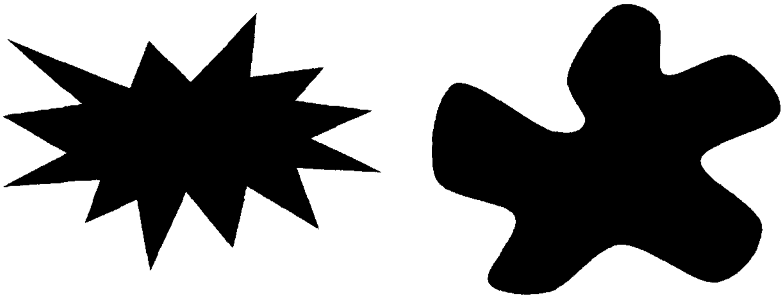


Figure 2

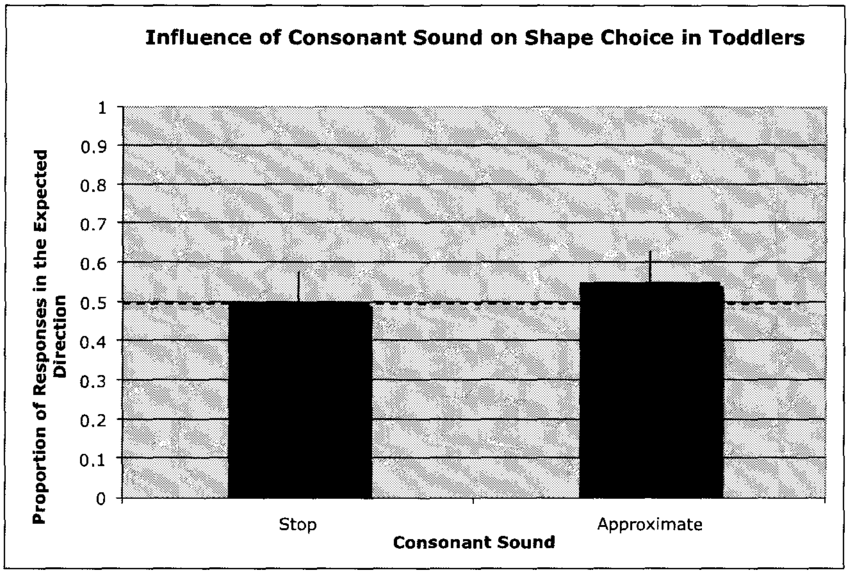
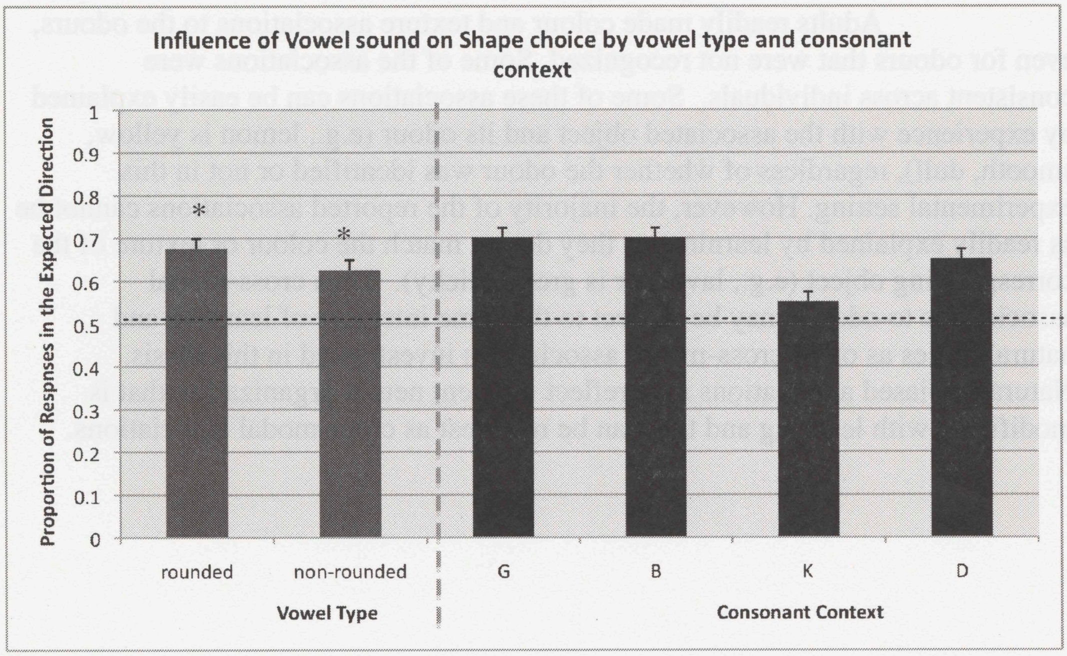


Figure 3


Influence of Vowel sound on Shape choice by vowel type and consonant context
Proportion of Respnses in the Expected Direction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
*
*
rounded
non-rounded
G
B
K
D
Vowel Type
Consonant Context

Introduction to Chapter 5:

In the research presented in Chapter 5, I examined cross-modal associations to odours, specifically examining whether there are any consistent colour and texture associations to odours in adults. Previous studies using a smaller set of odours documented systematic associations between odour and colour (Gilbert, Martin & Kemp, 1996) as well as between odour intensity and colour lightness (Kemp & Gilbert, 1997), but did not test for texture associations or measure familiarity with the odour. This is the first study to examine texture associations to odour in an overt association paradigm and to include a measure of identification to examine the effect of odour familiarity on colour and texture associations. Non-synaesthetic adults smelled 22 odours and reported any colour and/or texture association to each.

Adults readily made colour and texture associations to the odours, even for odours that were not recognized. Some of the associations were consistent across individuals. Some of these associations can be easily explained by experience with the associated object and its odour (e.g., lemon is yellow, smooth, dull), regardless of whether the odour was identified or not in this experimental setting. However, the majority of the reported associations cannot be as readily explained by learning, as they do not match the colour or texture of the corresponding object (e.g., lavender is green, sticky). Thus cross-modal associations to odours may be subject to the same interplay of learning and natural biases as other cross-modal associations investigated in this thesis. Naturally-biased associations may reflect inherent neural organization that is modifiable with learning and that can be manifest as cross-modal associations.

Making Sense of Scents: The Colour and Texture of Odours

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Abstract

The purpose of this study was to document colour and texture associations to odours using a variety of odours including some likely to be unfamiliar, and both pleasant and unpleasant odours. We asked non-synaesthetic adults (n = 78) to make colour and shape/texture associations to 22 odours. A subset of the participants (n = 41) smelled the odours a second time in order to identify them. Each odour stimulus was associated consistently to one or more specific colours and/or textures (all ps < .01 by binomial probability statistics). Associations to the four odours that were identified accurately (cinnamon, lemon, peppermint and licorice) seemed to be based on learning/memory (e.g., lemon = yellow). The associations to the 18 odours that were not identified accurately are less likely to be based on learning/memory (e.g., ginger = black, rough, sharp; lavender = green, white, liquid, sticky). The results suggest that sensory associations to odours, like those to pitch and letters (e.g., Mondloch & Maurer, 2004; Spector & Maurer, 2008), may result from the joint influence of learning and natural biases linking dimensions across sensory systems. Such links may reflect inherent neural organization that is modifiable with learning and that can manifest as cross-modal associations or synaesthetic percepts.

Introduction

Traditionally the senses have been considered as separate modalities that become integrated only at higher levels of the cortex. Recent research challenges this view by indicating that sensory modalities influence one another from the earliest stages of cortical processing (e.g., Ghazanfar & Shroeder, 2006; see Calvert, Spence & Stein, 2004 for a collection of relevant multisensory articles). Some of this research is motivated by studies of synaesthesia, a perceptual phenomenon in which for some individuals, stimulation of one sense elicits a percept in another sense or another dimension of the same sense. For example, the existence of individuals with coloured-hearing synaesthesia, who perceive colour in response to sound led researchers to examine the correspondence between colour and sound in individuals without synaesthesia. This examination led to the discovery of a relation between pitch and colour lightness in synaesthetic and non-synaesthetic adults, as well as non-synaesthetic toddlers: as pitch increases, all three groups associate it to increasingly lighter colours (Marks, 1989; Mondloch & Maurer, 2004; Ward, Huckstep & Tsakanikos, 2006). Of course, some cross-modal correspondences can be learned from the statistics of the environment; for example non-synaesthetic adults associate lower pitched sounds to larger objects and higher pitched sounds to smaller objects (Marks, 1989). A larger dog does have a lower pitched bark than a smaller dog. However, learning cannot easily explain the correspondence between pitch and lightness: darker animals do not make lower pitched sounds than lighter animals. Rather, these associations may represent natural biases between pitch and lightness that reflect systematic connections between sensory areas. Both mainstream research on crossmodal perception and research inspired by synaesthesia has shown that probing consistencies in cross-modal association can provide insights about how multisensory information is organized in the brain, how that organization relates to statistical regularities in the environment, and how it can influence behaviour. Research on consistent cross-dimensional associations within a single modality (e.g., between letter shape and colour) can provide similar insights (e.g., Day, 2004; Rich et al., 2005; Simner et al., 2005).

Most of the research on the consistency of cross-modal and cross-dimensional associations in adults has been conducted in the visual and audiovisual domains, with a smaller body of work on auditory and visual influences on somatosensory perception (e.g., Kai-Ming, 2003; Molholm et al, 2004). There has been little research on how vision, hearing, or touch influence the chemical senses, no doubt because the chemical senses are often thought of as fundamentally separate from other sensory modalities. The separation could be based on the difference in the nature of the inducing stimuli (chemical versus mechanical) and the fact that, at least for olfaction, unlike other sensory modalities, information can reach the cortex without first going through the thalamus (e.g., Mori, Nagao & Yoshihara, 1999). Moreover, taste and smell are interrelated with each other to such an extent that the typical individual experiences a ‘synaesthesia’ of flavour in which the separate contributions of taste and smell cannot be distinguished (e.g., Dalton, Doolittle, Nagata, & Breslin, 2000), unlike the easier separability of sight, hearing, and touch. According to this viewpoint, there is little reason to think that there would be strong cross-modal relations between odour and vision, odour and touch, or odour and hearing.

Consistent with the expectation of minimal crossmodal links between odour and touch, vision, or hearing, is the relative rarity of synaesthesia between taste/smell and other sensory modalities; synaesthesia between vision and hearing or within vision is far more common. (Day, 2004; Marks, 1978). In the rare cases of olfactory or gustatory synaesthesia, exposure to a specific odour or taste induces the percept of a specific colour or the feeling of a specific texture. The extra percepts are either experienced in the mind’s eye or projected into external space (e.g., the taste of marinara sauce may induce the feeling of running one’s hands over soft spikes). Like the expectations from mainstream multisensory research, the rarity of olfactory and gustatory synaesthesia suggests that there is a separation between the chemical senses and other sensory modalities.

Recently, the traditional view of olfaction as largely separate from the other modalities has been challenged by findings that adults’ perception of odour is modified by concurrent visual information. For example, their perception of the intensity of an odour can be altered by adding colour to the solution (Zellner & Kautz, 1990). A solution that smells like strawberry, for example, smells stronger when colour is added to it, even when the colour is inappropriate. For example, a green strawberry odour solution smells stronger, but not more pleasant, than clear strawberry solution, a result suggesting that the enhancement of odour by colour is not the result only of learned associations between specific colours and specific odours (Zellner & Kautz, 1990). In addition, adults are more likely to report an odourless solution as possessing an odour if the solution is coloured (Engen, 1972). Adults are also faster to classify odors when the odour (i.e., lemon or strawberry) is presented with either a congruent visual image (a lemon or a strawberry) or a congruent colour patch (red or yellow), even when the visual stimulus is irrelevant to the task (Dematte, Sanabria & Spence, in press). This kind of modification can even fool experts. When an odourless red dye is added to white wine, wine experts consistently describe the odour using language typically reserved for red wine, and avoid using language reserved for white wine (Morrot, Brochet & Dubourdieu, 2001). These modifications are similar to the manner in which vision, audition, and touch perception can be facilitated and/or modified by concurrent stimulation of another sense (e.g., Kennett, Taylor, Clarke, & Haggard, 2001; Odgaard, Arieh, & Marks, 2004; Shams, Kamitami, Thompson, & Shimojo, 2000). In fact, concurrent presentation of odours can alter touch perception. Adults rate swatches of fabric as softer when accompanied by a pleasant odour (e.g., lavender) compared to an unpleasant (animal) odour (Damatte, Sanabria, Sugarman & Spence, 2006). This occurs whether the odour emanates from the fabric itself or from another source. Together, the evidence suggests that olfaction interacts in a systematic way with other sensory modalities besides taste.

In one of the few previous studies on visual associations to smell, Gilbert, Martin & Kemp (1996) found that (non-synaesthetic) adults reliably associate specific colours to specific smells. Participants smelled 20 odours from the perfume industry and either described which colour goes with each odour, or chose from a set of coloured chips. Whichever measure was used, there was some consistency across participants in the colour choice for each odour (Gilbert, Martin & Kemp, 1996). In a later study, participants were presented with three concentrations of five odours that had a high rate of consistency in the previous study and matched each to a colour chip (Gilbert, Martin & Kemp, 1996). For three of the five odours, participants consistently paired darker colours to more concentrated solutions, and lighter colours to less concentrated solutions. These results suggest that odour intensity and colour lightness may be related sensory dimensions (Kemp & Gilbert, 1997), much like pitch and colour lightness (Marks, 1989, Mondloch & Maurer, 2004; Ward, Huckstep & Tsakanikos, 2006). In both studies, the target odours were ones used commonly in fragrances. It is therefore possible that the consistencies in colour associations were influenced by previous experience with the odours. In addition, because no measure of identification was included, there is no way to assess whether odour labels or familiarity influenced the colour associations.

The purpose of our study was to examine consistent colour and texture associations to odours in non-synaesthetic adults. We extended the findings from the previous studies on colour/odour associations by using more odours and analyzing the results for both common odours that are likely to be recognized and uncommon odours unlikely to be identified. Since odour influences touch perception in non-synaesthetic adults (Damatte et al., 2006), and induces felt texture in some individuals with gustatory and olfactory synaesthesia, we also examined texture association to odours. We included a measure of identification in order to examine the relation between semantic access to an odour name and its cross-modal associations.

Methods

Participants. Participants were 78 (8 male) non-synaesthetic adults, ranging in age from 17-44 (mean 19.2 yrs.)[1]. Participants were recruited from the undergraduate population at McMaster University and received class credit for their participation. Two additional participants were excluded because they reported having colour and texture experiences in reaction to odours, that is, they showed signs of olfactory synaesthesia.

Materials. Materials were 22 odourants (see Appendix A for chemical components and description) chosen in part based upon a preliminary survey of colour and texture associations to imagined smells in non-synaesthetic adults.

The odours included 14 smells that were likely to be familiar and 8 unfamiliar smells. They included odours from four of the five categories into which adults typically classify smells, namely food, floral, environment, and chemical/medicine (Chrea et al., 2005); we did not include odours from the animal category as the chemicals simulating those odours smell too noxious. Odourants were chemicals and/or essential oils obtained from various sources (Appendix A). All odourants were stored in glass containers, and were rated as non-harmful according to the standardized material safety data sheets (MSDS) for each substance.

Procedure. This research was cleared by the McMaster Research Ethics Board. Prior to the experiment, we explained the task to each participant and obtained informed consent. The experiment was administered in a well-ventilated area, with the experimenter and participant facing one another.

As background, we explained what synaesthesia is and described odour-related synaesthesia as the experiencing of a colour or texture when exposed to an odour. We then asked participants if they had ever experienced any synaesthetic tendencies. If they responded in the affirmative (n=2), then we continued with the experiment, but did not include the data in the general results.

We instructed participants not to identify the odours, but to smell each one as often as needed to find a colour and texture association or associations, if one existed. Previous research indicates that specific odour to colour associations remain the same whether participants verbally report associations to odours or are presented with specific colours to choose from (colour chips) (Gilbert & Kemp, 1996).

When the participant indicated a readiness to begin, the experimenter handed the participant the first odourant. The participant self-administered the odourant, and verbally reported any colour and texture association, which the experimenter recorded using a pen and paper. When the participant indicated readiness to proceed, the experimenter handed him/her the next odourant. The experimenter was naïve to the specific odourant being presented, and the order of odour presentation was randomized across participants. Participants were allowed as much time as needed with each odourant. In between odourants, they were encouraged to take a sip of water and/or smell coffee grounds in order to reduce odour cross-contamination. Any communication between trials was restricted to the experimenter clarifying the participants' response, and/or confirming their willingness to continue. After self-administering all 22 odourants, participants verbally rated the difficulty of associating colour to smell and texture to smell on a 1-7 scale (where 1 equals easy and 7 equals difficult), and the experimenter recorded the responses. Participants also rated the extent to which making these kinds of association "made sense" to them (where 1 is equal to "making sense" and 7 is nonsense). The last 41 participants to take part in the experiment smelled each odourant a second time in order to identify each one, as well as to place it into one of 5 standard smell categories (food, floral, environment, animal, chemical/medicine) (Chrea et al., 2005). The experimenter handed each odourant to the participant in the same order as during the original test and recorded the responses.

Insert Table 1 about here

Results

Identification and Categorization. Five of the 22 odours were correctly identified by at least 20% of the group asked to identify them: cinnamon (24%), lemon (44%), peppermint (59%), anise (licorice, 49%), and napthene (moth balls, 32%). Participants were slightly better at placing smells into the appropriate odour category, with 17 out of 22 odours categorized correctly by more than 20% of the group (see table 1). Individual participants correctly recognized a mean of 0.12 odours (SD = .09, range = 0 - 0.27) and correctly categorized a mean of 31% of the odours, or approximately ~7 odours (SD = 17.5, range = 0-54%).

Colour

Colour Terms. All participants made colour associations to at least one of the odours. The colour associations were classified into the 11 colours identified by Berlin and Kay (1969) as most frequently used across cultures: black, white, red, yellow, green, blue, brown, orange, purple, pink and grey. The term "clear" could not be fit into this classification because it co-occurred with white within individuals and often enough (1% of all responses) to warrant being included as a 12th colour classification. Each participant's reported colours were sorted into the 12 colour categories; for example, "dark violet" was categorized as purple, and "transparent" was categorized as clear. A second raters' classification of the colours reported for 3 odours (cinnamon, lavender and anisole) agreed with the original coding 98% of the time.

Analysis. Each participant reported no more than one colour for each odour and on average reported 0.99 colours for each of the 22 odours (SD = .031, range = 0.86 – 1.0). We counted the number of times each colour was associated to each odour. For example, cinnamon was most often associated to the colours red and brown. Since each participant reported no more than one colour for each odour, the individuals driving the consistent association of cinnamon to brown are different from those driving the consistent association of cinnamon to red.

In order to identify consistent colour associations to each odour across individuals, we estimated the probability that any odour–colour combination occurred by chance using probabilities derived from the data as a whole. For example, red accounted for 11% of all responses—so the probability that a given odour would be associated to red is .11 (Figure 1). Thus, instead of assuming that each colour has an equal chance of being reported, we used the data to calculate chance values for each colour. This method gives a conservative estimate of chance probabilities: if true cross-modal connections between odour and colour in fact occur more often for some colours than others, this statistical procedure will lead to an underestimate of the incidence of the phenomenon.

Insert figure 1 about here

We used binomial probabilities to determine whether the reported incidence of each colour was higher than expected by chance, using the formula below (see Baron-Cohen et al., 1993; Ward & Simner, 2003 for application to data on colour/letter and taste/phoneme consistency, respectively).

$$P_n(k) = \left(\frac{n!}{k!(n-k)!}\right) * (p^k(1-p)^{n-k})$$

P is the probability that the observed data occurred by chance (e.g., the probability that 22 people would say cinnamon is red by chance), p is the chance value for choosing a particular colour (e.g., the probability of choosing red overall, which was .11), n is the number of opportunities for a particular colour to be associated to an odour (i.e., the number of subjects), and k is the proportion of times a particular colour was associated to each odour (e.g., 22 people said cinnamon was red, out of 78 subjects = .29). In this example, the probability that 22 out of 78 people would respond that cinnamon is red by chance is less than .001. Thus, we can conclude that the smell of cinnamon is associated to the colour red more often than expected by chance. Applying the same analysis to all odour and colour combinations reveals significant colour associations for each odour (see Table 2 for overall results, and Figures 2 a-v for individual odour/colour graphs).

Colour associations to identified odours. All five of the reliably identified odours (cinnamon, lemon, peppermint, napthene and anise) had significant levels of consistent colour associations (*ps* < .01). There was little overlap between odours in the colours chosen and there was more than one colour chosen for four of the five odours. The colours reported were typically ones that can be explained easily by prior learning (e.g., lemon – yellow), although some choices (e.g., peppermint- blue) cannot be so readily explained.

Colour associations to non-identified odours. All 17 non-identified odours had significant levels of consistent colour associations (*ps* < .05). The significant colour associations occurred for all four odour categories and include ones not readily explained by learning (e.g., almond – red).

Insert Figure 2 a-v about here

Texture

Texture Terms. All participants reported texture associations to at least one odour. The texture associations were placed into categories based upon standard tactile texture classifications, namely smooth, rough, hard, soft, sharp, dull, thick, thin, directional and random orientation (e.g., Rao & Lohse, 1996; Hollins et al., 1993; Yoshida, 1968; Picard et al, 2003). We also used additional texture categories based upon texture descriptions used by the participants themselves, namely wet, dry, sticky, slippery, large, small, cold, and warm. As with colour, participants' responses were fit into these categories. For example, "the feeling of sandpaper" was categorized as "rough", and "slimy" was categorized as "slippery" and "wet". Though most tactile texture analyses organize texture space into polarized dimensions (e.g., rough-smooth) (e.g. Hollins et al., 1993), some individuals associated a specific odourant to both extremes of one dimension (e.g., smooth and rough). Thus we decided to treat each texture term independently. If the participant gave more than one texture term for an odourant, they were counted as separate associations both in the categorization for that odour and the calculation of overall baseline responses. A second rater's classification of the choices for 3 odours (cinnamon, lavender and anisole) agreed with the original coding more than 97% of the time.

Analysis. Individuals reported a mean of 1.52 texture associations per odour (SD = .24, range = 1.00 - 2.05). As with colour, we tabulated the total number of times each texture category was used across all the odours and calculated the proportion of the total for each odour. For example, cinnamon is most associated to the textures rough, hard, and slippery. Similar to the analyses reported for colour, we estimated the probability that a given odour–texture combination occurred by chance using the frequencies derived from the body of data as a whole. For example, the term rough accounted for 26% of the total responses and thus the probability that a given odour is associated to rough by chance was taken as .26.

Insert figure 3 about here

As with the colour terms, these frequencies were used as a chance value for calculating binomial probabilities. For example, 32% of participants said that the smell of cinnamon was rough, a value significantly higher than the chance value of 26% ($p < .01$). Applying the same analysis to all odour and texture combinations reveals significant texture associations for each odour (see Table 2 for summary of all results, and Figure 4 a-v for individual odour/texture graphs).

Texture associations to identified odours. All five reliably identified odours had significant levels of consistent texture associations ($p < .01$), with more than one texture associated to each. Although the textures included the ones that would be based on prior learning (e.g., lemon - smooth, dull), some choices (e.g., anise - rough) cannot be so readily explained.

Texture associations to non-identified odours. All 17 non-identified odours had significant levels of consistent texture associations ($p < .05$), with more than one texture significantly associated to each odour and not all associations readily explained by learning (e.g., lavender: sticky, large).

Rating scales. On the odour-colour difficulty scale, 44% of participants reported finding associating colours to odours to be a difficult task, 36% found it to be easy, and the remaining 20% found it to be neither easy nor difficult. On the odour-texture difficulty scale, 91% of participants reported finding associating textures to odours to be a difficult task, and 9% of the participants thought it was easy. On the task sense scale, 35% of participants reported that making these kinds of associations did not "make sense", whereas 65% people thought that the task made intuitive sense. Thus, associating colours to odours seems to be an easier task than associating textures to odours and despite the difficulty is making these associations, participants largely reported the task as making sense.

Insert table 4 a-v about here

Discussion

The analyses show that non-synaesthetic adults agree with each other about the specific colours and textures that they associate to odours. There were significant correspondences between colour and/or texture for each of the 22 odours studied. Four of the odours were also used in Gilbert & Kemp's (1996) study of colour associations to odours, and our results for those odours largely agree with theirs. Specifically, they also found cinnamon oil to be associated to red and brown, anise to be associated to black, bergamot to be associated to yellow and green (but also orange – which we did not find), and lavender oil to be associated to green (but also yellow, grey, and black – which we did not find). Most importantly, Gilbert and Kemp found that their odours were associated to colours largely independent of their semantic labels, as did we. We have extended their findings to show colour associations to odours outside of those used by the fragrance industry, and to those which adults do not readily identify. In addition, this is the first study to examine the relations between odour and tactile texture, many of which cannot be readily explained by learning. We found that adults do associate familiar odours to expected colours (e.g., lemon to yellow), and textures (e.g., cinnamon to rough), even if they cannot name the odour. However, learning cannot readily account for many of the colour and texture associations because there was no correspondence between the adults' choice and the characteristics of objects with that odor.

There is a widely held view that odour associations are very strongly influenced by personal experience (Ehrlichman & Bastone, 1992). For example, if one's grandmother always had blue hard peppermints, then the granddaughter may associate peppermint to the colour blue. From this viewpoint, we would expect to see common associations across non-synaesthetic adults for those odours for which the collective memory is similar. For example, the smell of lemons would be reported as being yellow, since that is their typical colour. In fact, we do see this pattern: odours that are easily identifiable (cinnamon, anise, napthene, lemon and peppermint) were reported as being the appropriate colour/texture based upon objects with these specific odours (e.g., lemon is yellow, smooth and dull). Even some odours that were not reliably identified seem to be associated to colours and textures in a manner that suggests memory (e.g., vanillin → white, brown, smooth, thick, liquid). These patterns suggests that even if a particular odour is not easy to name, the familiar smell of it may still be able to activate semantic knowledge that can influence the associated colour and texture in the absence of explicit identification.

If consistent colour and texture associations are based upon previous experience, we would expect to find little consensus in associations to odours which people are unlikely to encounter regularly or for which the experience is likely to be idiosyncratic. For example, anisole is a chemical additive in gasoline unlikely to be encountered in isolation, and therefore not likely to elicit a specific colour/texture association based upon experience with the single odour. However, despite participants' claim that most of the odours were unfamiliar, every odour tested had specific colour and texture associations. Moreover, 19 of the 22 odours had at least one consistent association to colours and/or textures that are not obviously representative of what the object with that smell looks like. For example, ginger was described as black and sharp; lavender was described as green, clear, large, liquid and sticky. Even some of the easily identifiable odours had some consistent associations that do not clearly fit with the physical properties of their source: cinnamon was described as slippery and anise was described as rough. Thus learning and memory cannot easily explain all of the correspondences we observed.

A possible explanation for the associations not readily explained by learning is that there are natural biases to associate certain odours to certain colours and/or textures. This explanation arises from growing evidence for seemingly naturally-biased cross-modal associations between other sensory domains. For example, synaesthetic adults with coloured hearing, non-synaesthetic adults, and toddlers all associate sounds of higher pitches to lighter coloured, smaller objects, and sounds of a lower pitch to darker coloured, larger objects (Marks, 1989, Mondloch & Maurer, 2004; Ward, Huckstep & Tsakanikos, 2006). While the associations between pitch and size can be easily explained by experience (larger animals = lower pitch noises), the origins of associating pitch and lightness is not as clear (darker animals ≠ lower pitched noises). Thus, there appear to be naturally-biased associations between pitch and surface lightness in toddlers, non-synaesthetic and synaesthetic adults that are not picked up from environmental statistics.

Clues as to why natural biases in sensory associations exist may lie in an examination of neural connections in the infant brain and how they change during development. There is evidence of functional cortical connections between sensory areas, which are present at birth and are largely, but not entirely, pruned or inhibited during development (e.g., Wolff, Matsumiya, Abrohms, van Velzer & Lombroso, 1974, Huttenlocher, 1994). For example, in young infants, spoken language elicits activity over the auditory cortex, as expected, but, it also 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). Similarly, at birth white noise modulates the size of the somatosensory evoked potential elicited by touch (Wolff et al., 1974). In other words, there are early connections among sensory areas responding to visual, auditory, and tactile stimuli. There is evidence that some of these connections persist in the adult brain, but are largely inhibited (Pascual-Leone & Hamlton, 2001; Grossenbacher & Lovelace, 2001). These connections can be selectively disinhibited; for example, when typically sighted adults are blindfolded for five days, they begin to show increasing activity in the visual cortex while discriminating tactile patterns, as if dormant connections between the tactile area and the visual area become active in the face of sensory loss (Pascual-Leone & Hamlton, 2001). Selective disinhbition (on its own, or combined with less-than-normal pruning) can also explain the co-activation of specific sensory areas that characterizes synaesthesia (Grossenbacher & Lovelace, 2001). Because neurons with similar response properties tend to lie contiguous to one another, such connections will lead to systematic cross-modal percepts that are to some extent similar from one synaesthete to another and cross-modal associations that are to some extent similar from one non-synethetic adult to another. This general pattern may result in natural biases that can be modified by learning. Within this model, there may be an initial natural bias to associate pitch and size. This would help the developing child to understand the statistics of the environment. Learning these statistics would reinforce the strength of this association as the child gains experience in a world where smaller organisms tend to make higher pitched sounds. Natural biases may persist to influence sensory associations in typical adults and yield actual percepts in synaesthetes.

There is some recent evidence of this interplay between learning and natural biases in the formation of colour associations to letters. Many letters of the alphabet are consistently mapped to specific colours in English-speaking adults (e.g., A tends to be red, B tends to be blue, etc), both in the general population and in individuals with grapheme-colour synaesthesia who perceive letters in colour (Day, 2004; Marks, 1975; Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005). Some of the consistent letter-colour associations appear to be based upon literacy (e.g., G to green), since they are related to the spelling of the colour term and reliably associated in literate children and adults, but not in pre-literate children (Spector & Maurer, 2008). However, some of the consistent colour-letter associations cannot be explained easily by literacy (e.g., X to black), and occur reliably even in pre-literate children. These reliable pre-literate associations appear to be based upon the shape and not the sound of the letter, and are influenced by shape smoothness/jaggedness (Spector & Maurer, 2008 and unpublished data). They may reflect associations between shape and colour that are naturally-biased by sensory cortical organization. These natural biases may initially bind colour to shape, but the development of literacy induces additional associations.

The associations adults made in the current study between odour and colour and odour and texture resemble the pattern reported previously for colour associations to letters in which some associations are readily explained by learning (G green) but others do not have a ready learning explanation (X black). In the results reported here, some odour associations can easily be explained by learning because the significant associations are to the expected colours and textures (e.g., lemon to yellow, smooth and dull). However, others do not have an easy learning explanation; for example, based on culturally agreed upon associations, we might expect lavender to be associated to purple, or blue, because lavender is a term for a light purple and the colour of the lavender flower is a bluish purple. However, the smell of lavender was most consistently associated to green, and to a smaller degree, clear. The results suggest that sensory associations to odours, like those between letters and colours, may result from the joint influence of learning and natural biases linking dimensions across sensory systems. Such links may reflect inherent neural organization that is modifiable with learning and that can be manifest as cross-modal associations in non-synaesthetic adults and conscious perceptions in adults with olfactory or gustatory synaesthesia.

Unlike pairing colours with letters, the majority of participants reported that associating colours and textures to odours was a difficult task; however, they also reported that making these kinds of sensory associations made intuitive sense. Anecdotally, many participants made comments to the effect that although it previously never occurred to them to associate a texture and a colour to an odour, the inclination to do so made perfect sense once it was requested of them.

Many of them further reported that the associations were "just coming" to them, they did not know from where. Thus, although most people never think about the relation between colour, texture and odour, they are able to recognize one when their attention is drawn to it. This may reflect the natural inclination of the sensory system towards multisensory relations.

Since the colour and texture of food are important indictors of edibility, it is not surprising that colour and texture information influence the perception of odor. Beyond interactions among primary cortical areas, the orbitofrontal cortex (OFC) seems to play a key role in the interactions. It receives direct input from the primary gustatory and olfactory cortices, and is in fact considered the secondary gustatory and olfactory cortex. The OFC also receives direct input from the primary and secondary auditory and somatosensory cortices as well as from higher ventral visual processing areas (Verhagen & Engelen, 2006; Francis et al., 1999; Ongur & Price, 2000). The OFC also appears to be involved in the cross-modal interaction of smell and colour. When presented with edible and pleasant odour/colour pairs previously rated as congruent, adults show increased activation in areas in the left OFC and left insular cortex that are also active in response to the presentation of odours alone (Osterbauer, Matthews, Jenkinson, Beckmann, Hansen & Calvert, 2005). This may be related to food choice: if an item of food smells pleasant in a way that is congruent with its colour, then it is likely ripe and palatable. Consistent with this interpretation is evidence that the left OFC shows strong activation when adults make hedonic judgments of odours (Royet et al., 2001). Hedonic judgements of odours could interact with colour/odour congruency judgments to maximize cues of palatability. In the tactile domain, the OFC responds to the positively affective quality (i.e., pleasantness) of touch as opposed to its intensity: the right OFC responds when adults touch a pleasant soft surface (e.g., velvet) versus a neutral stimulus (e.g. wood), regardless of the force with which the neutral stimulus is touched (Francis, et al., 1999). There is also activation in the right OFC when adults judge the familiarity of an odour (Royet et al., 2001). Texture and familiarity, like congruent colour, may signal that a food is palatable. Given the evidence for cross-modal olfactory interactions in the orbitofrontal cortex, it seems plausible that the OFC is a neural locus for multisensory links between olfaction, vision and touch.

This research lays the foundation for future studies, which could examine the specific variations in odourants that underlie the cross-modal associations. For example, future studies could probe whether odours that smell more intense are more likely to be associated to darker colours (as are lower pitches) and/or to rougher textures. Alternatively or additionally, odours that smell sweeter may be more likely to be associated to specific colours (e.g., the red colour of strawberries), and/or to softer, smoother textures. Such studies could present colour chips that separate colour into its components of hue, chroma, and lightness because there is some evidence in adults with olfactory synaesthesia that associations are more stable for chroma and lightness than for hue (van Campen & Froger, 2003). These studies could also explore whether opponent colours have a special status, as they do in colour grapheme synaesthesia (Nikolie, Lichti & Singer, 2007), by assessing whether adults are more consistent with each other when asked to make a forced choice between opponent colours rather than non-opponent options. Utilizing a similar forced-choice methodology could help to assess whether texture associates behave as dimensions of variation (smooth versus rough) or, as suggested by the verbal reports in this study, as unrelated attributes (e.g., an odour can be both smooth and rough). Developmental and cross-cultural studies would be useful for separating the learned and naturally-biased influences on sensory associations to odours. Specifically, testing infants and toddlers would be useful to more clearly distinguish colour and texture associations to odours likely to be familiar (e.g., milk, urine) from those likely to never have been encountered (e.g., not part of mom's diet or the child's environment). Such studies could utilize a forced choice methodology like that used successfully to measure pitch/lightness, sound/shape, colour/letter associations in toddlers (e.g., Mondloch & Maurer, 2004; Maurer, Pathman & Mondloch, 2006, Spector & Maurer, 2008). In addition, examining cross-cultural data on colour and texture associates for odours that are common in some but not all cultures or geographic areas (e.g., tamarind, garlic, roses) could help to discern the ways in which learning alters naturally biased associations. Testing for associations that are consistent across cultures and development would provide valuable insights into the organization of olfactory perception, and add to the understanding of the mechanisms underlying the interrelations among sensory modalities that are naturally biased versus based on learning.

In summary, we have shown that adults make non-random colour and texture associations to odours, which are consistent across individuals. Some of these associations can be easily explained by experience with the objects that are associated with the odours (e.g., lemon is yellow, smooth, dull), regardless of whether the odour is identified or not. However, the majority of the reported associations cannot be explained by learning, as they do not obviously match the physical properties (i.e., colour and texture) of the appropriate objects (e.g., lavender is green, sticky). These results complement previous research into cross-modal colour associations to odours through the addition of a measure of odour identification, and include the first evidence of texture associations to odours.

[1] Footnote: If restricted to females, the results are the same as those reported in the text including the 8 males.

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Table 1. List of odours used and the proportion of participants (n = 41) who correctly categorized or identified each odour.

Odour Category	Odour	Proportion Category Correct	Proportion ID correct
Food	Cinnamon	.41	.24
	Anise	.54	.49
	Onion	.51	.07
	Peppermint	.51	.59
	Lemon	.59	.44
	Almond	.22	.05
	Vanillin	.44	.05
	Ginger	.20	.05
Floral	Lavender	.22	.10
	Geranium	.22	.00
	Bergamot	.10	.00
	Violet	.02	.00
Environment	Cedar	.22	.12
	Musty	.12	.00
	Mushroom	.07	.00
	Eucalyptus	.05	.05
	Juniperberry	.27	.00
	Rosewood	.20	.00
Chemical/ Medicine	Napthene	.66	.32
	Anisole	.76	.00
	Menthol	.32	.00
	Camphene	.37	.00

Table 2. List of significant colour and texture associations for each odour as measured by a binomial probability statistic. Significant associations at the p < .01 level are listed separately from significant associations at the p < .05 level.

Odour	**Colour Associations (p<.01)**	**Additional Colour Associations (p<.05)**	**Texture Associations (p<.01)**	**Additional Texture Associations (p<.05)**
Cinnamon	red	brown	rough, hard	slippery
Peppermint	blue, white, green		smooth, wet, sticky, hard	sharp
Lemon	yellow, orange		smooth, dull, soft	sticky
Anise	black		rough, dull	directional
Napthene	white, gray		rough, dull, soft	small
Almond	red, purple, gray		dull	thick, directional
Onion		orange, brown	rough, sharp	dull, small
Vanillin	brown	white	smooth, soft, thick	liquid
Ginger		black, brown	rough, sharp, wet, thin	solid
Geranium		brown	smooth, rough, random	dull
Violet	red, pink	orange	smooth, soft, sticky	directional
Lavender		Green, clear	liquid, sticky, large	soft, thin
Bergamot	Yellow		smooth, sharp, dull, soft	
Rosewood		yellow	rough, soft, thick	
Cedar		Black, green	rough,thin	sharp, sticky, liquid, small
Mushroom	blue, yellow			Smooth, slippery
Musty	brown		liquid	hard, solid, thick
Eucalyptus	blue, green		sharp, liquid, wet, thick, cold	smooth
Juniperberry		yellow	rough, sharp, liquid	
Menthol		pink	rough, soft, hard	directional
Camphene		blue	rough, liquid, wet	thick
Anisole	black	clear	sharp, liquid	

Figure Captions

Figure 1. Overall frequency of each colour term. Bars represent the proportion of times each colour was chosen out of all colour responses in the data set.

Figure 2a-v. Graphs of all colour associations to each odour. Dotted grey lines indicate the chance level of responses for each colour. Asterisks indicate colour choices to the odor that were significantly higher than chance.

Figure 3. Overall frequency of each texture term. Bars represent the proportion of times each texture was chosen out of all texture responses in the data set.

Figure 4 a-v. Graphs of all texture associations to each odour. Dotted grey lines indicate the chance level of responses for each texture. Asterisks indicate texture choices to the odor that were significantly higher than chance.

Figure 1:

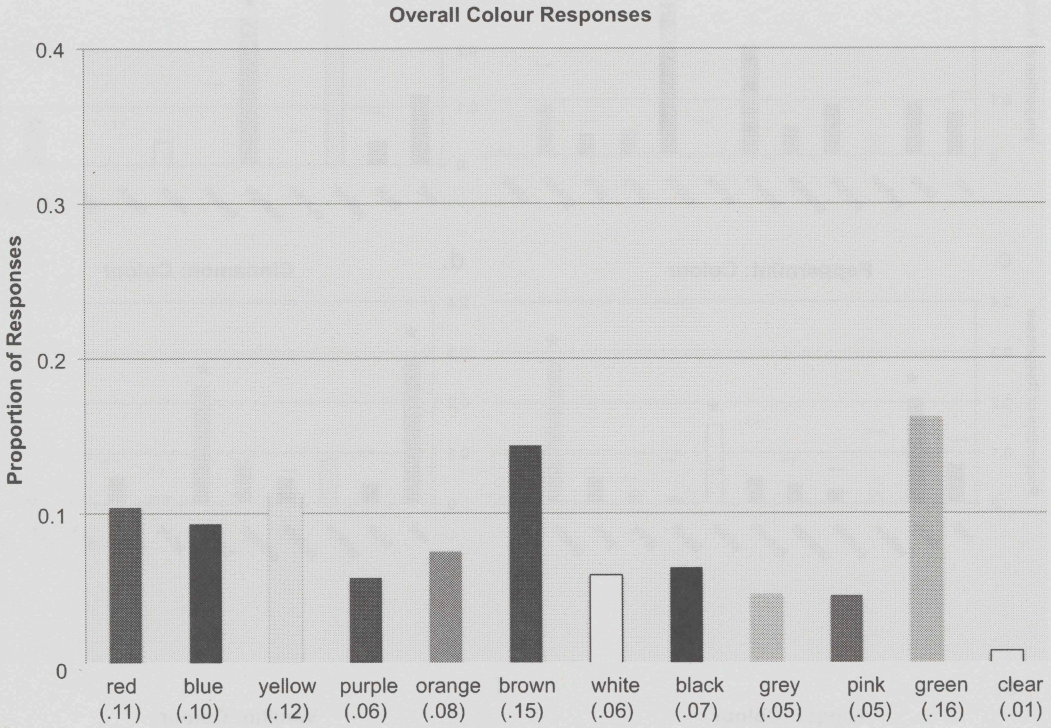
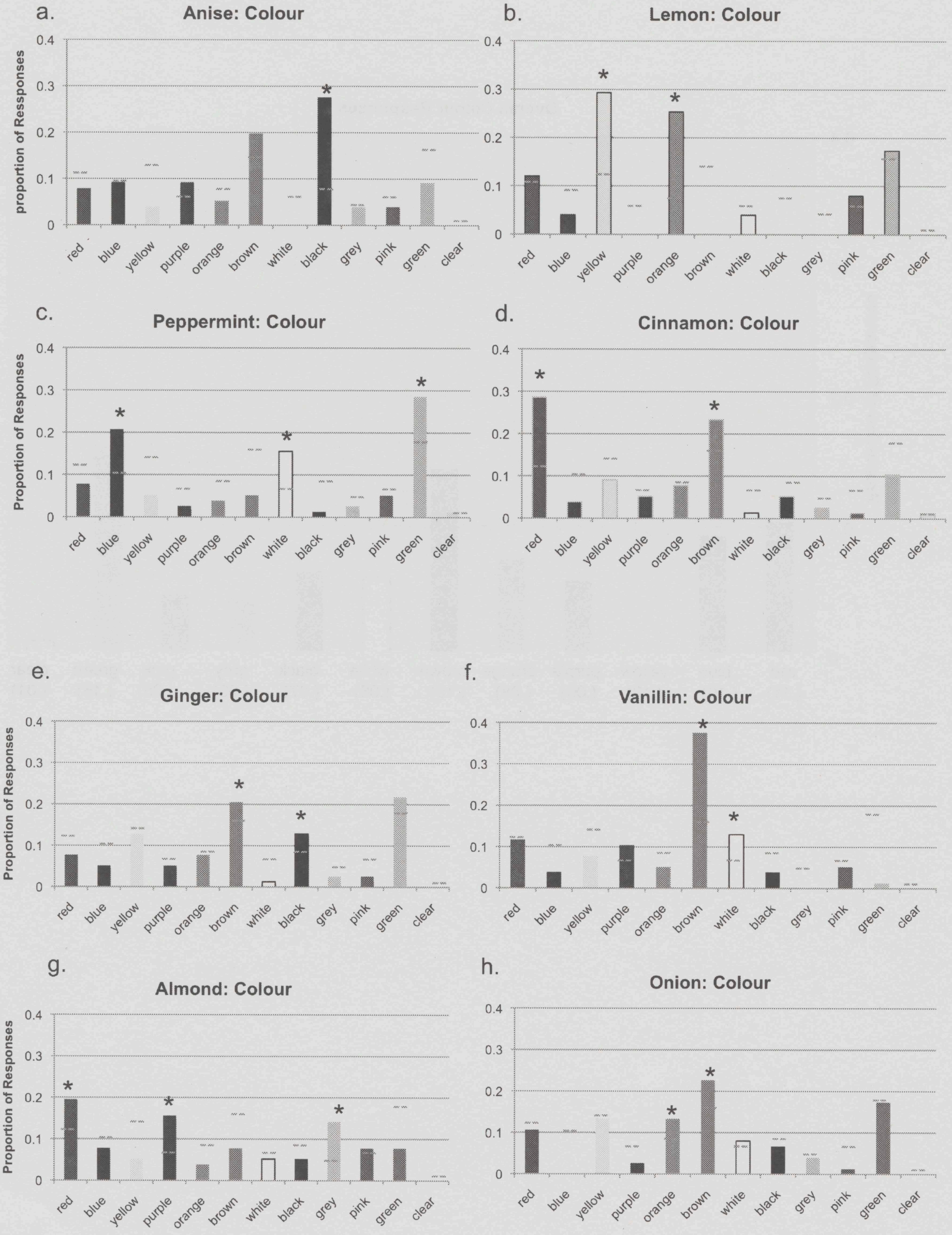
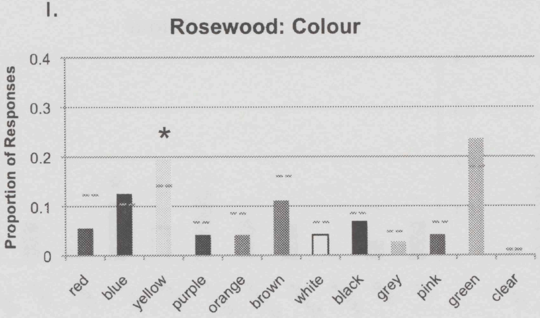

Overall Colour Responses
Proportion of Responses
0.4
0.3
0.2
0.1
0
red (.11)
blue (.10)
yellow (.12)
purple (.06)
orange (.08)
brown (.15)
white (.06)
black (.07)
grey (.05)
pink (.05)
green (.16)
clear (.01)

Figure 2:

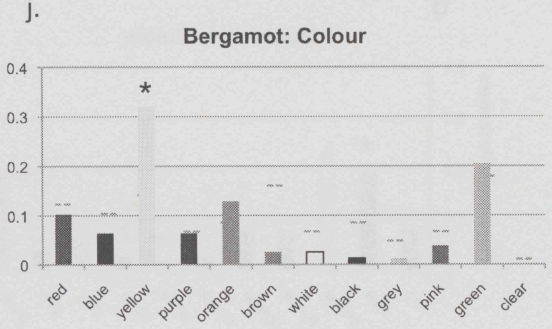

a.
Anise: Colour
proportion of Ressponses
0.4
0.3
0.2
0.1
0
red
blue
yellow
purple
orange
brown
white
black
grey
pink
green
clear
*
b.
Lemon: Colour
0.4
0.3
0.2
0.1
0
red
blue
yellow
purple
orange
brown
white
black
grey
pink
green
clear
*
*
c.
Peppermint: Colour
Proportion of Responses
0.4
0.3
0.2
0.1
0
red
blue
yellow
purple
orange
brown
white
black
grey
pink
green
clear
*
*
*
d.
Cinnamon: Colour
0.4
0.3
0.2
0.1
0
red
blue
yellow
purple
orange
brown
white
black
grey
pink
green
clear
*
*
e.
Ginger: Colour
Proportion of Responses
0.4
0.3
0.2
0.1
0
red
blue
yellow
purple
orange
brown
white
black
grey
pink
green
clear
*
*
f.
Vanillin: Colour
0.4
0.3
0.2
0.1
0
red
blue
yellow
purple
orange
brown
white
black
grey
pink
green
clear
*
*
g.
Almond: Colour
Proportion of Responses
0.4
0.3
0.2
0.1
0
red
blue
yellow
purple
orange
brown
white
black
grey
pink
green
clear
*
*
*
h.
Onion: Colour
0.4
0.3
0.2
0.1
0
red
blue
yellow
purple
orange
brown
white
black
grey
pink
green
clear
*
*

i.



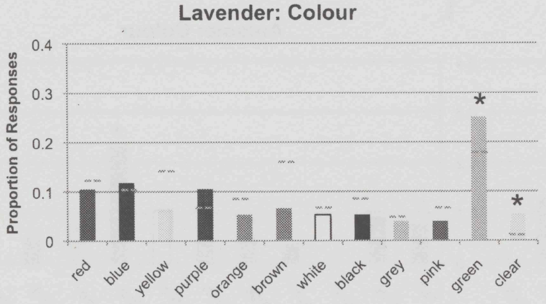
Rosewood: Colour

j.



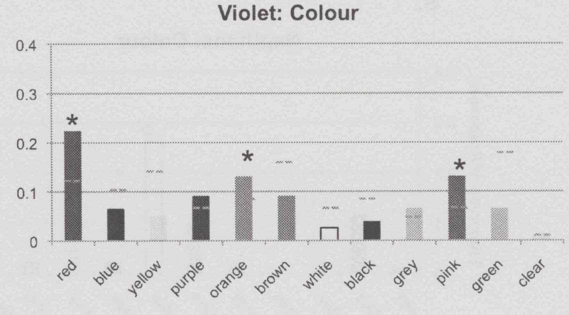
Bergamot: Colour

k.



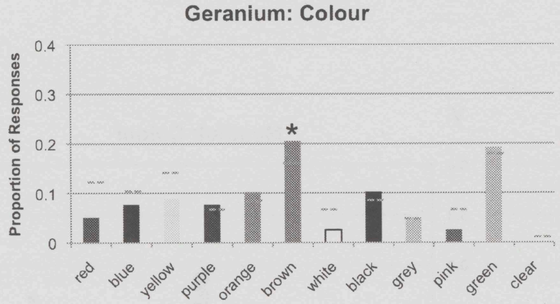
Lavender: Colour

l.



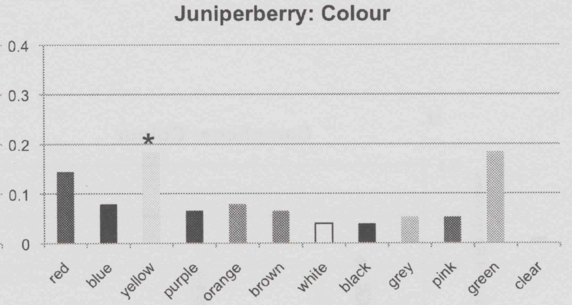
Violet: Colour

m.



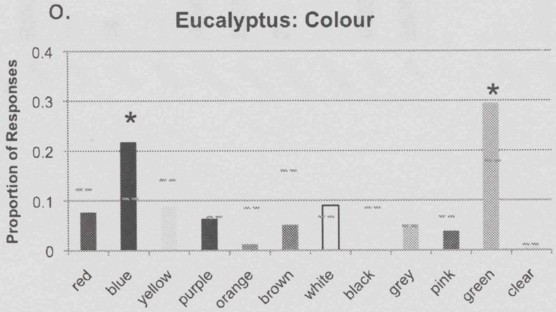
Geranium: Colour

n.



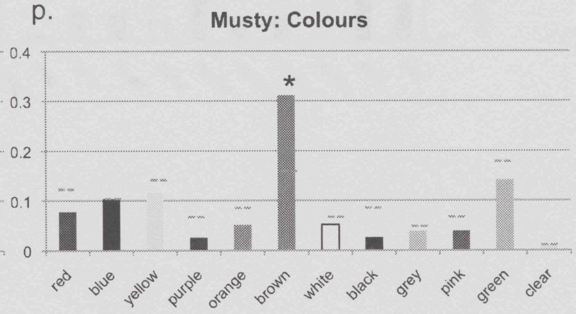
Juniperberry: Colour

o.



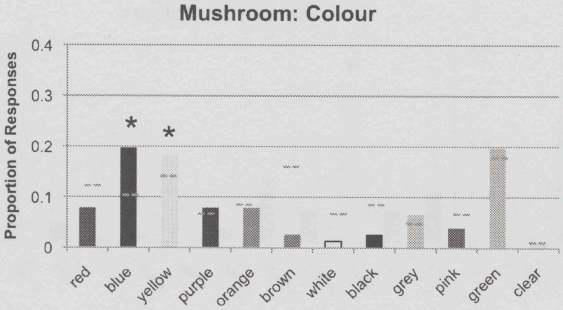
Eucalyptus: Colour

p.

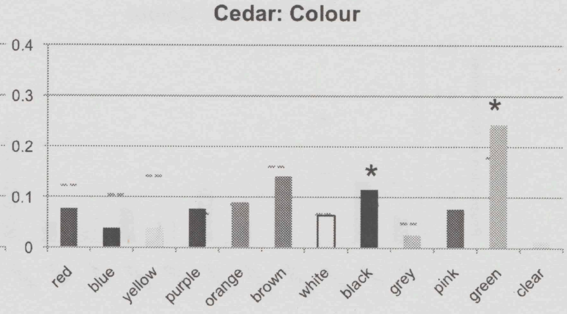


Musty: Colours

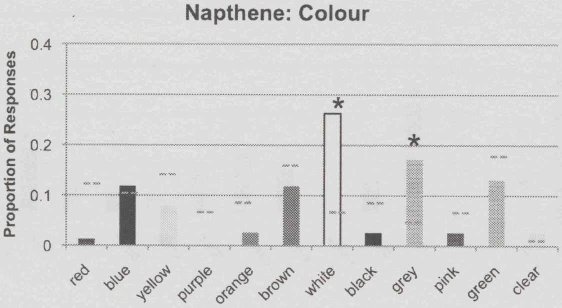
q.


Mushroom: Colour

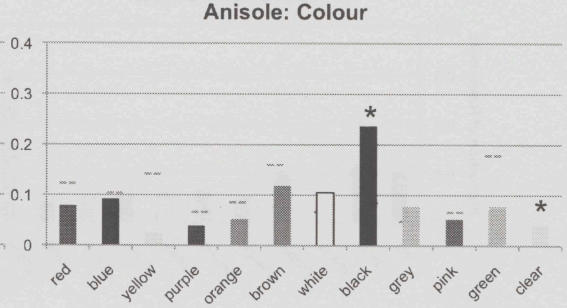
r.


Cedar: Colour

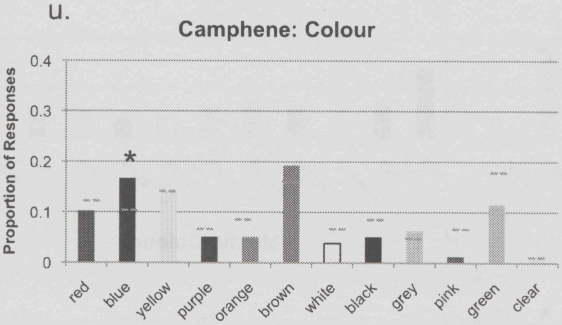
s.


Napthene: Colour

t.


Anisole: Colour

u.


Camphene: Colour

v.

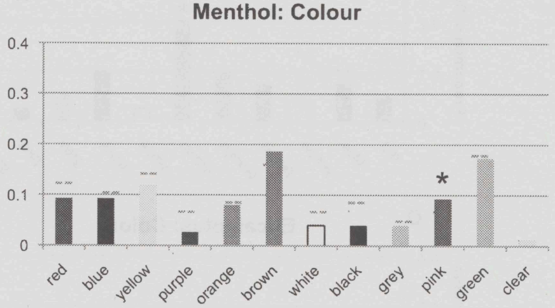

Menthol: Colour

Figure 3

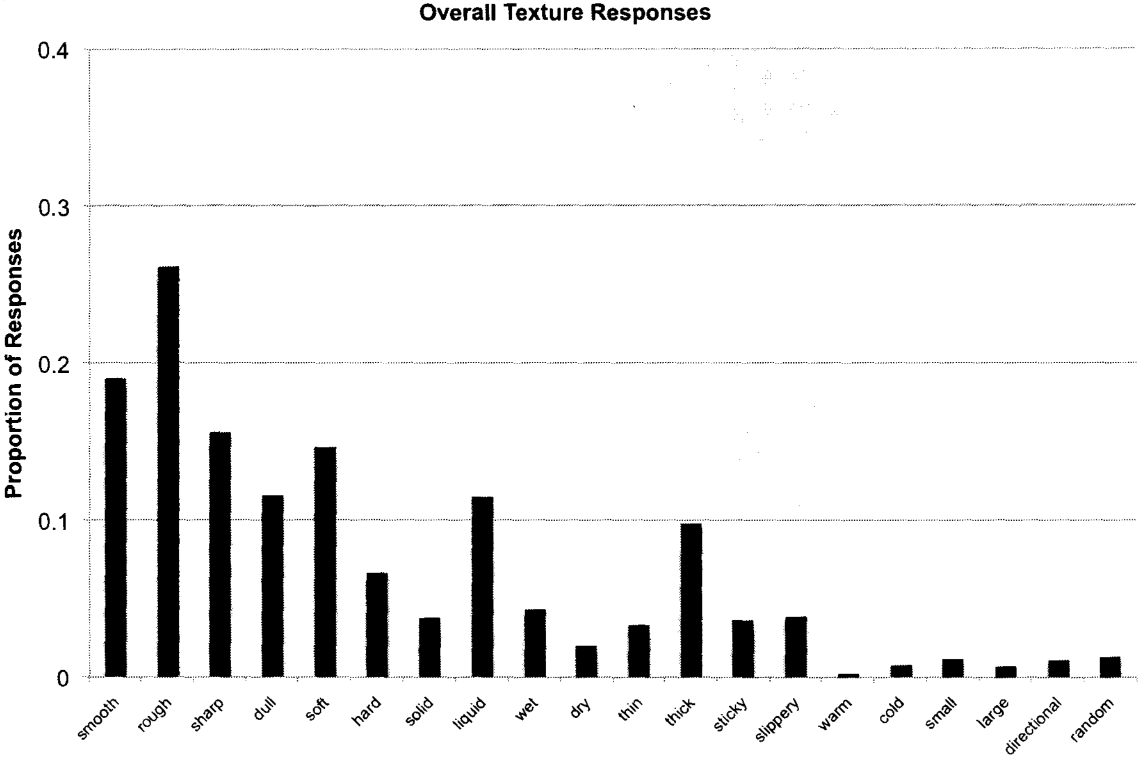
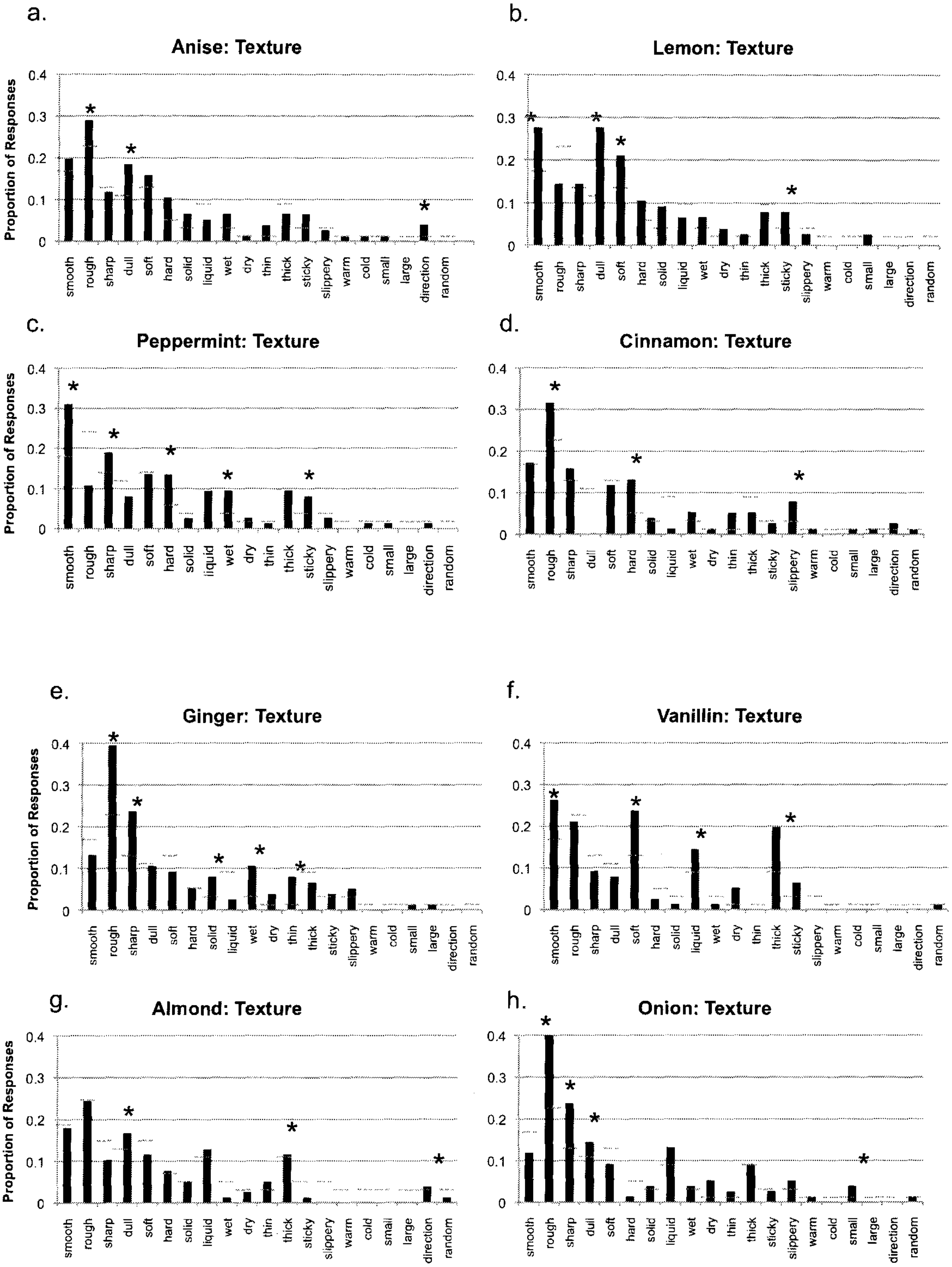
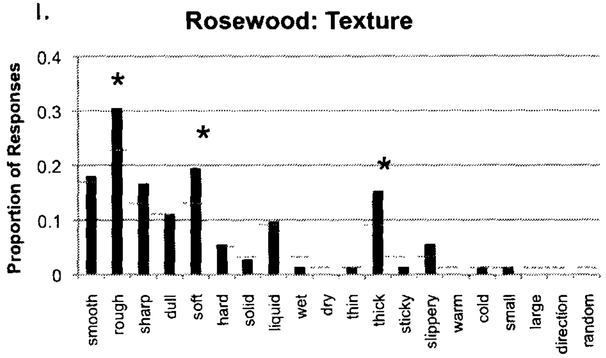

Overall Texture Responses
Proportion of Responses
0.4
0.3
0.2
0.1
0
smooth
rough
sharp
dull
soft
hard
solid
liquid
wet
dry
thin
thick
sticky
slippery
warm
cold
small
large
directional
random

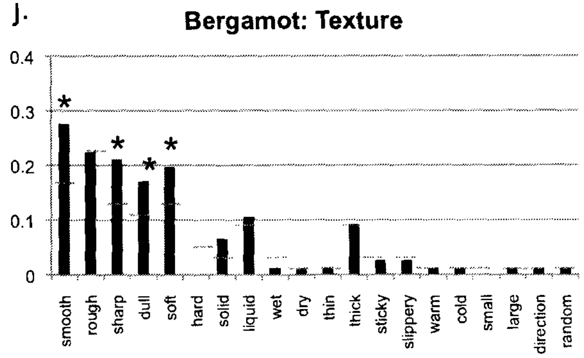
Figure 4 a-v:


a.
Anise: Texture
b.
Lemon: Texture
c.
Peppermint: Texture
d.
Cinnamon: Texture
e.
Ginger: Texture
f.
Vanillin: Texture
g.
Almond: Texture
h.
Onion: Texture
Proportion of Responses
0
0.1
0.2
0.3
0.4
*
smooth
rough
sharp
dull
soft
hard
solid
liquid
wet
dry
thin
thick
sticky
slippery
warm
cold
small
large
direction
random

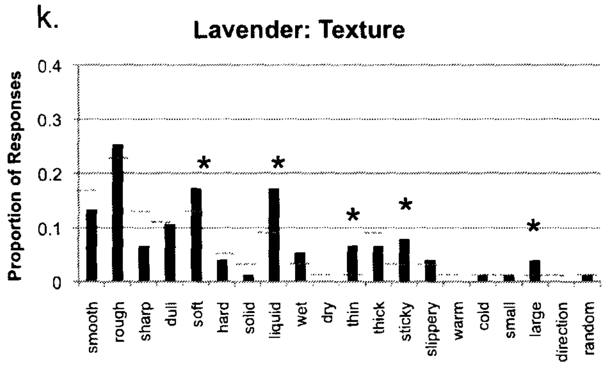
i.


Rosewood: Texture

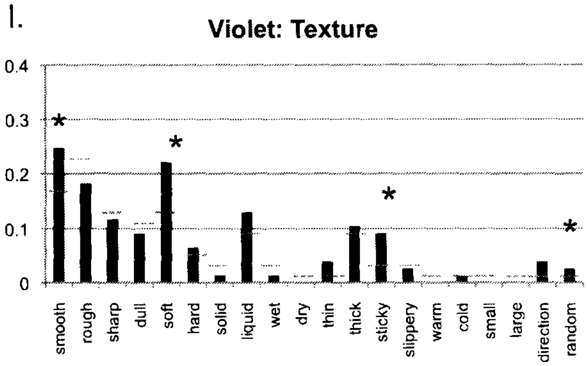
j.


Bergamot: Texture

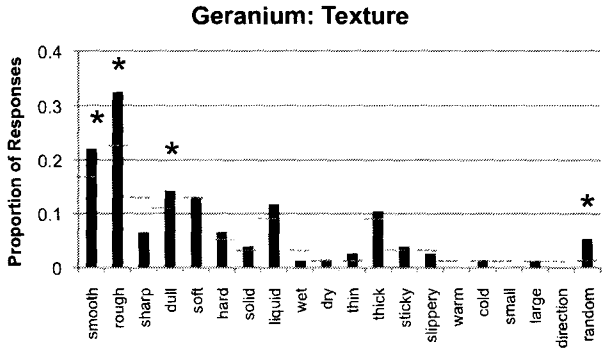
k.


Lavender: Texture

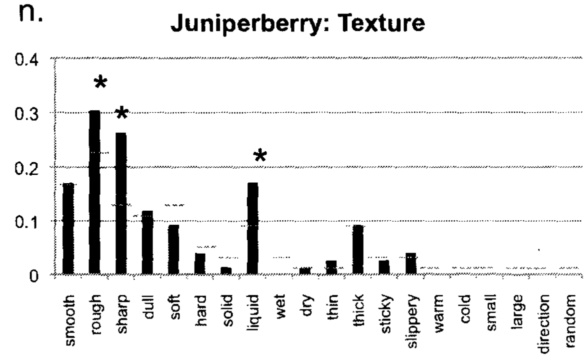
l.


Violet: Texture

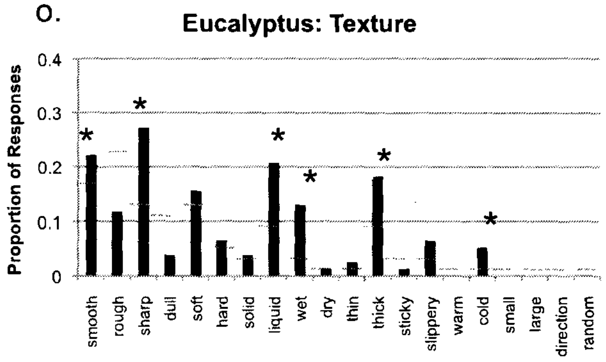
m.


Geranium: Texture

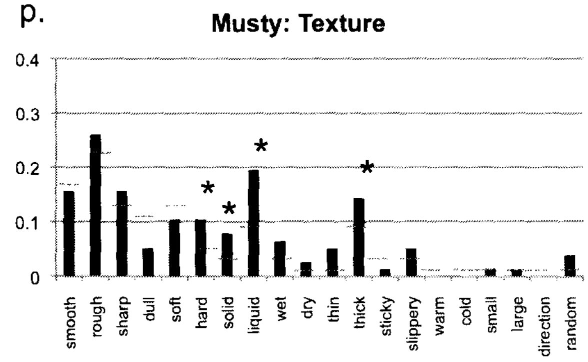
n.


Juniperberry: Texture

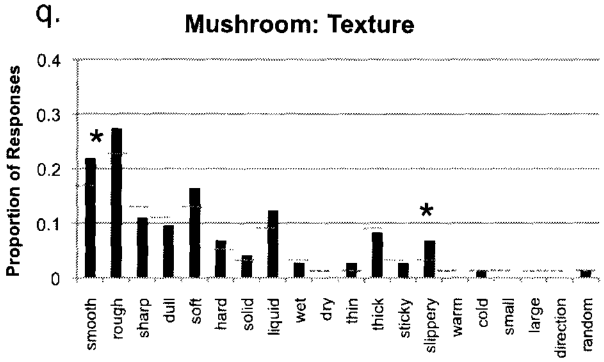
o.


Eucalyptus: Texture

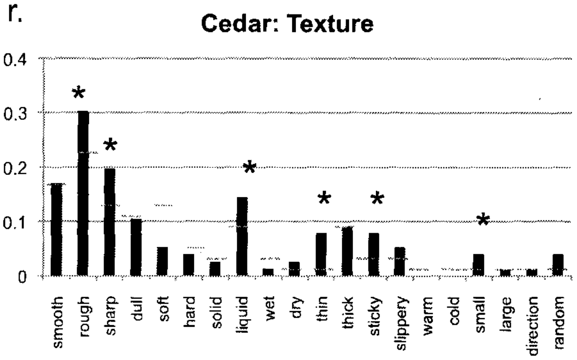
p.


Musty: Texture

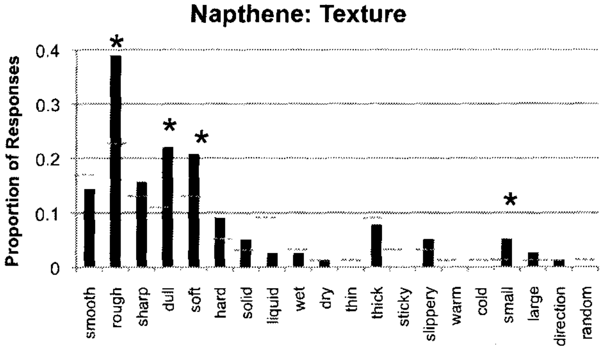
q.


Mushroom: Texture
Proportion of Responses
0.4
0.3
0.2
0.1
0
smooth
rough
sharp
dull
soft
hard
solid
liquid
wet
dry
thin
thick
sticky
slippery
warm
cold
small
large
direction
random

r.


Cedar: Texture
0.4
0.3
0.2
0.1
0
smooth
rough
sharp
dull
soft
hard
solid
liquid
wet
dry
thin
thick
sticky
slippery
warm
cold
small
large
direction
random

s.


Napthene: Texture
Proportion of Responses
0.4
0.3
0.2
0.1
0
smooth
rough
sharp
dull
soft
hard
solid
liquid
wet
dry
thin
thick
sticky
slippery
warm
cold
small
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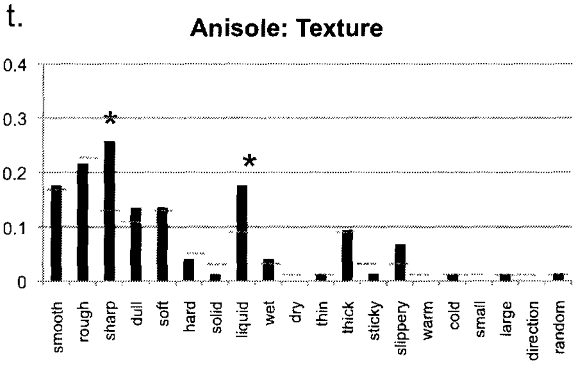
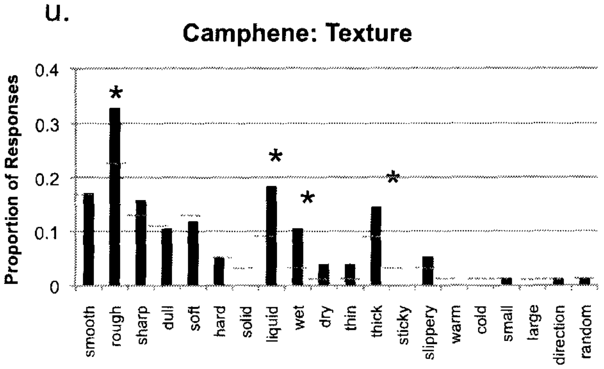
direction
random

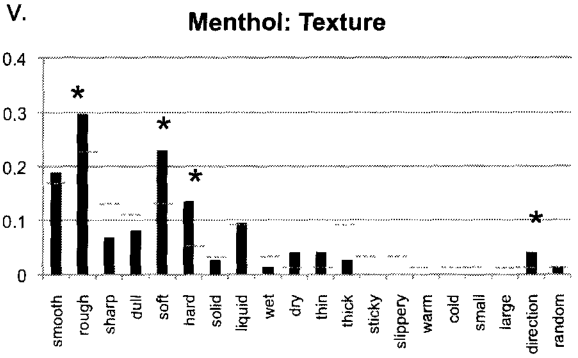
t.


Anisole: Texture
0.4
0.3
0.2
0.1
0
smooth
rough
sharp
dull
soft
hard
solid
liquid
wet
dry
thin
thick
sticky
slippery
warm
cold
small
large
direction
random

u.


Camphene: Texture
Proportion of Responses
0.4
0.3
0.2
0.1
0
smooth
rough
sharp
dull
soft
hard
solid
liquid
wet
dry
thin
thick
sticky
slippery
warm
cold
small
large
direction
random

v.


Menthol: Texture
0.4
0.3
0.2
0.1
0
smooth
rough
sharp
dull
soft
hard
solid
liquid
wet
dry
thin
thick
sticky
slippery
warm
cold
small
large
direction
random

Appendix A: Chemical composition, odour description, and retail source of each odour.

Substance	Description	Source
Cinnamon Oil	Cinnamon	Essential oil retail
Anise Oil	Anise	Essential oil retail
Onion Oil	Onion	Sigma Aldrich
Peppermint Oil	Peppermint	Sigma Aldrich
Lemon Oil	Lemon	Sigma Aldrich
2,4 Dimethylbenzaldehyde 90+%	Almond	Sigma Aldrich
Vanillin Isobutrate, 98+%	Vanilla	Sigma Aldrich
Ginger Oil	Ginger	Essential oil retail
Lavender Oil	Lavender	Essential oil retail
Geranium Oil	Geranium	Essential oil retail
Bergamot Oil	Bergamot	Sigma Aldrich
Alpha-Ionone, 90+%	Violet	Sigma Aldrich
Cedar Oil	Cedar	Essential oil retail
1-Octen-3-YL Butyrate, 97+%	Musty	Sigma Aldrich
1-Decen-3-OL, 98+%	Mushroom	Sigma Aldrich
Eucalyptus Oil, 70/75%	Eucalyptus	Sigma Aldrich
Juniperberry Oil	Juniperberry	Sigma Aldrich
Rosewood Oil	Rosewood	Essential oil retail
Napthene Crystals	Moth balls	Chemistry lab
Anisole, 99+%	Chemical, gasoline	Sigma Aldrich
L-Menthyl Lactate, 97+%	Menthol	Sigma Aldrich
-Camphene,80+%	Camphor	Sigma Aldrich

Chapter 6: Discussion

The research presented in this thesis examined three types of sensory association, all of which appear to reflect, in part, naturally biased associations between sensory stimuli that are not systematically related in the environment but which can be modified and/or replaced by learning.

Overall Results

In the research presented in chapters 2 and 3, I examined whether letter to colour associations found in synaesthetic and non-synaesthetic adults (Marks, 1975; Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005) are also seen in preliterate children. From the letters that produce consistent colour percepts among synaesthetic adults and consistent associations in non-synaesthetic adults, I tested four letter pairs (A/G, O/X, B/Y, I/Z), which are mapped to opposing colours (red/green, white/black, blue/yellow, white/black, respectively) (Marks, 1975; Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005). This included two pairs with potentially language-based colour associations (A for red, G for green, B for blue, Y for yellow), and two pairs without an obvious language basis for the colour mappings (O and I for white, X and Z for black). I used a novel way to test for colour/letter associations in pre-literate children, in which children are asked to find a letter in a box with two slots, each painted one of the colour choices. Preliterate toddlers, older children, and adults all consistently mapped the letters O and I to white, and X and Z to black: they searched for O and I on the white side of the box, and X and Z on the black side of the box. The early mapping suggests that these associations are not based on lexical associations that are understood only after learning to read. Instead they may be naturally-biased. Older children and adults consistently mapped A to red, G to green, B to blue and Y to yellow, whereas pre-literate children did not show consistent colour-letter associations to these letters. These mappings seem to reflect language-based colour associations that develop after a child learns to read (i.e., after the child realizes, for example, that G is the first letter of green). These developmental patterns of colour-letter associations were seen consistently through variations in methodology including replication with a blind observer and presentation of non-opponent colour pairs. These chapters are the first report of consistent colour letter associations in pre-literate, non-synaesthetic children.

The consistent mapping of black and white to these letters (X, Z, O, I) in toddlers appears to be based upon the shape of the letter, and not its sound, a pattern suggesting a natural bias between some colours and shape. I demonstrated this by modifying the methodology so that some toddlers searched in the box for a spoken letter (e.g., "...an Ay") and others searched for a presented shape (e.g., "...it looks like this"). The patterns replicated with the shape alone but not with the sound alone. A subsequent experiment indicated that the mapping is based, at least in part, on shape continuity: just as O and I, which have smooth contours that do not change direction rapidly, are mapped to white, so is an abstract continuously varying shape; just as X and Z, which are more complex shapes with angular contours, which change direction abruptly, are mapped to black, so is an abstract angular shape. These patterns linking continuously varying contours to white and angular contours to black were evident in toddlers, older children and adults.

Finally, I examined whether any natural biases between shape and colour extend to chromatic colours, since consistent mapping in toddlers in Chapter 2 and the first four experiments of Chapter 3 were only to achromatic colours. I found that toddlers, older children and adults consistently map C to yellow, a pattern suggesting that natural biases between shape and colour are not limited to achromatic colours. Overall, the research presented in Chapters 2 and 3 suggests that some colour letter associations in adults result from naturally-biased influences that are present before children learn to read while others develop as letters take on meaning.

In Chapter 4, I examined how the characteristics of a sound can influence the shape to which it is matched, using a previously reported phenomenon in which adults and pre-literate toddlers match a word with rounded vowels (e.g., maluma) to a rounded shape and a word with non-rounded vowels (e.g., kiki) to a jagged shape (Kohler, 1929; Lindauer, 1990; Marks, 1996; Ramachandran & Hubbard, 2001; Maurer, Pathman & Mondloch, 2006). Previous studies suggest that the effect is based on the roundness of the vowel (Maurer, Pathman & Mondloch, 2004; Ramachandran & Hubbard, 2001), though there is evidence that the consonant grapheme has some implicit effect in adults (Westbury, 2005). I extended previous findings by conducting the first study to examine the influence of the spoken consonant on shape matching in children or adults, and the first study to systematically control for the influence of consonant and vowel variation by presenting only repeating syllables. Specifically, I examined whether toddlers associate approximant consonants (i.e., *w*, *l*, *r* and *y*) or rounded vowels (i.e., *o*) to rounded shapes and stop consonants (i.e., *g*, *d*, *k* and *b*) or non-rounded vowels (i.e., *i*) to jagged shapes. I played a game with two groups of English-speaking toddlers in which we contrasted four pairings of nonsense words differing only in consonant type or only in vowel roundness and asked the child to choose which of two unfamiliar shapes, one round and one angular, the nonsense words corresponded to. There was no effect of the consonant sound on toddlers' shape choices. However, toddlers did match words with rounded vowels to rounded shapes and words with non-rounded vowels to jagged shapes, even with better controlled stimuli than those used in previous studies. These findings are the first to suggest that the consonant has no influence on mapping of sound to shape in toddlers. Thus, the crucial characteristic of a nonsense word that determines its mapping to shape in toddlers seems to be the vowel roundedness.

In the research presented in Chapter 5, I examined cross-modal associations to odours, specifically examining whether there are any consistent colour and texture associations to odours in adults. Previous studies using a smaller set of odours documented systematic associations between odour and colour (Gilbert, Martin & Kemp, 1996) as well as between odour intensity and colour lightness (Kemp & Gilbert, 1997), but did not test for texture associations or measure familiarity with the odour. This is the first study to examine texture associations to odour in an overt association paradigm and to include a measure of identification to examine the effect of odour familiarity on colour and texture associations. Non-synaesthetic adults smelled 22 odours and reported any colour and/or texture association to each. Adults readily made colour and texture associations to the odours, even for odours that were not recognized. Some of the associations were consistent across individuals. Some of these associations can be easily explained by experience with the associated object and its odour (e.g., lemon is yellow, smooth, dull), regardless of whether the odour was identified or not in this experimental setting. However, the majority of the reported associations cannot be as readily explained by learning, as they do not match the colour or texture of the corresponding object (e.g., lavender is green, sticky). Thus, cross-modal associations to odours may be subject to the same interplay of learning and natural biases as other cross-modal associations investigated in this thesis.

Theoretical Implications & Contribution to the Literature

The research reported in this thesis involves a new approach to understanding perceptual development that is inspired by the findings on synaesthesia in adults. It is based on evidence that adult synaesthesia is the result of a developmental process in which exuberant connections among cortical areas that are present in early childhood are only partially pruned and/or inhibited (e.g., Maurer & Mondloch, 2005). By implication, those connections commonly seen in synaesthetic adults, should influence the perception of young children and, to a lesser extent, the sensory associations of non-synaesthetic adults. In each of three domains, the research began from evidence in the literature of cross-modal or cross-dimensional associations that are not readily explained by learning. Testing for those associations in non-synaesthetic adults (Chapters 2, 3, and 5) and young children (Chapters 2, 3, and 4) yielded new insights about the interplay of natural biases and learning in the formation of sensory associations.

Our findings in Chapters 2 and 3 that some associations between shape and colour exist in pre-literate toddlers, while others associations exist only in older children and adults, were the first to indicate that there are natural biases to associate certain shapes to specific colours, and that literacy associations may induce additional colour-letter associations. This pattern suggests that cross-and intra-modal sensory associations in adulthood result from the joint influence of naturally occurring cortical organization and of the experience with specific associations. Thus, sensory cortical organization may initially bind colour to shape in a systematic manner to yield associations which later change with the development of literacy. Our subsequent findings that the consistent associations in toddlers are based upon the shape of the letter and not its sound suggest that colour-letter associations in non-synaesthetes may be based initially on interactions between the colour and form pathways within the extrastriate visual pathway. This interaction could occur within or among V4 cells that respond to both colour and form (Desimone, Schein, Moran, & Ungerleider, 1985) or it could be mediated by the posterior parietal cortex, given its documented role in the binding of colour to shape in adults (Donner et al., 2002). Learning to read may shift the processing of colour-letter associations away from the perceptual level, which would be based in shape, towards the cognitive level, which is based in understanding the meaning of letters. Our results indicate that the early associations persevere into adulthood when they do not conflict with later learned associations.

This line of research can be understood in light of the mechanisms underlying colour- grapheme synaesthesia. Consistent with our finding that colour-letter associations in toddlers are based upon the shape of the letter, previous evidence suggests that colour-grapheme synaesthesia is mediated by connections to and within areas of the visual cortex that respond to colour and form. In synaesthetes for whom black letters evoke coloured percepts (i.e, who have coloured-grapheme synaesthesia), viewing black-and-white letters during functional magnetic resonance imaging (fMRI) reveals activation in visual cortical area V4/V8, where neurons respond to specific basic shapes and to specific colour, with some reports of additional activation in lower visual areas, including primary visual cortex V1, and in a number of higher cortical areas, including the intraparietal cortex (Hubbard et al., 2005; Rouw & Scholte, 2007; Sperling, Prvulovic, Linden, Singer, & Stirn, 2006; but see Rich et al., 2006; Weiss, Zilles, & Fink, 2005). Consistent with the idea of cross-activation among these area is evidence that adults with colour-grapheme synaesthesia show greater connectivity than do controls in three brain regions, including the word form area in the inferior temporal cortex that lies contiguous to V4/V8, with the strength of hyperconnectivity correlated with the strength of degree of projection of the synaesthetic colours onto the inducing black letters (Rouw & Scholte, 2007). In synaesthesia, those connections are thought to reflect a failure of pruning during development and/or a failure of normal inhibitory feedback (e.g., Grossenbacher & Lovelace, 2001; Ramachandran & Hubbard, 2001). Thus, some such connections are expected to remain in the nonsynaesthetic adult, but the number is insufficient to influence conscious perception. Consistent with this expectation is our finding of colour-letter shape associations that match some synaesthetic percepts and that cannot be explained by lexical associations. The results provide further support for the oft-proposed idea that synaesthesia results from an amplification of sensory mechanisms that are common to everyone, or a "supernormal integration" (e.g., Esterman et al., 2006; Mulvenna & Walsh, 2006; Simner et al., 2005; Ward, Huckstep, & Tsakanikos, 2006).

The research reported in Chapter 4 confirms, with better controlled stimuli, that toddlers associate nonsense words with rounded vowels to rounded shapes, and those with non-rounded vowels to jagged shapes, and for the first time indicates that consonant contrasts have no apparent effect. Toddlers' consistent associations of rounded vowels to rounded shapes and non-rounded vowels to jagged shapes may influence the ease with which they learn vocabulary: rounded objects labeled with nouns with rounded vowels may be easier for them to learn than object/word mappings that violate this association. The association may have come about through experience, as English-speaking toddlers have had enough experience with words and the objects that they represent to pick up statistical regularities in English semantics. It is possible that English words that have non-rounded vowels tend to represent objects that are sharp and that English words that have rounded vowels tend to represent objects with curved contours. However, it is also possible that this effect represents a naturally-biased association between shape and the sound of the phoneme, between shape and the sight of the shape of the mouth when producing the sound, and/or between shape and the feeling (degree of lip rounding) needed to produce the same sound oneself, and that these natural associations influenced the evolution of languages (Ramachandran & Hubbard, 2001). Within this framework, words used to represent rounder objects would tend to have vowels that round the mouth, taking advantage of natural biases (e.g., needle, spike, round, ball). By the time a child is 2 ½ years old, the combination of the natural bias and sensitivity to statistical regularities in the words already learned, would jointly influence the continued acquisition of vocabulary.

The research reported in Chapter 5 for the first time documented that adults make colour and texture associations even to odours they do not recognize. The pattern of associations resembles the pattern reported for colour associations to letters in which some associations are readily explained by learning (G/green) but others do not have a ready learning explanation (X/black). In the results reported here, some odour associations can easily be explained by learning because the significant associations are to the expected colours and textures (e.g., lemon to yellow and smooth, dull). However, others do not have an easy learning explanation; for example, based on learning, we would expect lavender to be associated to purple, or blue, but it was most consistently associated to green, and to a smaller degree, clear. The results suggest that sensory associations to odours, like those between letters and colours, may result from the joint influence of learning and natural biases linking dimensions across sensory systems. Such links may reflect an inherent neural organization that is modifiable with learning and that can be manifest as cross-modal associations in non-synaesthetic adults and conscious perceptions in adults with olfactory or gustatory synaesthesia.

The balance between natural biases and influence of learning seems to change during development such that natural biases have more of an effect at an earlier stage of development whereas what we learn can add new associations at a later period and perhaps override the influence of natural biases. This is the pattern seen for colour/letter associations. Associations that cannot be easily explained by learning were present in very young children and remained in adults (e.g., I, O → white, X, Z → black; smooth contours → white, angular contours → black; C → yellow). Likewise there is not an easy learning explanation for the findings that toddlers associate rounded vowel to amoeboid shapes and non-rounded vowel to jagged shapes, and that adults associate, for example, the smell of onion oil to rough and sharp textures, or lavender to liquid and sticky textures, as well as the colours green and clear.

Other sensory associations can easily be explained by learning and likely arise postnatally as the child learns environmental associations that are common, such as the first letter of colour names (e.g., G for green) and the texture and colour of objects with familiar odours (e.g., lemons are yellow and smooth and dull). These additional associations may override an initial natural bias and/or cause a novel association to form between two previously unconnected attributes. Some of these associations become apparent only after the child has learned to read (e.g., G → green, A → red, B → blue, Y → yellow). Thus, G may be naturally associated to no colour or to a colour other than green and the smell of cinnamon may be naturally associated to no colour or a colour other than red, but learning from the environmental associations reinforces new or different associations so strongly that they override any previous natural biases. However, if no such learning occurs for a particular stimulus, then the naturally biased association may remain into adulthood (e.g., X, Z → black).

While the neural basis of these natural associations is beyond the scope of this thesis, there are clues in the literature on synaesthesia and on neural development. Natural biases in sensory associations may reflect initial sensory cortical organization. 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. However, sensory cortical areas are initially not as specialized as they will become. Support for this claim comes from evidence for transient connections among sensory cortical areas that are pruned during childhood in an experience-dependent manner. In fact, one explanation of the development of synaesthesia is that it arises from the preservation of some of these connections (e.g., Ramachandran & Hubbard, 2001). In the kitten, there are transient connections among the visual, auditory, tactile, and motor cortices (Dehay, Bullier & Kennedy, 1984; Dehay, Kennedy & Bullier, 1988), and, although such ubiquitious overwiring does not appear to occur in the infant monkey brain, there are transient connections from auditory cortex to visual area V4 (Kennedy, Batardiere, Dehay & Barone, 1997), the colour area that is active when adult synaesthetes with coloured hearing listen to an inducing sound. There is indirect evidence that the same phenomenon—a superabundance of connections among sensory cortical areas followed by experience-dependent pruning—occurs in humans, and that the extra connections are functional during early childhood. 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, Matsumiya, Abrohms, van Velzer & Lombroso, 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 years (Neville, 1995). Converging evidence comes from a blood flow study (using positron emission tomography; PET) examining 2-month-olds watching 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 specialized exclusively for language (Tzourio-Mazoyer, de Schonen, Crivello, Reutter, Aujard, Mazoyer, 2002; see also Huttenlocher, de Courten, Garey & Van der Loos, 1982; Huttenlocher, 1984; Huttenlocher, 1994; Huttenlocher & de Courten, 1987; Huttenlocher & Dabhokar, 1997). These findings, combined with the animal data, support the existence of functional connections among sensory cortical areas during early childhood that are later pruned.

Sensory associations in adults may be influenced by connections among sensory cortices that are not all eliminated by pruning. Evidence for such direct connections has emerged in recent animal studies: sensory cortical areas that were thought traditionally to be unimodal have been found to receive input from other sensory areas. For example, in the adult marmoset, the primary auditory cortex receives inputs from a number of visual cortical areas and from the somatosensory cortex, and in the monkey, the response of neurons in the primary auditory cortex is modulated by simultaneous visual input (reviewed in Bulkin & Groh, 2006). Also in monkeys, neurons in the primary visual cortex with receptive fields in the periphery receive input from the primary auditory cortex (Falchier, Clavagnier, Barone, & Kennedy, 2002; see also Cappe & Barone, 2005; Rockland & Ojima, 2003).

In adulthood, the unpruned connections among primary sensory cortical areas are thought to be functionally inhibited, perhaps by re-entrant feedback reinforcing firing in response to input from the "correct" modality. Indirect evidence for the preservation of connections among sensory areas the excitation of which is inhibited during typical perception comes from studies of the visual cortex of typical sighted adults after a period of visual deprivation (blindfolding)

(Pascual-Leone & Hamilton, 2001). Over the course of 5 days of blindfolding, sighted individuals were taught to discriminate tactile patterns. From day 2 onward, the visual cortex was increasingly active during these tactile tasks and the somatosensory cortex was increasingly less active (Pascual-Leone & Hamilton, 2001). The role of the visual cortex was investigated by repetitive transcranial Magnetic Stimulation (rTMS), a procedure which involves the temporary modification of neuronal firing in targeted brain areas by the induction of magnetic fields which induce electrical currents. When TMS was applied over the visual cortex in these blindfolded individuals, it disrupted their tactile discrimination. A similar pattern of activation over the visual cortex occurred when the blindfolded adults discriminated between auditory tones, a task unlikely to be mediated by visual imagery. A half-day after the blindfold was removed—after normal visual input was restored, auditory and tactile stimulation no longer caused activation of the visual cortex and rTMS over the visual cortex no longer interfered with tactile discrimination, even if the blindfold was temporarily restored. These results suggest that cross-modal connections from the auditory and somatosensory areas to the visual cortex exist in the typical adult but that they are not normally active, likely because the stronger visual signals are reinforced by reentrant feedback, which may also inhibit responses to input from other senses (Merabet et al., 2008). In a more recent study, adults were blindfolded only briefly while they performed tactile discriminations in an fMRI scanner (Merabet et al., 2007). The tactile stimuli produced significant activation in the primary visual cortex and significant deactivation in higher levels of the visual pathway—as would be expected if the activation of the primary visual cortex by touch is evident only if higher level visual responses are suppressed.

Alterations in inhibitory feedback have also been used to explain the development of synaesthesia (Grossenbacher & Lovelace, 2001). In the typical adult, the feedback strengthens firing of neurons consistent with the expected stimulus (e.g., neurons tuned to horizontal and vertical orientations when a square is expected or begins to be perceived) and inhibits inconsistent firing (e.g., neurons tuned to diagonal orientations or responding to input from an unexpected modality such as audition) (e.g., Campbell & Kilikowski, 1966; Harth, Unnikrshnan & Pandya, 1987). Synaesthesia may arise when the re-entrant feedback that develops post-natally from higher cortical areas onto lower sensory cortical areas is not strong enough to inhibit effects from connections among primary sensory cortical areas (Grossenbacher & Lovelace, 2001). When the normal amount of inhibitory feedback does not occur, the connections that remain among primary sensory cortical areas allow neurons to be activated by unexpected input from the "wrong" sense. This can occur in typical adults when the normal input is removed (e.g., by blindfolding), allowing the few connections that were not pruned to be active, and in synaesthetic adults in which more connections remain and are less likely to be inhibited effectively.

The evidence for pruning and inhibitory feedback indicates that development involves the proliferation of connections among sensory cortical areas and then the specialization of each sensory cortex for a particular sensory modality. The specialization is driven by experience, which both influences which connections are pruned, and shapes the strength of re-entrant feedback. For example, experience teaches speakers of English that there is an association between the letter G and the colour green. If there was an initial connection between the shape of the letter G and another colour, experience with the spelling of the word green would lead to its pruning while the learned association between G and the colour green would enhance feedback in response to G from the word form area to the colour areas of the visual cortex. Some of the extra, unlearned connections appear to persist into adulthood, as conscious percepts in synaesthetes and as influences on perception in the typical adult. For example, although experience teaches English speakers an association between the letter O and orange, the unlearned association of O to white nevertheless persists even in non-synaesthetic adults. These mechanisms of pruning and inhibitory feedback carry the implication that cross-modal influences will be even stronger during early childhood, before pruning of many of the excess connections among sensory cortices and before the relatively late development of inhibitory reentrant feedback that inhibits responses to (unpruned) crossmodal input from the "wrong" sensory modality. (Sowell, Thompson, Holmes, Jernigan & Toga, 1999). They also imply that synaesthesia is an exaggeration of processes common to us all (e.g., Marks, 1975, 1982; Mulvenna & Walsh, 2006; Ramachandran & Hubbard, 2001; Sagiv & Ward, 2006; Ward et al., 2006). The developmental processes of experience-dependent pruning and re-entrant feedback (which is also modified by pruning) have clear adaptive value and an unexpected side-effect when they are not complete: cross-modal and cross-dimensional correspondences that are not readily explained by learning such as the associations we found between shape and colour, shape and sound, and odour and colour/texture.

The evidence presented in this thesis of cross-modal and cross-dimensional correspondences across seemingly unrelated stimuli add to the growing evidence that characteristics of a stimulus can reliably influence its sensory associations. Consistencies among synaesthetic and non-synaesthetic adults suggest that these associations may arise from the intrinsic wiring of the nervous system and hence influence the perception of young children. Thus, connections within the fusiform gyrus between colour and shape areas may lead to consistent associations between shape and colour, and connections between auditory and/or motor areas and visual areas may lead to associations between a jagged shape and a non-rounded vowel. In presenting this argument, we do not imply that adults' cross-modal perception arises only from the effects of pruning and inhibition on intrinsic connections among sensory cortical areas. Learning clearly also plays a role as the child learns how to spell the word blue, the shape of a mouth when it makes certain sounds, and the association between the smell and sight of cinnamon. However, the influences we describe here may also constrain that learning, facilitating the learning of some associations and interfering with the learning of others. Thus, a child would have an easy time learning the word for a pointed object if it contains a non-rounded vowel, which forms the mouth into a shape similar to the object. It would be more difficult if the word contained a rounded vowel, which forms the mouth into a shape unrelated to the shape of the object. In other words, consistent sensory associations across development may be the by-product of intrinsic sensory cortical organization, which facilitates the learning of certain common cross-sensory correspondences in the environment and thereby helps a developing child make sense of the world. Other cross-sensory correspondences can also be learned but perhaps with not as much ease.

Natural biases discovered in the research in this thesis fit with other examples that have emerged in the recent literature of cross-sensory associations that do not appear to be learned from the environment. For example, toddlers, as well as synaesthetic and non-synaesthetic adults, match higher pitch to colour lightness (Marks, 1996; Mondloch & Maurer, 2004; Ward, Huckstep & Tsakanikos, 2006), even though lighter coloured objects do not always make higher pitched sounds (e.g., a brown mouse squeaks at the same frequency as does a white mouse). Likewise, even some multisensory correspondences that seem to be based in learning from the environment generalize to contexts unrelated to learning. For example, the finding that adding an appropriate colour to an odoured solution (e.g., adding red to strawberry) increases adults' perception of the intensity and pleasantness of the odour (Zellner & Kautz, 1990), even when the colour and odour/flavour are mismatched: red lemon smells stronger than pink lemon, which in turn smells stronger than colourless lemon (Zellner & Kautz, 1990). As in these examples and the present research, specific experience may not explain all sensory associations. Rather, there appear to be consistent ways in which sensory information translates across modalities throughout development and which influence what we learn from the environment. Synaesthetes may have conscious access to some of this translation process, the origins of which lie in the initial organization of the sensory neural system. Investigations such as those contained in this thesis demonstrate the utility in studying synaesthesia as far more than an isolated, quirky phenomenon, but rather as a window into the very nature of sensory processing and development.

Limitations

In the research program summarized in this thesis, toddlers provided much of the data from which I concluded that there are naturally biased sensory associations. These results can be difficult to interpret because toddlers have had two and a half years of postnatal experience with the statistics of the environment as well as prenatal experience. While it is safe to assume that their associations do not result from literacy—as they have not learned to read—we cannot say that their associations are not related to other features of language that they have encountered during their lives. For example, letters necessarily have to be learned; by age 2 ½ toddlers have some familiarity with letters. Thus, although in Chapters 2 and 3, the pattern of results for X, O, I, Z, C versus A, G, B, Y suggest that the colour associations to the former set of letters are not based on literacy, we cannot rule out all influences of learning. In addition, the associations made by toddlers from white to continuous shapes and from black to discontinuous shapes could be based upon valence judgments, which may have been taught from a very young age. Parents may use language that teaches a child that black is bad and white is good; sharp is dangerous (bad) and round is safe (good) (e.g., Lakoff & Johnson, 1980). Likewise, we cannot rule out an experiential explanation for sound-shape mappings since toddlers have had enough experience with words and the objects that they represent to pick up statistical regularities in English semantics. It is possible that words that have non-rounded vowels tend to represent objects that are jagged and that words that have rounded vowels tend to represent objects with curved contours. Therefore, without asking the same questions in infants, we cannot rule out the possibility that the associations we documented in toddlers result from learning from the environment. Note that the most common synaesthetic percepts—and many of our predictions—involve vision (i.e., colour, shape, and/or spatial location) and hence are not likely to have been influenced by experience in utero. In the section on future studies below, I describe how these questions might be studied during infancy.

Another limitation in the study of toddlers is the use of a simple binary response choice in order to make the task simple enough for them to perform. However, it is possible that when given a forced choice of black and white, choosing black does not mean that toddlers think the object is black, but simply that they do not think it is white. Experiment 1 in Chapter 3 evaluated this possibility to some extent by showing that toddlers chose black for X (and white for O) even when the alternative choice was red or green rather than white (or black). However, this control experiment still involved only a limited choice of colours. The research reported in Chapter 5 on adults' colour and texture associations to odours, in contrast, had in a sense too many choices because they were completely unconstrained. Participants could offer as many words as they wished to describe their associations. This method yielded very rich descriptions that were unbiased by fixed, preselected responses. However, coding the responses into quantifiable units necessitated some interpretation on the part of the experimenter, introducing the possibility of bias or incorrect classification. Although an independent rater largely agreed with the experimenter's classification, there was not perfect overlap (~2-3% disagreement) and no assurance that the classification captured the nuances of the participants' description (e.g., is lavender the same as light purple?).

Overt matching paradigms such as those used in this thesis are useful for elucidating how multisensory interactions influence conscious behaviour.

However, with such an overt paradigm, it is difficult to ascertain whether participants are simply deducing what the experimenter wants to hear, and responding accordingly, or reporting cross-modal associations that influence their perception in everyday life. An alternative methodology is implicit tasks that involve speeded choices, or the presentation of one stimulus that interferes with the discrimination of another. Such implicit tasks provide an alternative way of exploring how sensory information is related across modalities, and have the advantage over overt tasks of decreasing participants' ability to modify their responses to fit their reading of the experimenter's expectations. Comparing results from overt matching tasks and implicit tasks would help to elucidate which associations affect everyday perception, and which are elicited only by the overt nature of the matching task.

The conclusions of this thesis are based on inferences about neural development based on the literature but those inferences require hypotheses linking behavioural cross-modal associations to neural pathways among sensory cortical areas. At this point, the linking hypotheses are highly speculative. I used the term 'naturally-biased' for associations that cannot be readily explained by learning, but just because something is not obviously learned from the environment does not mean it is derived from connections between primary sensory areas. In the section on future studies, I describe ways to empirically test some of the linking hypotheses.

Future Studies

The understanding of the development of cross-dimensional and cross-modal associations would be greatly enhanced by studies of young infants in whom there has been less opportunity for learning. Intersensory associations such as shape associations to sound could be tested in infancy with the methodology devised by Bahrick to test infants' understanding of arbitrary cross-modal correspondences (e.g., pitch to shape/colour; face to voice): infants are habituated to two specific cross-modal pairings (the face of woman A paired with voice A; the face of woman B paired with voice B) and following habituation, tested for recovery when the pairings are switched (e.g., face A with voice B) (e.g., Bahrick, 1992, 1994, 2001; Bahrick, Hernandez-Reif, & Flom, 2005). Using this method, young infants evidence sensitivity to changes in the amodal property of temporal synchrony between visual and auditory impact at the youngest age tested (4 weeks): after habituating to alternating views of two different object clusters making distinctive sounds as they hit a surface, they dishabituate when the sound and visual impact are out of sync. However, they do not dishabituate until much later (4-7 months) when arbitrary cross-modal correspondences are switched (e.g., the high-pitched impact of a yellow metal washer versus the lower pitched impact of a orange metal nut) and even then, temporal synchrony facilitates the learning of the correspondence. (e.g., Bahrick, 1992, 2001; Bahrick & Pickens, 1994; Bahrick, Hernandez-Reif, & Flom, 2005; see also Flom & Bahrick, 2007). We could examine whether very young infants are sensitive to association between shape and sound by habituating infants to presentations of rounded shapes paired with nonsense words with round vowels and jagged shapes paired with nonsense words with non-rounded vowels. Once habituated, we could switch the combinations to see if infants notice the change. We predict that many of the associations outlined in this thesis would be evident with this method before 4 months of age, long before the emergence of sensitivity to learned arbitrary correspondences.

The habituation-switch method appears to be more sensitive than preferential looking for revealing cross-modal understanding in young infants: when presented with two visual stimuli, only one of which matches a centrally presented sound, infants often respond randomly, despite showing evidence with the habituation switch method of cross-modal matching (e.g., Bahrick et al., 2005). In addition, some studies have found that babies look at the matching stimulus (e.g., mother's face when hearing mother's voice) while other studies have found that babies look at the *non*-matching stimulus (e.g., stranger's face when hearing mother's voice; the moving legs of another baby instead of the current movements of the baby's own legs) (Rochat &Morgan, 1995; Schmuckler, 1996; Spelke; Bahrick & Watson, 1985;). Such inconsistent findings from the preferential looking technique make it difficult to draw conclusions about which stimuli the baby links across modalities. The habituation-switch method seems preferable.

It would also be useful to examine sound/shape associations during the period when children begin learning words. A similar habituation-switch design could be used to test hypotheses about natural mappings between properties of objects and of words. When infants are habituated to two word/object pairings and then tested with switched pairings, 14-month-old infants show recovery, indicating that they had learned the arbitrary word-object pairings in the lab (Werker, Cohen, Lloyd, Casasola, & Stager, 1998). When the difference between the words is acoustically minimal ("bih" versus "dih"), infants do not learn the word-object mappings with this laboratory procedure until 17 months of age (Werker, Fennell, Corcoran, & Stager, 2002). Even with more easily distinguished words, 8- and 12-month-old infants show evidence of remembering the words and of remembering the objects, but not of remembering the association between them (Werker et al., 1998). This paradigm could be used to test whether the shape/sound pairings found here (e.g., "bobo" as the name of an ameboid shape; "didi as the name for a jagged shape) are easier for infants to learn, such that they can be learned at a younger age or after shorter training during habituation, or such that they endure for a longer time after training.

As much as it is useful to study infants, it is nevertheless of theoretical interest to test the cross-modal and cross-dimensional associations in toddlers, rather than infants, when there is no obvious environmental explanation of how the cross-modal association would have developed post-natally. The advantage of testing toddlers over infants is that they understand simple verbal instructions and can be tested with methods that yield more easily interpreted data from more test points. The advantage of testing toddlers over testing older children or adults is that they have been influenced minimally by culturally-mediated associations evident in the metaphorical use of language and do not know how to read. Also useful would be cross-linguistic studies of cross-dimensional and cross-modal associations in adults speaking languages with colour terms beginning with different letters and with different names for the odors tested.

Future studies with toddlers could ascertain whether natural biases to associate letters to chromatic colours (i.e., C to yellow) are based upon the shape of the letter, as it is for natural biases between shape and achromatic colour. This could be done very simply by testing toddlers with only the sound of the letter or only its shape, as I did to examine the influence of sound versus shape for O, X, I and Z in Chapters 2 and 3. It would also be worthwhile to examine whether valence judgments of good/bad influence the toddlers' associations of continuous shapes to white and discontinuous shapes to black. To do this, one could use a single shape and ask toddlers to put it on the good or bad side of a black-and-white box and/or use a homogenously coloured box and ask them to pick up the "good" shape or "bad" shape (smooth or angular contours) and put it in the designated side. Future studies examining sound symbolism in toddlers could clarify the components of the sound that influence its associations. Are consistent associations between vowel roundedness and shape based upon the sound of the word, the shape of the speaker's mouth while producing the sound, or the proprioceptive information of one's own mouth shape while pronouncing the word? Ramachandran and Hubbard (2001) speculate that these phenomena arise from connections among contiguous cortical areas mediating decoding of the visual percept of the nonsense shape (round or angular), the appearance of the speaker's lips (open and round or wide and narrow), and the feeling of saying the same words oneself. Using the same forced choice between two shapes (one rounded and one jagged), we could create a storyline in which characters' names are represented in one of three ways; participants hear only the sound information, they see only information about mouth shape (i.e., speaker mouths the word but does not speak it), or they say or soundlessly mouth the word. These three conditions would serve to examine the influences of sound, mouth shape and proprioceptive information on shape matching.

The research presented in Chapter 5 on sensory associations to odour lays the foundation for future studies, which could examine the specific variations in odourants that underlie the cross-modal associations. For example, in order to examine how smell intensity, colour and texture are related dimensions, future studies could probe whether odours that smell more intense are more likely to be associated to darker colours (as are lower pitches) and/or to rougher textures. Alternatively or additionally, odours that smell sweeter may be more likely to be associated to specific colours (e.g., the red colour of strawberries), and/or to softer, smoother textures. To understand how aspects of odour such as sweetness and intensity are related to specific colour characteristics, such studies could present colour chips that separate colour into its components of hue, chroma, and lightness because there is some evidence in adults with olfactory synaesthesia that associations are more stable for chroma and lightness than for hue (van Campen & Froger, 2003). These studies could also explore whether opponent colours have a special status, as they do in colour grapheme synaesthesia (Nikolie, Lichti & Singer, 2007), by assessing whether adults are more consistent with each other when asked to make a forced choice between opponent colours rather than non-opponent options. Utilizing a similar forced-choice methodology could help to assess whether texture associates behave as dimensions of variation (smooth versus rough) or, as suggested by the verbal reports in this study, as unrelated attributes (e.g., an odour can be both smooth and rough). Similar to what has been done for the associations between sound and color, examining the characteristics of odours that reliably predict their cross-modal associations, could further understanding of how dimensions of sensory stimuli translate across modalities. Developmental and cross-cultural studies would be useful for separating the learned and naturally-biased influences on sensory associations to odours. Specifically, testing infants and toddlers would be useful to more clearly distinguish colour and texture associations to odours likely to be familiar (e.g., milk, urine) from those likely to never have been encountered (e.g., not part of mom's diet or the child's environment). Such studies could utilize a forced choice methodology like that used successfully to measure pitch/lightness, sound/shape, colour/letter associations in toddlers (e.g., Maurer, Pathman & Mondloch, 2006; Mondloch & Maurer, 2004; Spector & Maurer, 2008). In addition, examining cross-cultural data on colour and texture associates for odours that are common in some but not all cultures or geographic areas (e.g., tamarind, garlic, roses) could help to clarify the ways in which learning alters naturally biased associations. Testing for associations that are consistent across cultures and development would provide valuable insights into the organization of olfactory perception, and add to the understanding of the mechanisms underlying the interrelations among sensory modalities that are naturally biased versus based on learning.

Summary

Here I have outlined a program of research designed to examine how stimulus characteristics relate to one another cross-dimensionally and cross-modally, as well as the learned versus naturally biased influences on sensory associations. I have shown that there appear to be some natural biases for specific associations between shapes and colours, which are in part influenced by angularity of shape; between sound and shape which are influenced by the roundness of the vowel; and between some odors and colours and textures. I have laid the groundwork for future studies by asking questions that lead to novel predictions. The research provides further support for the study of synaesthesia as a phenomenon intimately related to everyday perception, and highlights the importance of looking at it from a developmental perspective. Most importantly, I have contributed to the knowledge about the perceptual system and the ways in which it changes during development.

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