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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 both pleasant and unpleasant odours, some of which were likely to be unfamiliar. 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 p's < 0.01 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). We speculate that sensory associations to odours, like those to pitch and letters (e.g. Mondloch and Maurer, 2004; Spector and 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.

Keywords

Cross-modal, olfactory, multisensory, colour, texture, perception

1. 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 and Shroeder, 2006; see Calvert *et al.*, 2004 for a collection of relevant multisensory articles). Early multisensory interactions may contribute to the ease and consistency with which we make cross-modal asso-

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ciations. For example, adults and toddlers associate pitch to surface lightness such that higher pitches are associated with lighter visual stimuli (Mondloch and Maurer, 2004; Ward *et al.*, 2006). Of course, some cross-modal correspondences can be learned from the statistics of the environment; for example, a larger dog has a lower pitched bark than a smaller dog, and adults do associate lower pitched sounds to larger objects (Marks, 1989). However, darker animals do not make lower pitched sounds than lighter animals, so learning cannot easily explain the correspondence between pitch and lightness. Rather, these associations may represent natural biases between pitch and lightness that reflect systematic connections between sensory areas. Interestingly, in adults with coloured hearing synaesthesia, for whom stimulation by sound elicits an actual percept of colour, higher pitches elicit lighter coloured percepts and lower pitches elicit darker percepts (Marks, 1989; Ward *et al.*, 2006). The evidence on pitch/lightness suggests that there are natural biases between these two dimensions that influence crossmodal associations in typical adults and toddlers and the actual percepts in one form of synaesthesia. Research such as this has shown that examining consistencies in cross-modal associations among typical adults and between typical adults and synaesthetes can provide insights about how multisensory information is organized in the brain, and how it can influence behaviour.

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 *et al.*, 2003; Molholm *et al.*, 2004). For the chemical senses, it has long been known that visual appearance, texture, and auditory ambience (e.g. soft music, clatter) affect the intensity and pleasantness of food flavours (e.g. Dematte *et al.*, 2006b; Kemp and Gilbert, 1997). There are also more specific effects. Thus, adults are slightly less accurate at classifying odors as lemon or strawberry in a speeded task when they co-occur with an irrelevant incongruent visual stimulus (e.g. a red colour or strawberry shape when smelling lemon; Dematte *et al.*, 2009). Similarly, in a modification of the Implicit Association Test, adults are faster and more accurate at discriminating odors and colors with congruent response pairings (e.g. when responding to pink color and strawberry odor with the same response key) than when response pairings are incongruent (e.g. when responding to green color and strawberry odor with the same response key) (Dematte *et al.*, 2006a). Such effects presumably result from having learned that strawberries are red/pink and have a specific shape and odour.

However, there are also visual effects not so clearly tied to learning. In adults with gustatory or olfactory synaesthesia, specific flavours evoke the perception of specific colours and/or textures that often are not easily explained by learning (e.g. chicken has a pointed shape, Cytowic, 2002; Day, 2005). Even in typical adults without synesthesia, perception of the intensity of an odour can be increased by adding colour to the solution, even when the colour is inappropriate; for example, green strawberry smells more intense than clear strawberry, with a stronger effect for more saturated colours (Zellner and Kautz, 1990). In addition, adults are more likely to report that an odourless solution has an odour if the solution is coloured (Engen, 1972). Adults also consistently pair darker colours to more concentrated odor solutions, and lighter colours to less concentrated odor solutions (Kemp and Gilbert, 1997). These effects are similar to the manner in which vision, audition, and touch perception can be facilitated and/or modified by concurrent stimulation of another sense in ways that suggest a common code for magnitude (e.g. Kennett *et al.*, 2001; Odgaard *et al.*, 2004; Shams *et al.*, 2001). 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 (Dematte *et al.*, 2006b). 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 *et al.* (1996) found that (non-synaesthetic) adults reliably associate specific colours to specific smells. For example, bergamot (an aromatic oil made from a bitter orange and used in Earl Gray tea) was associated to yellow and patchouli (an aromatic oil obtained from a Southeast Asian shrub in the mint family) was associated to brown. 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 the current 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 (Dematte *et al.*, 2006), and induces felt texture in some individuals with gustatory and olfactory synaesthesia (Day, 2005), 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.

2. Methods

2.1. Participants

Participants were 78 (8 male) non-synaesthetic adults, ranging in age from 17–44 (mean 19.2 yrs.) (see Note 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.

2.2. Materials

Materials were 22 odourants (see Appendix 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 noxious. Odourants were chemicals and/or essential oils obtained from various sources (Appendix). 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.

2.3. 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 they 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 *et al.*, 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. Between odourants, they were encouraged to take a sip of water and/or smell coffee grounds in order to reduce odour cross-contamination. 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 five 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.

3. Results

3.1. 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 naphthene (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 (Table 1). Individual participants correctly

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	0.41	0.24
	Anise	0.54	0.49
	Onion	0.51	0.07
	Peppermint	0.51	0.59
	Lemon	0.59	0.44
	Almond	0.22	0.05
	Vanillin	0.44	0.05
	Ginger	0.20	0.05
Floral	Lavender	0.22	0.10
	Geranium	0.22	0.00
	Bergamot	0.10	0.00
	Violet	0.02	0.00
Environment	Cedar	0.22	0.12
	Musty	0.12	0.00
	Mushroom	0.07	0.00
	Eucalyptus	0.05	0.05
	Juniperberry	0.27	0.00
	Rosewood	0.20	0.00
Chemical/medicine	Napthene	0.66	0.32
	Anisole	0.76	0.00
	Menthol	0.32	0.00
	Camphene	0.37	0.00

recognized a mean of 0.12 odours (SD = 0.09, range = 0–0.27), that is, roughly 2 of the 22 odours. Participants correctly categorized a mean of 31% of the odours, or approximately ~7 of the 22 odours (SD = 17.5, range = 0–54%).

3.2. Colour

3.2.1. 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.

3.2.2. 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 = 0.031, range = 0.86–1.0). 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 0.11 (Fig. 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.

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 and Simner, 2003, for application of this approach to data on colour/letter and taste/phoneme consistency, respectively).

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

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

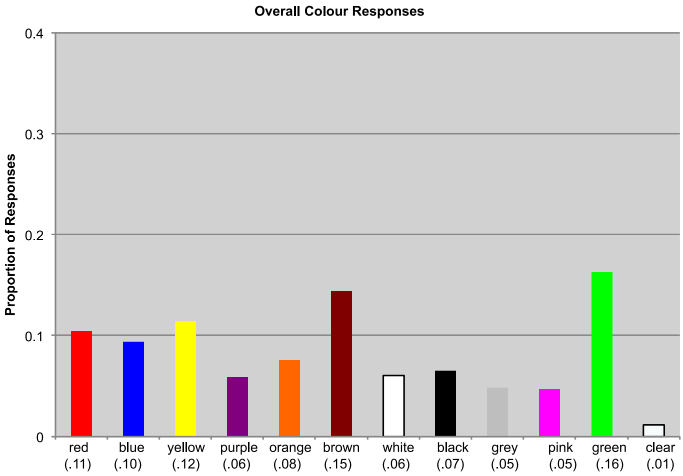

Figure 1. Overall frequency of each colour term. Bars represent the proportion of times each colour was chosen out of all colour responses in the data set. This figure is published in colour in the online version.

0.11), 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 = 0.29). In this example, the probability that 22 out of 78 people would respond that cinnamon is red by chance is less than 0.001. 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 Fig. 2a–v for individual odour/colour graphs).

3.2.3. 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 (p's < 0.01). 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.

3.2.4. Colour Associations to Non-identified Odours

All 17 non-identified odours had significant levels of consistent colour associations (p's < 0.05). The significant colour associations occurred for all four odour categories and include ones not readily explained by learning (e.g. almond — red).

3.3. Texture

3.3.1. Texture Terms

All participants reported texture associations to at least one odour. The texture associations were placed into categories based upon standard tactile texture clas-

Table 2.
List of significant colour and texture associations for each odour as measured by a binomial probability statistic. Significant associations at the $p < 0.01$ level are listed separately from associations significant at only the $p < 0.05$ level

Odour	Colour associations ($p < 0.01$)	Additional colour associations ($p < 0.05$)	Texture associations ($p < 0.01$)	Additional texture associations ($p < 0.05$)
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	

sifications, namely smooth, rough, hard, soft, sharp, dull, thick, thin, directional and random orientation (e.g. Hollins *et al.*, 1993; Picard *et al.*, 2003; Rao and Lohse, 1996; Yoshida, 1968). 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 fitted 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). Therefore, we decided to treat each texture term independently. If the participant

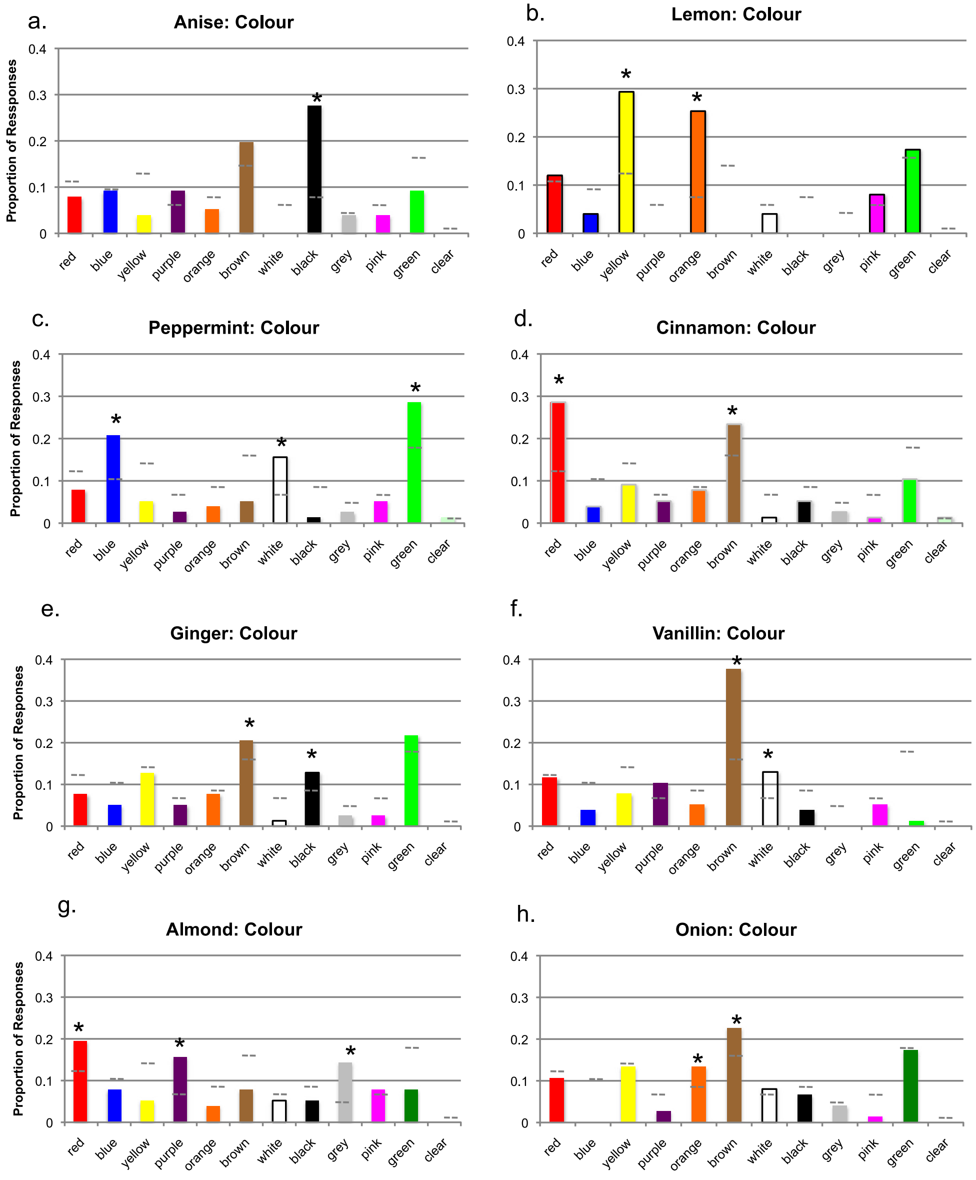

Figure 2. a–v. Graphs of all colour associations to each odour. Dotted grey lines indicate the chance level of responses for each colour based on the probabilities in Fig. 1. Asterisks indicate colour choices to the odor that were significantly higher than chance. This figure is published in colour in the online version.

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 (cin-

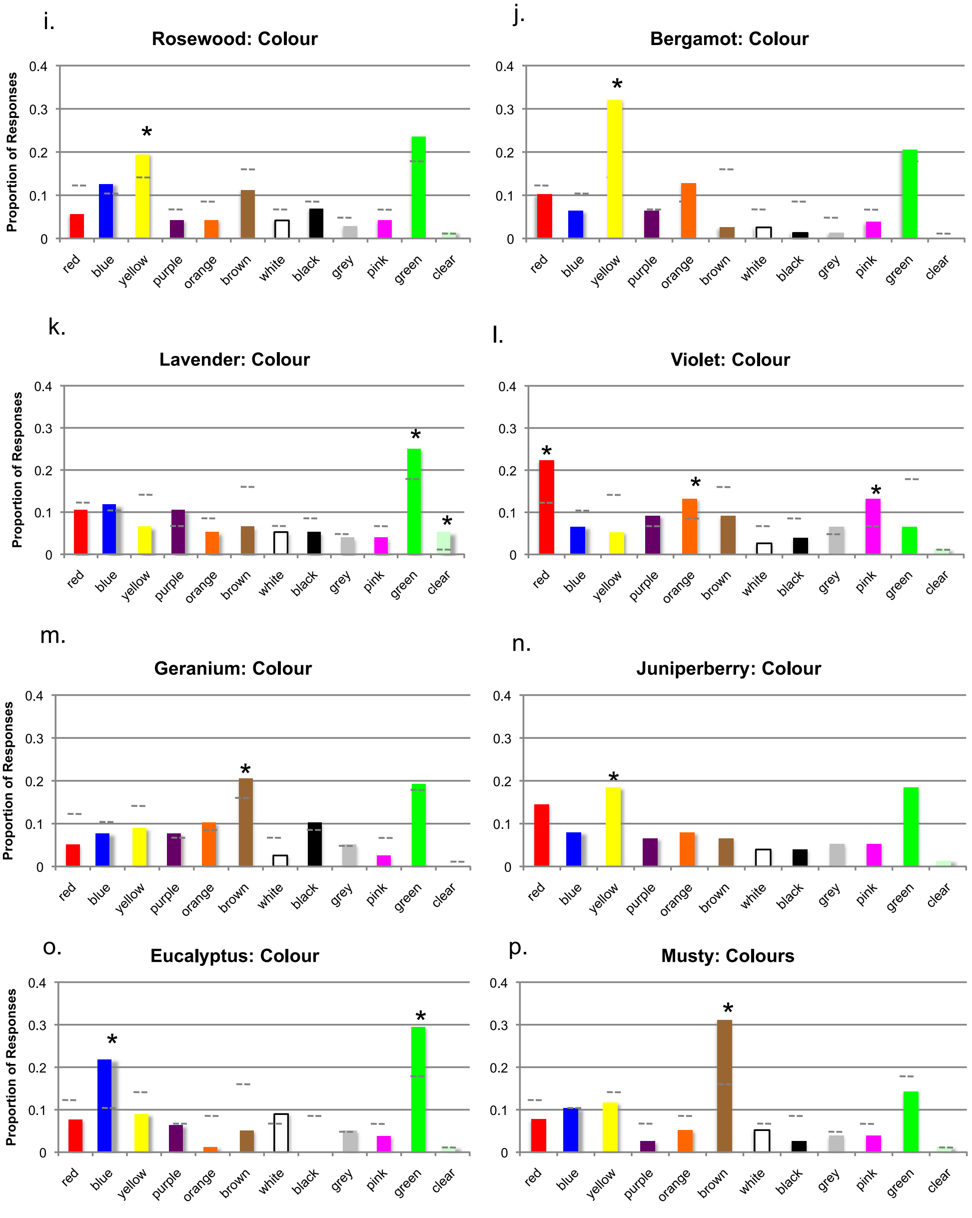

Figure 2. (Continued.)

namon, lavender and anisole) agreed with the original coding more than 97% of the time (Fig. 3).

3.3.2. Analysis

Individuals reported a mean of 1.52 texture associations per odour (SD = 0.24, range = 1.00–2.05). As with colour, we tabulated the total number of times each

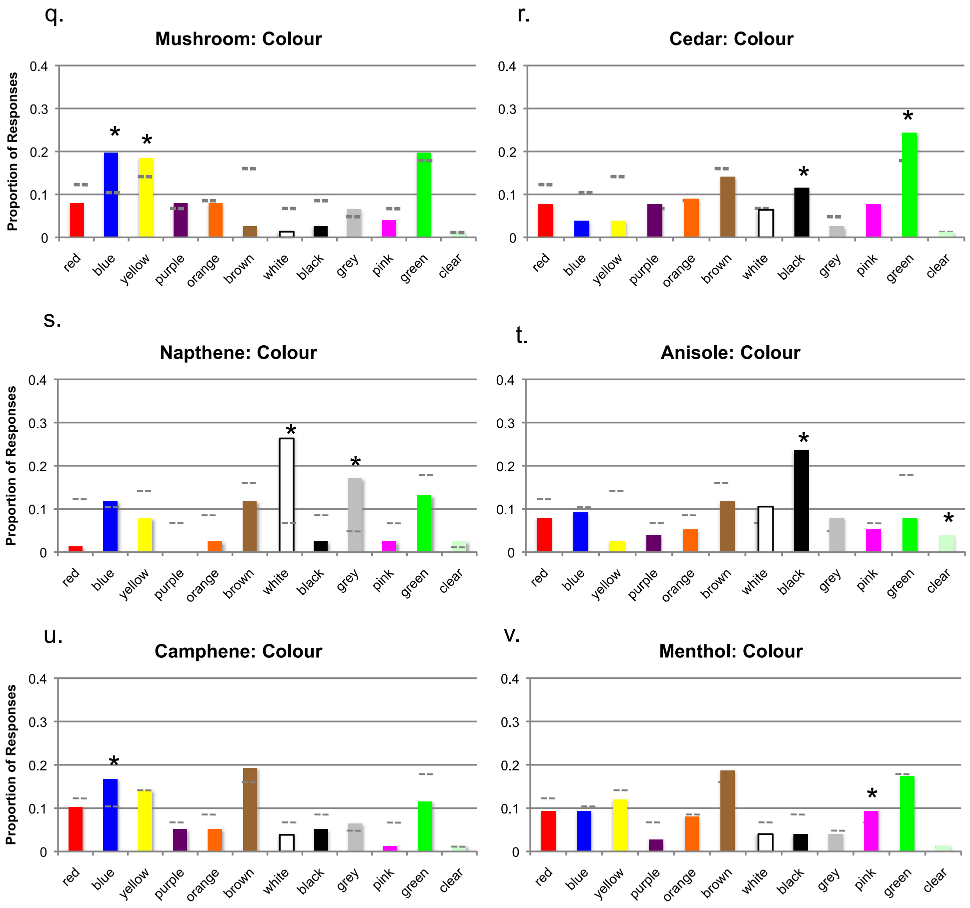

Figure 2. (Continued.)

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 0.26.

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% ($p < 0.01$). Applying the same analysis to all odour and texture combinations reveals significant texture associations for each of the 22 odours (see Table 2 for summary of all results, and Fig. 4a–v for individual odour/texture graphs).

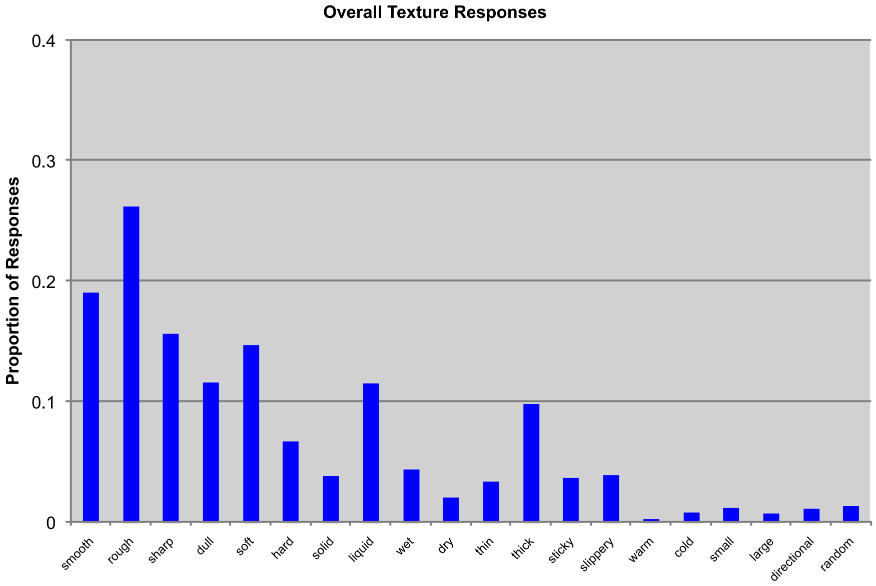

Figure 3. Overall frequency of each texture term. Bars represent the proportion of times each texture was chosen out of all texture responses in the data set. This figure is published in colour in the online version.

3.3.3. Texture Associations to Identified Odours

All five reliably identified odours had significant levels of consistent texture associations ($p < 0.01$), 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.

3.3.4. Texture Associations to Non-identified Odours

All 17 non-identified odours had significant levels of consistent texture associations ($p < 0.05$), with more than one texture significantly associated to each odour and not all associations readily explained by learning (e.g. lavender: sticky, large).

3.4. 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.

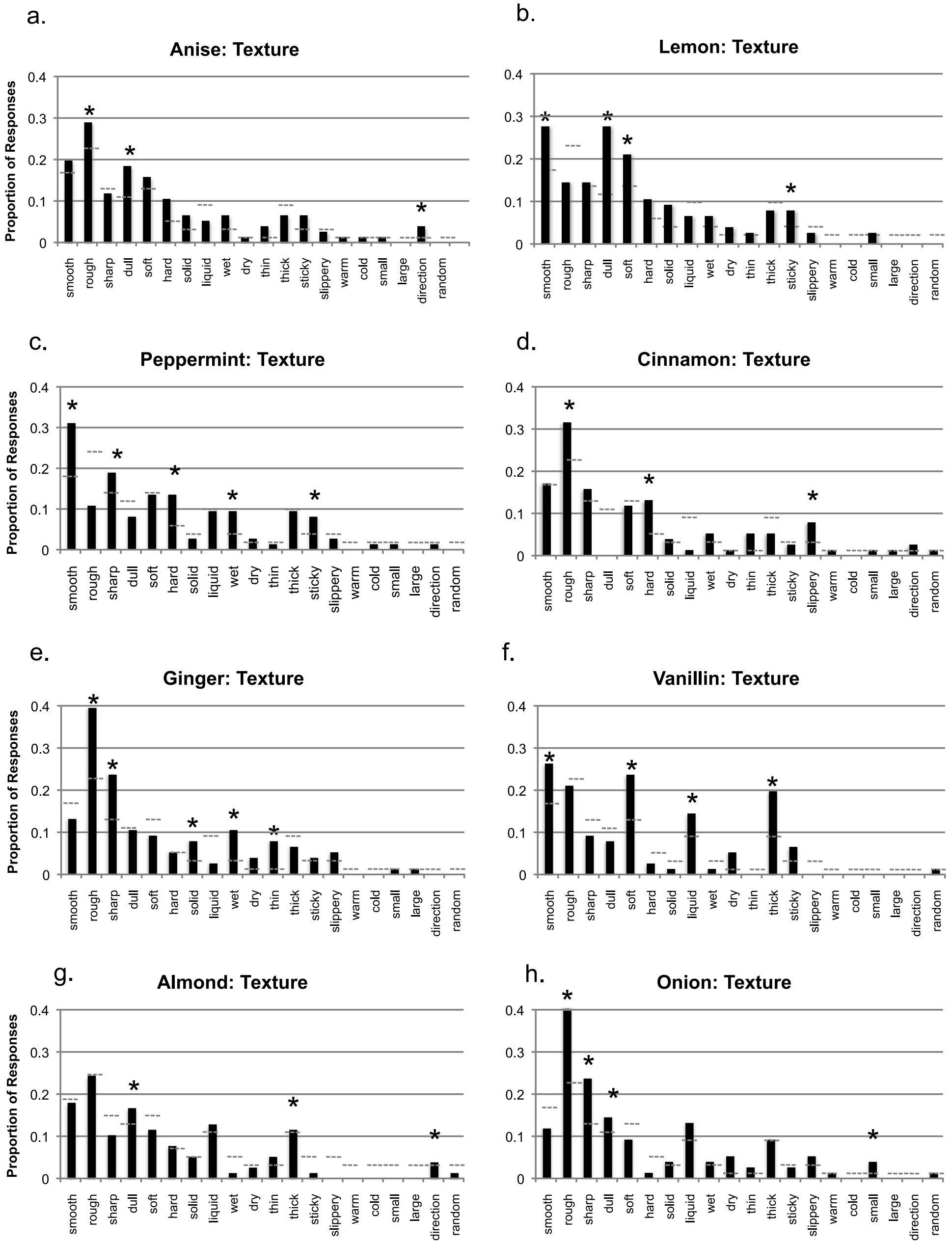

Figure 4. a–v. Graphs of all texture associations to each odour. Dotted grey lines indicate the chance level of responses for each texture based on the probabilities in Fig. 3. Asterisks indicate texture choices to the odor that were significantly higher than chance.

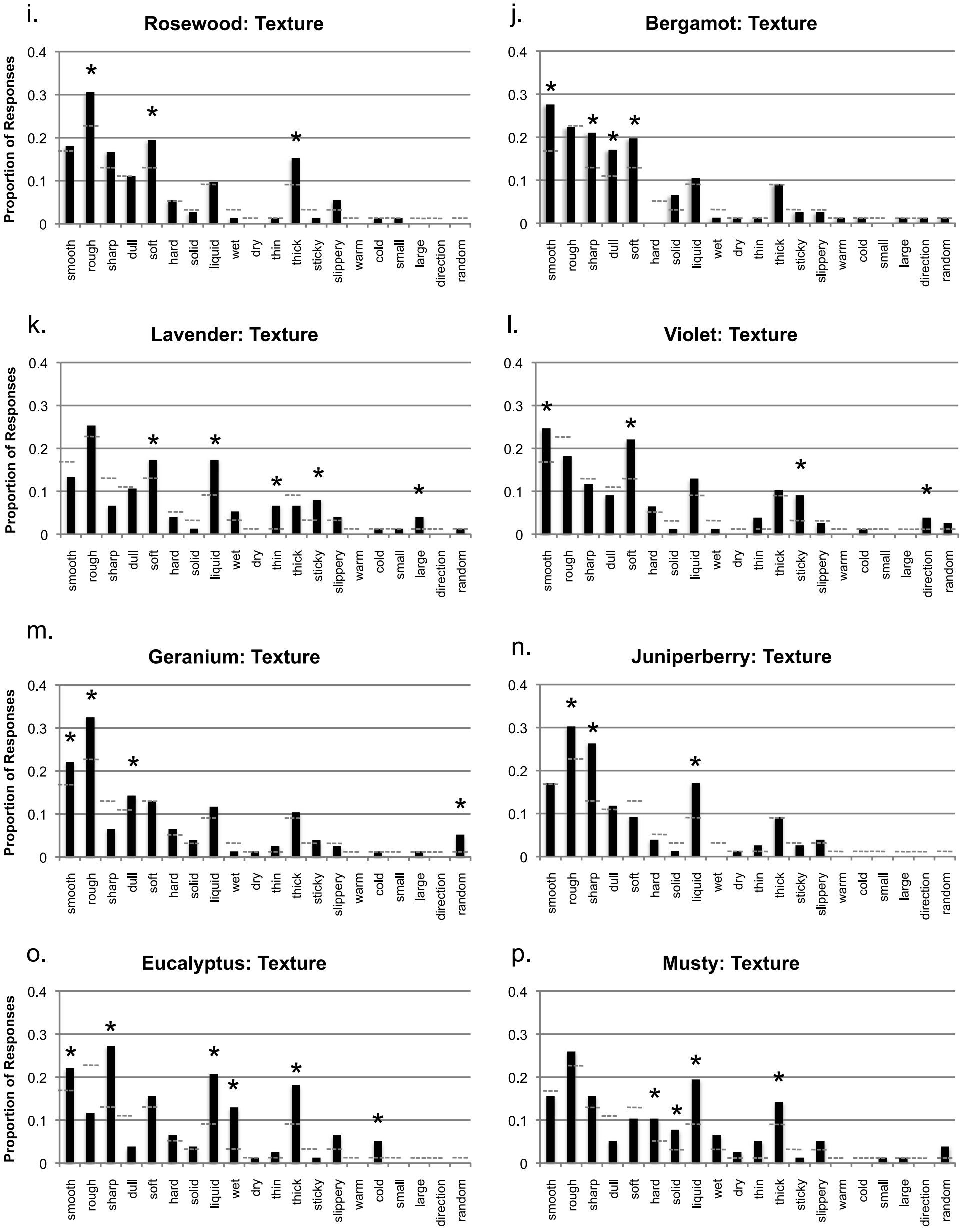

Figure 4. (Continued.)

4. Discussion

The analyses show that non-synaesthetic adults agree with each other about the specific colours and textures that they associate to odours more often than can be expected by chance. There were significant correspondences between colour and/or

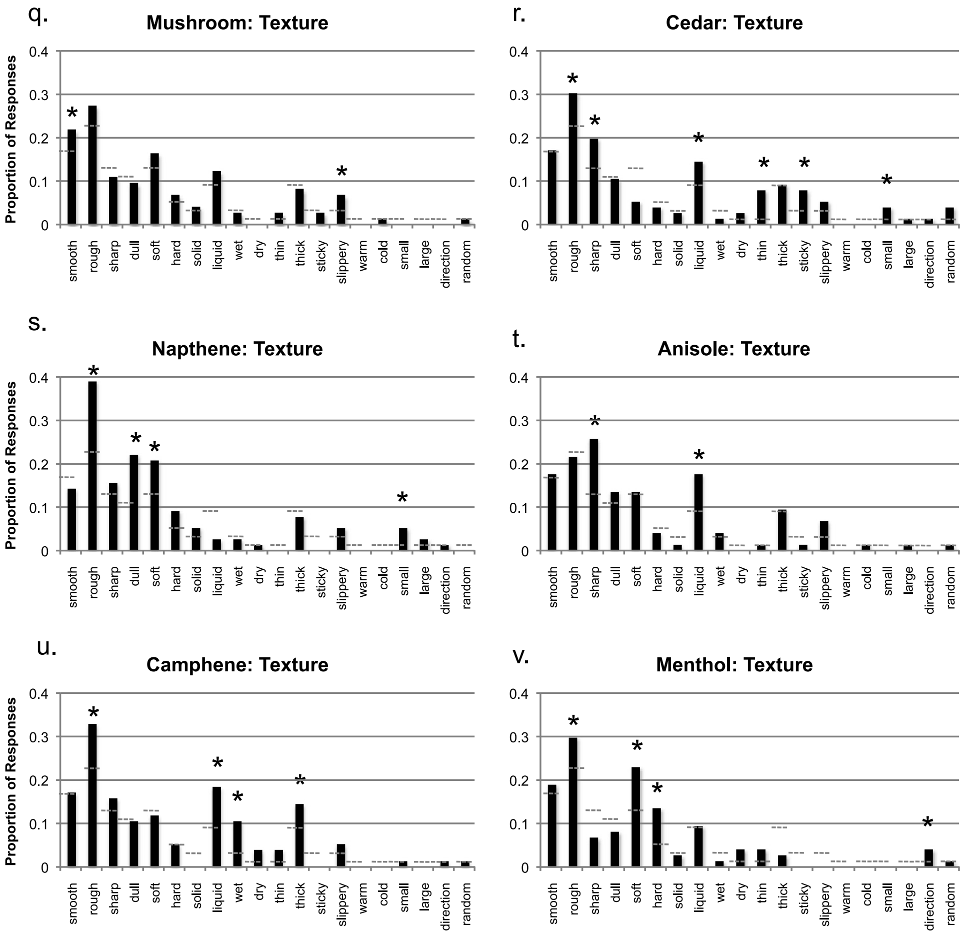

Figure 4. (Continued.)

texture for each of the 22 odours studied. Four of the odours were also used in Gilbert *et al.*'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 *et al.* found that their odours were associated to colours largely independently 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.

There is a widely held view that odour associations are very strongly influenced by personal experience (Ehrlichman and 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, naphthene, 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 for which experience is likely to be idiosyncratic or uncommon. 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 characteristic of the object with that smell. 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 a combination of learned and naturally biased cross-modal associations between other sensory domains and dimensions, such as the association of sounds of higher pitch to lighter colours and smaller objects, and sounds of a lower pitch to darker colours and larger objects (Marks, 1989; Mondloch and Maurer, 2004; Ward *et al.*, 2006). While the associations between pitch and size can be easily explained by experience (larger animals = lower pitched noises), the origins of the association between pitch and lightness is not related clearly to learning (darker animals ≠ lower pitched noises). Instead, 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. Data on the association of sensory dimensions shows a similar pattern: some colour associations to letters are readily explained by learning (G green) and are reliably associated in literate children and adults, but not in pre-literate children, but others do not have a ready learning explanation (X black) and occur reliably even in pre-literate children (Spector and Maurer, 2008, 2011; see Simner *et al.*, 2005 for adult data; see Simner, 2007, for review). Thus, sensory associations to odours, like those between letters and colours and between pitch and surface lightness, may result from the joint influence of learning and natural biases linking dimensions across sensory systems and sensory dimensions. 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.

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 which are largely, but not entirely, pruned or inhibited during development (e.g. Huttenlocher, 1994; Wolff *et al.*, 1974). There is evidence that some of these connections persist in the adult brain, but are largely inhibited (Pascual-Leone and Hamilton, 2001). Because neurons with similar response properties tend to lie contiguous to one another within each cortical area, 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-synaesthetic 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 the characteristics of the smell of lemon to yellow or to another color. If the natural bias is yellow, it 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 edible lemons are yellow. If the natural bias is another colour, it may be harder for the child to learn the correct association. When not overridden by learning, natural biases may persist to influence sensory associations in typical adults and yield actual percepts in synaesthetes.

Unlike pairing colours with letters, (e.g. Rich *et al.*, 2005; Spector and Maurer, 2008) 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 sensory systems towards multisensory relations.

4.1. Limitations

It is important to note that the majority of the participants were native Anglophone Canadians, who may share some cultural experiences (e.g. television shows, common candy colors) leading to a culture-specific collective memory that drove some of the less obvious associations to smell. In addition, according to the Ecological Valence Theory of colour preferences, colour preferences are influenced by affective responses to correspondingly coloured objects (Palmer and Schloss, 2010). Thus, people may have a preference for the colour blue because it elicits their affective response to blue skies or clear water, and may not prefer the colour brown because of its affective association to rotten food or faeces. Within this framework, there will be cross-cultural similarities in colour preferences when such experiences are universal and significant cultural differences when colour preferences are shaped by different objects or different affective responses to the same objects.. However, infants do show some colour preferences (e.g. Zemach *et al.*, 2007), suggesting that at least some colour preferences might be universal and hence lead to universal baseline responses against which to compare the responses to specific odour.

A second limitation is that the majority of the participants were female undergraduates, and hence it is possible that these results may not be generalizable to male adults. In addition, there is come evidence for sex differences in colour preferences (e.g. Hurlbert and Ling, 2007) that could alter the baseline responses against which the specific associations were compared. However, analysis of the data from the males in the study yielded the same pattern of results as the whole data set, but further study with a more representative sample would certainly strengthen the generalizability of the findings.

Finally, although every participant was presented with the same odorous solutions, and thus the same odour concentrations, we did not control for how deeply each participant inhaled. We cannot discount the possibility that the magnitude of the odour inhaled differed across participants and affected the associations to smells. We note, though, that any such confound would decrease the consistency of the associations across participants and hence mean that the consistency reported here is an underestimate of what we would have found with a procedure controlling for the depth of inhalation.

4.2. Future Directions

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 and Froger, 2003). These studies could also explore whether opponent colours have a special status, as they do in colour grapheme synaesthesia (Nikolie *et al.*, 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, and colour/letter associations in toddlers (e.g. Maurer *et al.*, 2006; Mondloch and Maurer, 2004; Spector and Maurer, 2008, 2011). 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* those 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 easily 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 extend research into cross-modal colour associations to odours and provide the first evidence of texture associations.

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Note

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

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Appendix.

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

Appendix.
(Continued)

Substance	Description	Source
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