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Crossmodal Associations Between Olfaction and Vision: Color and Shape Visualizations of Odors

Kathrin Kaeppler[1] (ID)

Abstract

Introduction In the present study, we assessed crossmodal associations between odors and both color and shape, with particular interest in the principles beneath these mappings. We hypothesized that visual associations of odors would primarily reflect observable features of a smelling object and thus vary with different source assumptions of the very same smell.
Methods We asked 30 participants to visualize their odor associations on a drawing tablet, freely deciding on color and shape. Additionally, subjects provided ratings on perceptual and shape-related dimensions as well as a verbal label for each sample.
Results With respect to color selection, the results confirmed a source-based mapping approach: odors rated as familiar were associated with very particular colors that typically resembled the appearance of their source. For less familiar odors, color selection was rather inconsistent but still then went along with assumed odor objects. Shape ratings changed with odor identifications as well, but considerably less than for color associations. Shape ratings and shape drawings produced very different results. While shape ratings were unlikely rooted in the mental imagery of a shape, drawings frequently displayed concrete objects that depended on odor label.
Conclusions Results confirm the existence of stable odor–vision correspondences and suggest that language plays a major part in mediating these mappings. The frequently assumed hedonic foundation of crossmodal matchings could not be confirmed for this stimuli set.
Implications Odor sensations may trigger odor naming spontaneously. Assumptions about an odor's identity, as well as the multisensory knowledge we have acquired on it, affect the visual associations of an odor.

Keywords Crossmodal associations · Crossmodal correspondences · Odor · Olfaction · Color · Shape

Introduction

An extensive body of research has investigated crossmodal associations of odors and found stable mappings between odors and specific stimuli, classes, and dimensions of other sensory modalities (for a review, see Spence (2011)). Among these, the correspondence between smell and vision has been of particular interest (Table 1(a, b)) as visual information has been shown to affect odor perception considerably (Engen 1972; Österbauer et al. 2005; Stevenson et al. 2012; Zellner

2013) in terms of intensity (Kemp and Gilbert 1997; Zellner and Kautz 1990; Zellner and Whitten 1999), pleasantness (Sakai 2005; Zellner et al. 1991), and quality evaluations or odor source identification, respectively (Blackwell 1995; Gilbert et al. 1996; Lavin and Lawless 1998; Morrot et al. 2001; Sakai 2005; Streeter and White 2011; Zellner et al. 1991). While the existence of consistent crossmodal matchings is uncontroversial, the mechanisms underlying these associations have been characterized diversely. Among the most frequently adduced principles in published research have been mentioned *natural co-occurrence* (Knöferle and Spence 2012; Spence 2011; Spence and Deroy 2013; Zellner et al. 2008), *hedonics* (Collier 1996; Crisinel et al. 2013; Crisinel et al. 2012; Crisinel and Spence 2010; Hanson-Vaux et al. 2013; Maric and Jacquot 2013; Pauli et al. 1999; Seo et al. 2010; Stevenson et al. 2012; Zellner et al. 2008), *emotions* (Charney et al. 2015; Schifferstein and Tanudjaja 2004), and *semantics* (Dematte et al. 2006; Gilbert et al. 1996; Jacquot et al. 2016; Knöferle and Spence 2012; Maric

✉ Kathrin Kaeppler
kaeppler@leuphana.de

[1] Institute of Experimental Business Psychology, Leuphana University Lueneburg, Wilschenbrucher Weg 84a, 21335 Lueneburg, Germany

Table 1 (a) Overview of studies on crossmodal associations between odor and color. (b) Overview of studies on crossmodal associations between odor and shape

A

Study (chronological order)	Dimension	Odors Number	Qualities	Crossmodal stimuli	Matching approach	Results LI[1]	CM[2]	SM[3]
Fiore (1993)	Color (lightness)	3	Floral, chypre, oriental	Thirty fabric swatches varying in color, texture, shape	Rating of fit on a seven-point scale	×		
Gilbert et al. (1996)	Color	20	Aldehyde C-16, bergamot oil, birch tar oil, caramel lactone, cinnamic aldehyde, civet artificial, 2-ethyl fenchol, galbanum oil, jasmine, lavender oil, lilial, methyl anthranilate, methyl salicylate, neroli oil, olibanum oil, patchouli oil, pine oil, rosalva, star anise oil, tarragon oil	11 color terms: red, orange, yellow, green, blue, purple, pink, white, brown, gray, black	Rating of fit by distributing five points across color terms		×	×
				One thousand five hundred sixty-five color chips varying in hue, saturation and brightness	Matching of one color to each odor		×	×
Kemp and Gilbert (1997)	Color (lightness)	15	Five odors in three concentrations each: caramel lactone, cinnamic aldehyde, aldehyde C-16, galbanum oil, methyl anthranilate	One thousand five hundred sixty-five color chips varying in hue, saturation and brightness	Matching of one color to each odor	×		
Schifferstein and Tanudjaja (2004)	Color (hue, saturation)	14	Aqua Woman, DKNY, Aromatonic, Paris, Calandre, Escada Sport Spirit, Beautiful, Boss Bottled, Le Male, Kouros Fraicheur, Indecence Organza, Miss Dior, Wish, Opium	Seventeen color chips: red, orange, yellow, green, blue, purple each in highest saturation and pastel, pink, white, brown, gray, black	Rating of fit on a nine-point scale	×	×	
Demattè et al. (2006)	Color (hue)	6	Caramel, cucumber, leather, lemon, spearmint, strawberry	Ten color patches: red, orange, yellow, green, turquoise, blue, purple, pink, brown, gray	Matching of one color to each odor		×	×
Zellner et al. (2008)	Color (hue terms)	6	Three feminine fragrances: Beautiful, Calyx, Tresor; Three masculine fragrances: Ralph Lauren Polo, Hugo Boss, Drakkar Noir	Eleven color terms: red, orange, yellow, green, blue, purple, brown, white, pink, gray, black	Rating of fit by distributing five points across color terms	×	×	
Spector and Maurer (2012)	Color (hue terms)	22	Almond, anise, bergamot, camphor, cedar, cinnamon, eucalyptus, gasoline, geranium, ginger, juniper berry, lavender, lemon, menthol, moth balls, mushroom, musty, onion, peppermint, rosewood, vanilla, violet	Twelve color terms: red, orange, yellow, green, blue, purple, pink, white, brown, gray, black, clear	Free association of one or more color hue terms, subsequent classification in 12 color categories		×	×
Maric and Jacquot (2013)	Color	16	Caramel, cucumber, lavender, lemon, lime, mint chlorophyll, mirabelle plum, orange blossom, peppermint, rose, pineapple, shallot, smoked, violet, wild strawberry	24 color patches varying in hue, saturation and brightness	Matching of one color to each odor		×	×
Levitan et al. (2014)[4]	Color	14	Burnt, candy, fish, flower, fruity, hazelnut, meat, musty, plastic, rice, soap, vegetable, vinegar, woody	Thirty-six color patches varying in hue, saturation and brightness	Selection of three most congruent and three most incongruent colors for each odor		×	×
Jacquot et al. (2016)	Color	16	Caramel, cucumber, lavender, lemon, lime, mint chlorophyll, mirabelle plum, orange blossom, peppermint, rose, pineapple, shallot, smoked, violet, wild strawberry	Twenty-four color patches varying in hue, saturation, and brightness	Matching of one color to each odor		×	×
Valk et al. (2016)[4]	Color	15	Five odors common in Western Europe: cheese, mustard, licorice, red wine, peanut butter; 5 odors common in Asia: fermented petai beans, dried durian, shrimp paste, coconut milk,	Eighty-four color chips varying in hue, saturation, and brightness	Matching of one color to each odor		×	×

Table 1 (continued)

galangal; 5 odors common in both cultures: banana, tobacco, garlic, canned fish, cooked rice

B

Study (chronological order)	Dimension	Odors		Crossmodal stimuli	Matching approach	Results		
		Number	Qualities			AI[5]	AP[6]	AT[7]
Fiore (1993)	Shape (angularity)	3	Floral, chypre, oriental	Thirty fabric swatches varying in color, texture, and shape	Rating of fit on a seven-point scale	x		
Seo et al. (2010)	Shape (angularity)	6	Banana, honey melon, mint, parmesan cheese, pepper, truffle, vanilla, viola	Eighteen abstract symbols varying in shape, complexity, and direction	Dichotomous rating of fit (yes/no) for each symbol		x	x
Hanson-Vaux et al. (2013)	Shape (angularity)	25	Almond, apple, apricot, blackberry, caramel, cedar, dark chocolate, cut hay, green pepper, honey, lemon, licorice, mushroom, musk, pepper, pineapple, raspberry, smoked, vanilla, violet	Angularity scale (anchored with angular and round shape)	Rating of angularity on a nine-point scale	x	x	x
Crisinel et al. (2013)	Shape (angularity)	7	Ginger cookies, dried plums, roasted coffee, crème brulée, candied orange, iris flower, musk	Angularity scale (anchored with angular and round shape)	Rating of angularity on a nine-point scale	x	x	

[1] LI = lightness–intensity: inverse relation between color lightness and perceived odor intensity

[2] CM = consistent matching: consistent color matching or characteristic color profile for each odor

[3] SM = source matching: matchings of odor and color hue agree with natural source associations and indicate odor source considerations of subjects

[4] Cross-cultural study, results of Western European participants reported here

[5] AI = angularity–intensity: direct relation between angularity and perceived odor intensity; less intense odors associated with soft-edged, curved shapes; intense odors associated with angular shapes

[6] AP = angularity–pleasantness: inverse relation between angularity and odor pleasantness

[7] AT = angularity–trigeminal stimulation: relation between angularity and experienced pungency (caused by trigeminal component of an odorant); relationship not explicitly considered by Seo et al. (2010)

and Jacquot 2013; Marks 1996, 2004; Martino and Marks 2000, 2001; Nehmé et al. 2016; Spence 2011; Spence and Deroy 2013; Stevenson et al. 2012; Zellner et al. 2008).

Co-Occurrence Several attributes from different sensory modalities co-occur naturally in our environment. These matchings are internalized early in life and expressed in crossmodal associations, for example, between size and loudness or angularity and softness of objects.

Hedonics and Emotion In numerous studies, pleasantness has been suggested as the prime mediator of olfactory crossmodal correspondences with pleasant odors being matched to pleasant stimuli of other sensory modalities and vice versa. However, as pleasantness ratings fail to predict matchings in any instance (Knöferle and Spence 2012), one might reason that this principle is only one of several underlying mechanisms or a side effect of, for example, odor identification, i.e., a semantic process. A more recent study by Charney et al. (2015) provided evidence for the mediating role of several other affective dimensions like anger, happiness, romance, and energy in odor–music matchings.

Semantics With respect to crossmodal associations, the mechanism of "semantic matching" has been explained in different ways. Some authors (Knöferle and Spence 2012; Spence 2011) have referred to semantic matching when perceptual evaluations depend on the same terminology in different sensory modalities (as *high* or *low* for pitch, temperature, intensity, and elevation). We, however, use the term *semantic*—or specifically *lexical–semantic*—in the meaning of experience–based, i.e. learned, associations that very often go along with source considerations when an odor is presented. In particular, the term lexical–semantic is used when language is assumed to be mediating the crossmodal association. Several authors have adduced this principle to explain crossmodal matches, though they may have labeled it differently (Dematte et al. 2006; Gilbert et al. 1996; Jacquot et al. 2016; Maric and Jacquot 2013; Nehmé et al. 2016; Schifferstein and Tanudjaja 2004; Stevenson et al. 2012; Zellner et al. 2008).

We can assume with good reason that the mentioned attempts are neither mutually exclusive, nor may one explain each type of crossmodal correspondence. Lexical–semantic effects have received most empirical attention concerning mappings between smell and color. It seems plausible that associations of odors primarily reflect visual features of an assumed odor source when considering the olfactory vocabulary of many languages. Linguistic expressions of odor perceptions lack superordinate categories and dimensions (for a review, see Kaeppler and Mueller (2013)); hence, associations may simply be traced back to the visual features of an odorous object and what is more important, odors may more easily prompt naming processes than perceptions in other sensory

modalities. Empirical indications for this assumption can be found in the results of all odor–color studies (Table 1(a)). Interestingly, recent cross-cultural studies have provided evidence that a dominance of source references may be truly rooted in language as this effect is limited to cultures with insufficient smell–related vocabulary (Majid 2015; Majid and Burenhult 2014; Valk et al. 2016).

Meanwhile, interest and evidence for semantic principles beneath odor–shape mappings have been sparse. Recent studies have mostly bypassed the option that shape selection could reflect visual features of odorous objects and rather focused on pleasantness and perceived intensity as mediating factors. Therefore, the present study aimed to assess whether visual associations of odors depend on the imagery of an odor's source in terms of color and shape dimensions and if they change systematically with varying odor names. Specifically, we assumed that (1) colors correspond with the natural color of an assumed odor source object: different odor names go along with different colors for the same odorant. Color selection is non-random for easy-to-label odors (independent from the accuracy of this label) and rather arbitrary for hard-to-label odors. (2) Shapes correspond with basic visual features of the assumed odor source object: Shape features are distinct for easy-to-label odors and rather arbitrary for hard-to-label odors.

Different from previous methodological approaches where subjects matched odors to a given set of visual stimuli or rated on several visual dimensions, we asked participants to create free drawings of their visual associations. We wanted to introduce a novel method for examining visual matchings of odors. With an exploratory attempt, we aimed to obtain a more holistic impression of visual odor matches that also reflected the relationships between color and shape associations. We expected that providing fewer restrictions for the dimensions of these associations could help to further the understandings of the principles behind these correspondences.

Materials and Methods

Procedure

Subjects carried out three sequential tasks: computer-assisted drawing (*visualization task*), odor evaluation (*evaluation task*) on perceptual dimensions, and odor identification (*identification task*). Before proceeding with the next, each task was completed for all odors.

Visualization Task

Participants were asked to display their associations to each odor presented by employing a digital drawing tablet (Wacom Bamboo Pen & Touch, third generation) and the painting software *ArtRage* (Ambient Design). For color selection,

participants passed through a fixed sequence of steps: They first picked a color hue from a linear color spectrum, then varying lightness and saturation with a slider bar on both dimensions. They were then asked to draw a shape or pattern in any size, direction, and complexity that they felt most closely matched their visual association of the odor presented. Subjects could draw freely but were explicitly instructed not to draw figurative objects. The task had no time limit. Subjects could see their drawings on a 21.5-in computer screen in front of them. They could erase parts or the whole sketch if desired. Each participant was instructed comprehensively and in written form about the procedure. Subjects completed several standardized tasks to practice color selection as well as the usage of pen and tablet before proceeding with the actual experimental session. A session consisted of 10 blocks (i.e., 10 odors), intermitted by breaks of at least 90 s. For each new block the white canvas on the screen was blank and the color picker in a neutral position. Instructions on procedure and sequence of color selection were visible at all times.

Odors were presented in white pen-like devices that carried a cotton swab soaked with the diluted odorant. Pens were coded by a random two-digit number.

Evaluation Task

In the second task, subjects were asked to evaluate the same odors one by one on 11 dimensions using a nine-point rating scale. Five dimensions were labeled and anchored on both sides: *intensity* (low–high), *pleasantness* (very unpleasant–very pleasant), *edibility* (not at all edible–edible), *temperature* (cold–hot), *masculinity–femininity* (very masculine–very feminine). Six dimensions were supposed to be shape related: for five of them terms were provided on each extreme (regular–irregular, small–big, abstract–realistic, simple–complex, geometric–organic), one was anchored by the images and (Maluma–Takete) comparable to previous crossmodal studies (Crisinel et al. 2013; Hanson-Vaux et al. 2013).

Identification Task

In the last part, participants rated the familiarity of each odorant (not familiar at all–very familiar) and whether they were able to identify it (not at all–very confident) on a nine-point rating scale. Subjects were then asked to provide the most accurate source name of each odor and to judge the certainty of their answer ("How certain do you feel in having identified the correct odor source?" not at all–very certain).

The order of stimuli presentation was fully randomized across participants and experimental tasks. Subjects were free to sniff an odor sample as often, as they wished and to interrupt a session when they felt their perceptual sensitivity or concentration decreasing.

Odorants

We selected ten odors from a larger stimuli set of a previous study (details on this unpublished study may be requested from the author). The selection was based on two criteria:

1. Rate of correct identifications in a free identification task: As we assumed that the consistency of associations across subjects would vary with the ease to name an odor, we included odors with different rates of correct identifications: high (lemon, peppermint), low (elder, patchouli), and intermediate (ethyl acetate, isoamyl acetate, licorice, mustard, coconut, cinnamaldehyde). To determine naming accuracy, we applied a definition of an odor's *veridical label* proposed by Dubois and Rouby (2002): "the commonly encountered object that produces an odor quite similar to the one produced by the presented odorant" (p. 50). That is, for an odorant *Lemon Oil* both labels *lemon* and *lime* would be treated as correct identification. Nevertheless, we would expect different visual associations for each of these labels.

2. Naming consistency in a free identification task: As we wanted to investigate how an assumed odor source affected color and shape associations, we chose odors for which different source assumptions could be contrasted. Thus, we only included odors that had been labeled reliably with at least two different odor names a free identification task. For example, a *lemon odor* that was repeatedly identified as lemon or lime, respectively.

Odorants and most common source names are listed in Table 2.

Participants

In total, 30 participants (60% women; mean age 22.8; SD = 3.37; range = 18–35) were recruited from the Leuphana University Lueneburg. They were tested individually and participated for course credit. Participants provided verbal informed consent about being tested. Ahead of the experimental session, they were instructed not to use perfume, body lotions, or odorous cosmetics at the day of the experiment and not to smoke 1 h prior to the study. None of the subjects reported respiratory infections, allergies or another impairment of their sense of smell at the time they were being tested. They had no previous experience in olfactory testing and were naive to the experimental aim of the study. At the end of the experiment, participants were fully debriefed. The study was conducted according to the Declaration of Helsinki—Ethical Principles for Medical Research Involving Human Subjects and approved by the Ethics Committee of Leuphana University Lueneburg.

Table 2 Set of odorants and most common labels (applied in a free identification task)

Product name/substance (supplier)	Label A	Label B	Abbreviation
Anethol Supra (Symrise)	Anise	Licorice	ANI
Cinnamaldehyde (Symrise)	Cinnamon	Marzipan	CIN
Aromatic oil "Coco" (Aromell)	Coconut	Vanilla	COC
Elder flavor (Symrise)	Elder	Rotten fruit	ELD
Isoamyl acetate	Ice drops	Solvent	ISO
Lemon oil (Symrise)	Lemon	Lime	LEM
Mustard flavor (Symrise)	Mustard	Wasabi	MUS
Aromatic oil "Patchouli" (Aromell)	Wood	After shave	PAT
Peppermint oil (Symrise)	Peppermint	Chewing gum	PEP
Ethyl acetate (Symrise)	Nail polish remover	Glue	TUR

Results

All statistical analyses were conducted with the SPSS statistics (version 24.0) for Windows. Testing revealed no significant gender differences. Hence, data was collapsed across gender. Ratings on all dimensions applied in the evaluation task were treated as metric data. With respect to correlations, we calculated Spearman coefficients as data was not normally distributed on these dimensions (details of analysis may be requested from the author). All drawings are available in Online Resource 1.

Odor Identifications

Overall, odors were identified correctly in 43% of the cases, with considerable differences in naming accuracy between odors (Fig. 1). As expected, the highest naming accuracy was found for LEM (86.67%) and PEP (80%) and lowest for PAT (0%) and ELD (0%). We additionally applied a scheme proposed by Cain (1979) and further classified incorrect identifications in far misses (evidently false labels—*wood*

for *elder*) and near misses (similar or closely related odor labels—*orange* for lemon). When near misses were treated as correct, the overall identification rate increased to 65%. The highest rates of near misses were found for the six odors with (initially) moderate identification rates and as expected, these labels had a certain consistency across subjects. That is, very often one and the same incorrect odor name was applied by several participants.

Additional data on perceptual ratings and the relationships between ratings of odor familiarity, naming ability, and naming certainty are provided in Online Resources 2–4.

Color Analysis

Non-Randomness

To compare color selection within and across stimuli, values for the three-color space dimensions hue (0–360°), saturation (0–100%), and chroma (0–100%) were extracted from the set of 300 images (30 subjects, 10 odors) using the software *GIMP* (version 2.8).
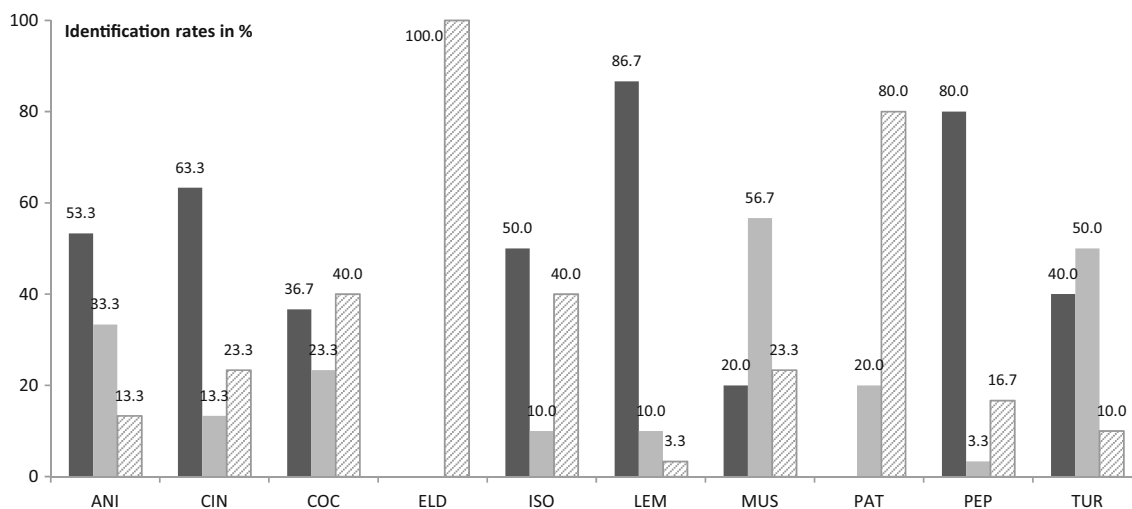
Fig. 1 Identification rates: correct identification (dark grey bars), near miss (light gray bars), and far miss (shaded bars)

While saturation and chroma parameters can be treated and analyzed as metric data, hue is based on a circular distribution and suitable statistical methods are not readily available. We therefore classified hue scores in either six or 12 equally broad color categories for further analysis. Figure 2 depicts the colors chosen for each odor.

As some odors seemed to be associated with colors more consistently than others, we first tested whether color matches were odor specific and non-random across participants, i.e., whether a given odor influenced color choice or not. The observed hue scores were divided in six equally broad color groups (red, yellow, green, cyan, blue, magenta) and compared to a random equal distribution using a non-parametric χ^2 test (Table 3). If color matching was determined by an odor's name, one might expect to find a stronger preference across subjects for particular colors for easy-to-label samples and a rather arbitrary color selection for unfamiliar odors. The test showed significant results for the common and easy to name odors LEM and PEP as well as for CIN, COC, ISO, and MUS. For these odors, subjects preferred some colors over others. Non-significant results referring to a rather random color matching were found for the unfamiliar odors ELD and PAT. Interestingly, non-significant p values were also calculated for ANI and TUR. They, however, do not indicate a random color selection as subjects disproportionally often chose grey and black for both odors, color categories that do not go along with a variance in hue, but in saturation and lightness.

Given that color selection was reliable for odors with certain identification ease, we ought to answer whether this consistency was determined by an assumed odor source only or mediated by other variables.

Dimensional Ratings

While several studies have reported robust crossmodal associations between color and likeability (Hanson-Vaux et al. 2013; Jacquot et al. 2016; Maric and Jacquot 2013; Schifferstein and Tanudjaja 2004; Zellner et al. 2008) or perceived intensity of odors (Fiore 1993; Kemp and Gilbert 1997; Schifferstein and Tanudjaja 2004), we found only small relations between pleasantness or intensity ratings and lightness, saturation, or color hue, respectively (Table 4). These results imply that—at least for this set of odors—pleasantness and intensity ratings did not mediate the matching between odor and color: "Red odors" were evaluated, as no more pleasing than "black odors" and "dark odors" were not generally perceived as more intense than "light odors", etc.

Color Profiles

To generate color profiles, hue scores were classified in 12 equally broad classes (30° of the hue circle each). The frequency of mappings per color category is displayed for each
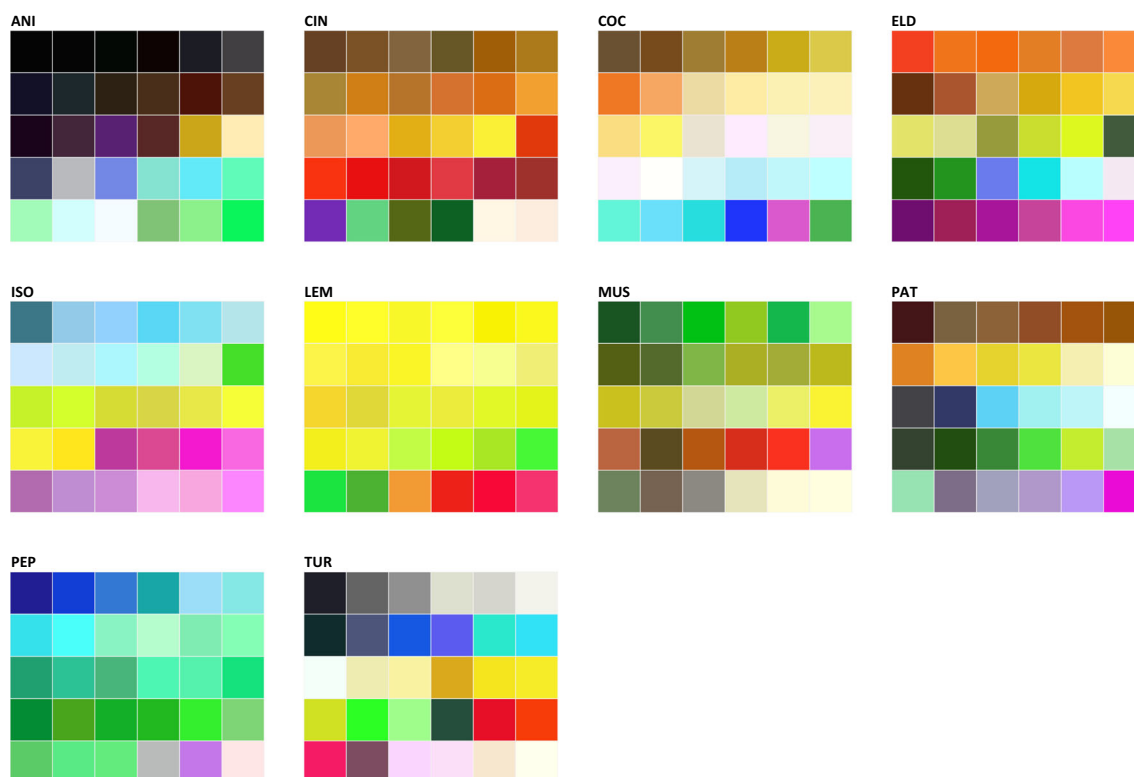
Fig. 2 Color matching for each odor. Patches are sorted by color, not by subject (Color figure online)

Table 3 Results of χ^2 test on color hues selected for each odor[1]

Odor	χ^2	p
ANI	2.0	0.8491
CIN	44.0	< 0.001
COC	29.2	< 0.001
ELD	12.4	0.0297
ISO	23.6	< 0.001
LEM	88.8	< 0.001
MUS	47.2	< 0.001
PAT	4.0	0.5494
PEP	37.2	< 0.001
TUR	10.4	0.0647

[1] Based on six equally broad categories: red (331–30°), yellow (31–90°), green (91–150°), cyan (151–210°), blue (211–270°), magenta (271–330°)

odor in general and—if enough cases available—as a function of assumed odor source in Fig. 3.

Color patterns are visibly odor specific. However, while unfamiliar odors like PAT and ELD show a rather constant distribution across all classes while familiar odors like LEM and PEP have distinctive profiles with high peaks in particular color classes. When color profiles were generated as a function of assumed odor name, the color mappings for some odors varied considerably—although odor naming was performed only after color and shape matching for all odor samples. Exemplary color patches for three odors are displayed in Fig. 4 and suggest a source-driven color matching.

Remarkably, often the color selection for outliers went along with (wrong) odor source names as well: for example, for ANI, dark yellow–green was chosen for *fennel sirup*, for MUS red for *salami*, for COC bright blue for *NIVEA sun cream* (blue packaging), for TUR a bright red for *Pritt glue* (red packaging), etc.

In several cases, color selection alone suggested a source-independent mapping. Very often, shape features countered

Table 4 Spearman correlation coefficients between perceptual and color dimensions, η coefficient between hue classes and perceptual dimensions

Dimension	Lightness	Saturation	Hue	
Intensity	− 0.031	0.045	*0.202*	*(0.041)*
Pleasantness	0.128*	0.063	*0.176*	*(0.031)*
Edibility	0.087	0.053	*0.190*	*(0.036)*
Temperature	− 0.117*	0.117*	*0.483*	*(0.233)*
Masculinity–femininity	0.180**	0.056	*0.379*	*(0.144)*

Scores in italics are η coefficients that describe the relationship between hue categories (12 equally broad classes) and perceptual dimensions; η^2 in brackets

*$p < .05$; **$p < .01$

this impression of an arbitrary color selection: for example, when CIN was identified as cinnamon and matched with a very light red, a drawn rectangle or flat cuboid implied a source-based visualization—however, not in the proper sense of cinnamon as a seasoning but as chewing gum flavor (in this case *Wrigley's Big Red*).

Shape Analysis

Shape associations were assessed in two approaches: (a) in the visualization task, subjects were asked to draw any shape or pattern that best matched a given odor; (b) in the evaluation task (after visualization of all odors), participants rated each sample on six shape-related dimensions anchored with shape-related terms or symbols. We analyzed the tasks separately and assessed the closeness of agreement in order to test whether both approaches reflect shape associations similarly.

Shape Dimension Ratings

We conducted repeated-measure ANOVAs (Greenhouse–Geisser corrected) to assess whether there were any differences in average shape ratings between odors. Results were significant for all dimensions except for small to big (Table 5), suggesting that the tested odors had a significant effect on the rating of all shape dimensions except size.

Previous studies have emphasized that shape associations may not be explained by mental imagery of an odor's source: "Smells were not matched to shapes in a manner that could be explained simply by suggesting that participants were matching to the shape properties of their typical source" (Deroy et al. 2013, p. 882). We calculated correlation coefficients to test whether differences in shape were mediated by pleasantness or intensity as reported by other authors (Table 1(b)) and found small to moderate effects (Table 6(a)), with the highest coefficients for the angularity dimension. Our results are comparable to associations reported by Crisinel et al. (2013): dors rated as rather unpleasant or intense were regarded as more ⟨angular shape⟩ while pleasant or less intense samples were more likely matched to the rounded, organic ⟨rounded shape⟩ shape (Fig. 5a, b).

As with color classes, we generated shape profiles for all odors (across all subjects and as a function of assumed odor source) displaying the mean score of each of the six shape dimensions (Fig. 6).

In general, shape dimension ratings appeared to be less pronounced than color hue profiles suggesting a minor effect of assumed odor source. Uncommon odors like ELD or PAT as well as more familiar samples like ISO, CIN, or MUS resulted in rather flat, i.e., unpronounced patterns with mean ratings close to the midpoint of each dimension. Interestingly, the most tangible shape dimension *size* was the least affected by an odor or assumed odor source—only two odors (ISO,

Fig. 3 Color hue profiles for each odor across all judgments and as a function of assumed odor source name; *x*-axis: R–O red–orange (346–15°), Y–O yellow–orange (16–45°), Y yellow (46–75°), Y–G yellow–green (76–105°), G green (106–135°), B-G blue–green (136–165°), C cyan (166–195°), B blue (196–225°), B–V blue–violet (226–255°), V violet (256°–285°), M magenta (286–315°), R red (316–345°); *y*-axis: frequency of color class selected (in %)
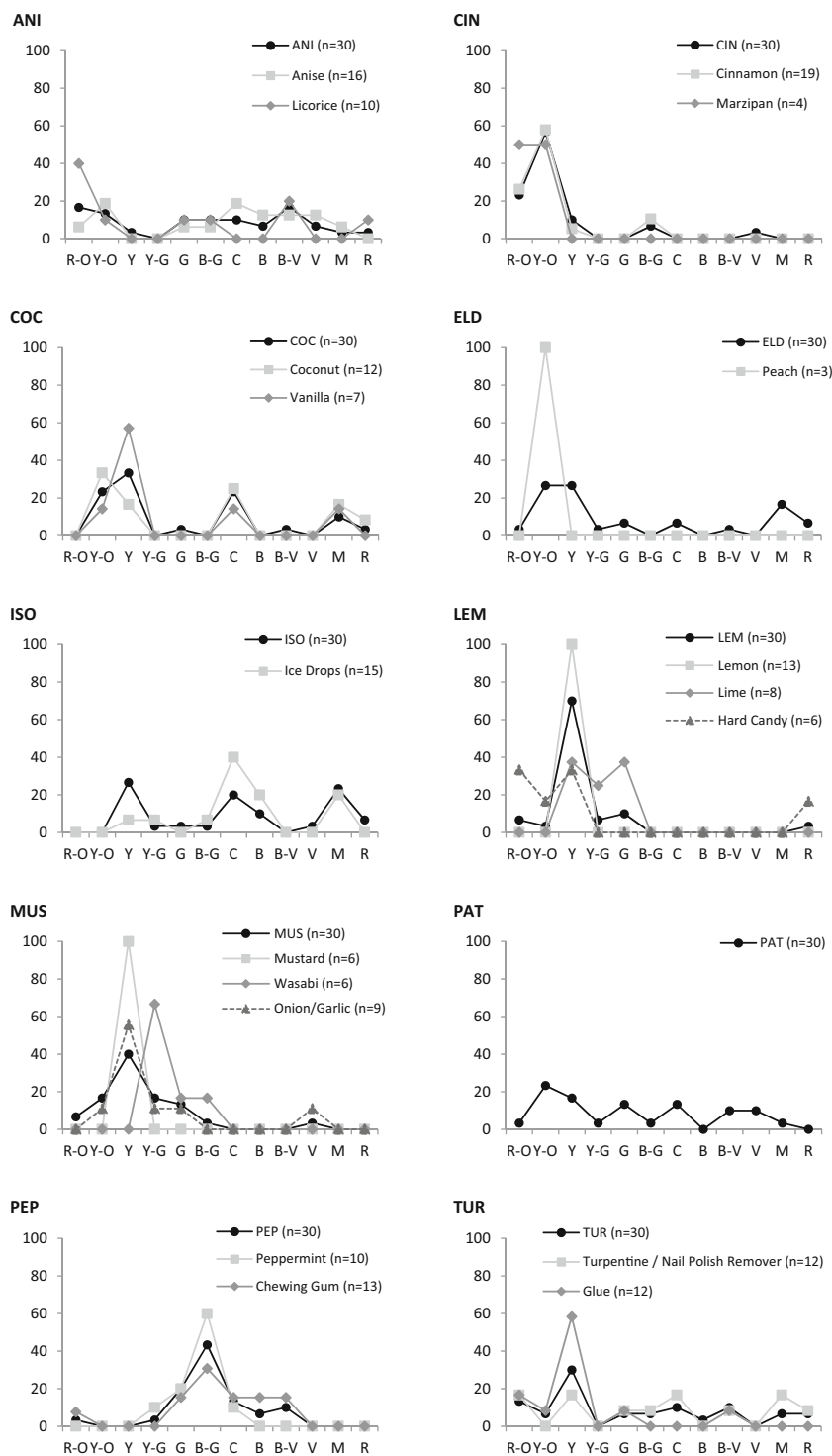
LEM) varied significantly from the scales midpoint and the influence of different source names was marginal.

These results may indicate that (a) shape (different from color) associations are generally less affected by semantic principles. However, it may imply as well that (b) untrained subjects are not capable or willing to link theoretical ratings of shape to the visual imagery of an odor. Evidence for the latter is provided

by the finding, that—among all shape dimensions—the *abstract–realistic dimension* shows the highest correlation with familiarity scores ($r_s = 0.295$; $p < 0.01$). That is, the evaluation of abstractness may not refer to an imagined shape but more likely to the question "How realistic, i.e. recognizable, is the smell to me?" If this is true, participants should have rated odors higher on this dimension if they were able to identify
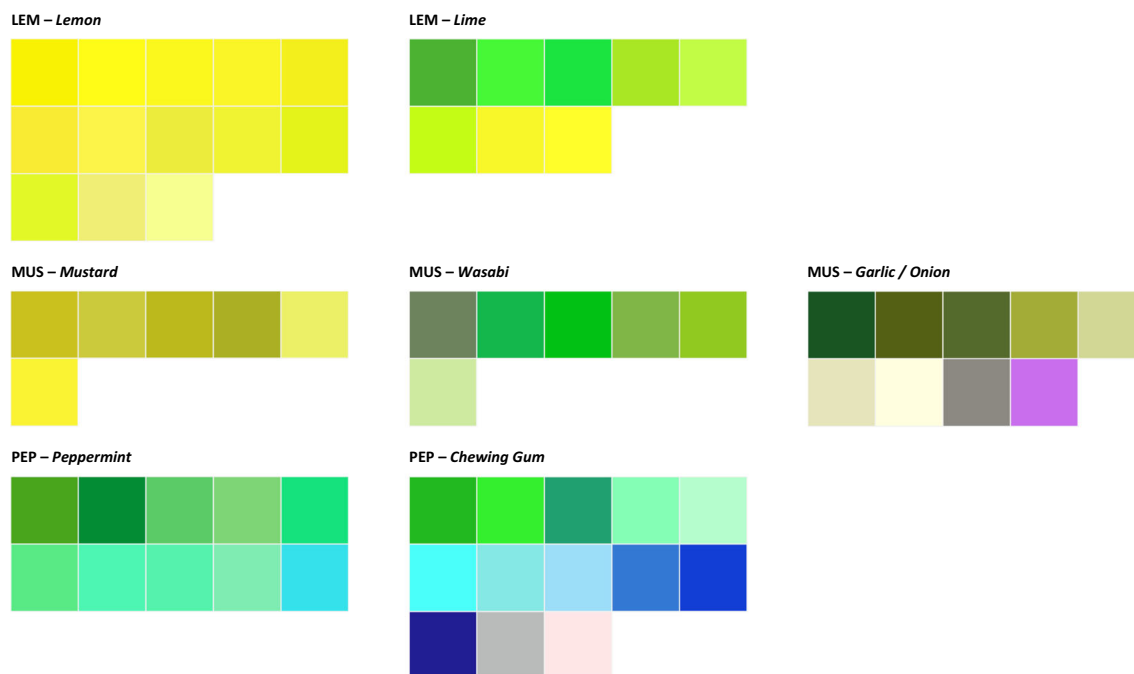
Fig. 4 Color matching as function of associated odor source: exemplary color patches for three odors. Patches are sorted by color, not by subject

them correctly. We therefore contrasted the ratings of incorrectly named odors against correct identifications or near misses and found a significant difference in *abstract–realistic* ratings ($t(298) = -6.298$; $p < 0.001$; $M_{incorrect} = 3.03$, $SD_{incorrect} = 2.03$, $M_{correct} = 4.67$, $SD_{correct} = 2.28$).

Image Analysis

Interestingly, the most salient characteristic of many images was their concreteness: despite an explicit demand not to draw real items, subjects frequently visualized tangible objects rather than abstract patterns or shapes. And these objects often depicted, not surprisingly, an odor source or a related item (like a palm for COC). That is, visualized shape associations were in this setting strongly affected by the participants' odor source considerations which resulted in findings that

contradict previous research. The mappings of LEM, for example, were often curved rather than angular and sharp as reported by Hanson-Vaux et al. (2013); they displayed circles or more or less obvious lemons (Fig. 7a). The same pattern was found for PEP (illustration of leaves or chewing gum, Fig. 7b), MUS (illustration of mustard "blobs" or onion and garlic bulbs, Fig. 7c), and ISO (illustration of candy, Fig. 7d). Every time, an odor source could be named and imagined with certain ease, this was expressed in the visualization. Note, that in several cases, visualizations illustrated the correct odor source, but subjects were unable to name this odorant with accuracy in the subsequent identification task.

In order to analyze shape features of the images in more detail, images were rated on the six shape dimensions used in the evaluation task—by one well-informed and two naive raters. Images were decolorized and presented on a computer screen. Naive subjects were untrained and unaware that the images originated from the visualization of odors. Assignment and order of images were fully randomized. Raters repeated the evaluation of all 300 images 7 days after the first session, i.e., eventually each drawing was rated six times (three raters, two sessions). Intra-rater reliability (0.85–0.92 across 1 week) as well as inter-rater reliability (0.74–0.84) reached adequate levels. Scores of the six ratings were averaged for each image to display results for the shape dimensions across all odors (Fig. 6).

At a first glance, the shape profiles created from image analysis show very similar patterns for all ten odors. To test whether odor makes a difference in what subjects visualize (with respect to these dimensions), we again applied repeated-measure ANOVAs (Greenhouse–Geisser corrected)

Table 5 Results of repeated-measure ANOVAs for shape dimensions: the subjects' ratings (left) and image analysis (right)

Dimension	Subjects' ratings		Image analysis	
	F	p	F	p
"Maluma"–"Takete"	4.353	< 0.001	2.646	0.014
Regular–irregular	3.510	0.003	2.925	0.009
Small–big	1.590	0.144	1.067	0.385
Abstract–realistic	4.084	< 0.001	0.510	0.800
Simple–complex	3.029	0.007	1.222	0.296
Geometric–organic	8.044	< 0.001	2.206	0.046

Table 6 (a) Spearman correlation between perceptual and shape dimension ratings. (b) Spearman correlation between perceptual and image analysis ratings

Dimension	M–T	R–I	S–B	A–R	S–C	G–O
a						
Intensity	0.348**	0.203**	0.190**	− 0.074	0.189**	− 0.151**
Pleasantness	− 0.370**	0.329**	− 0.099	0.345**	− 0.264**	0.261**
Edibility	− 0.235**	− 0.255**	− 0.139*	0.374**	− 0.205**	0.296**
Temperature	− 0.344**	0.030	0.075	0.097	− 0.027	0.405**
Masculinity–femininity	− 0.412**	− 0.101	− 0.041	0.026	− 0.047	0.228**
b						
Intensity	0.134*	0.046	0.026	− 0.106	0.058	− 0.081
Pleasantness	− 0.141*	− 0.091	− 0.049	0.031	− 0.007	0.087
Edibility	− 0.124*	− 0.034	− 0.035	0.038	0.040	0.141*
Temperature	− 0.089	0.200**	0.034	− 0.058	0.050	0.083
Masculinity–femininity	− 0.197**	0.054	0.076	0.079	0.055	0.131*

M–T = ⌣ ⌣ , R–I regular–irregular, S–B small–big, A–R abstract–realistic, S–C simple–complex, G–O geometric–organic

*p < 0.05; **p < 0.01

and found significant differences for only three dimensions (Table 5). On each dimension post hoc tests (Bonferroni corrected) revealed a significant difference for only one pair of odors (in brackets) *Maluma–Takete* (PEP–LEM, p < 0.001), *regular–irregular* (MUS–LEM, p = .028), and

geometric–organic (ISO–TUR, p = .067). Also, when directly comparing the results of the subjects' shape ratings and the image analysis, correlations ranged from zero to moderate association (Online Resource 5). The highest correlation was found for the angularity dimension ($r_s = 0.319$; $p < 0.01$),

Fig. 5 a Mean scores of angularity and intensity ratings across odors. b Mean scores of angularity and pleasantness ratings across odors
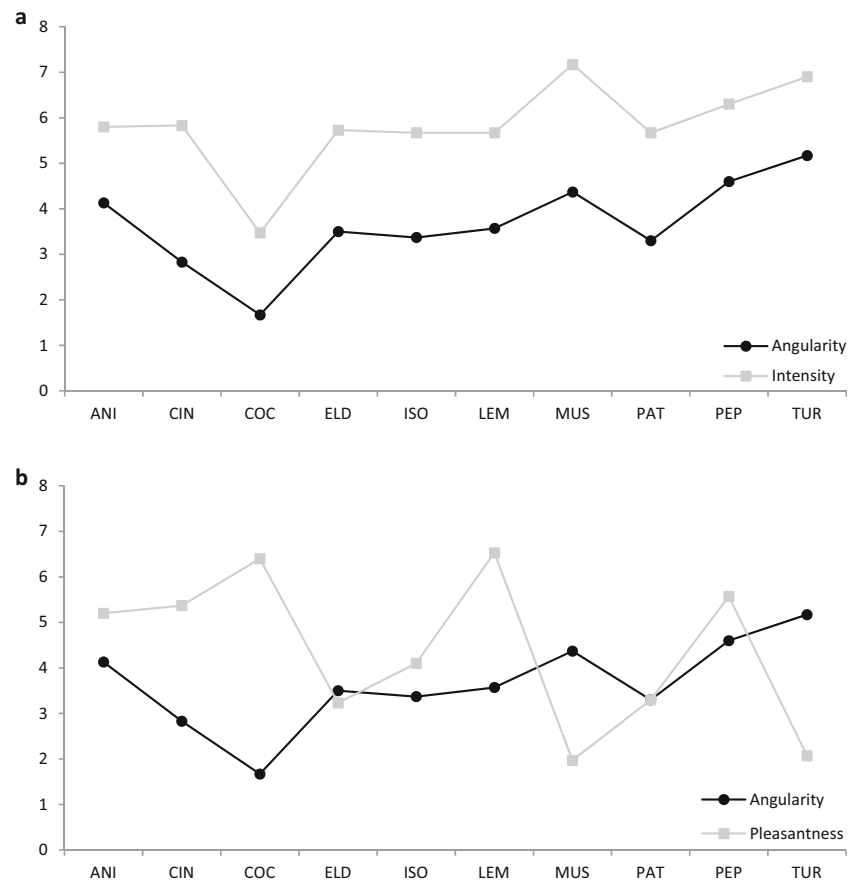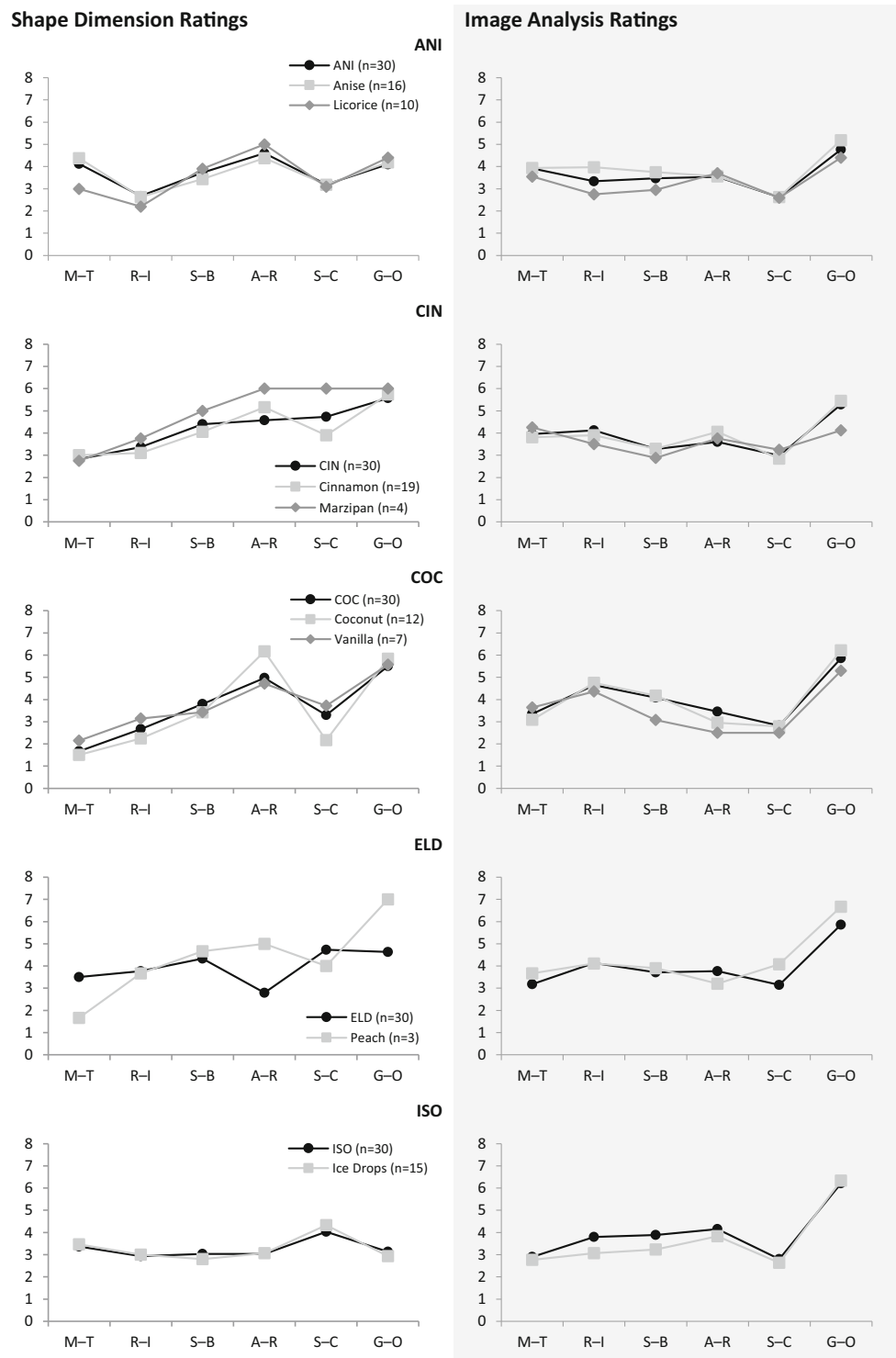
Fig. 6 Shape profiles for each odor across all judgments and as a function of assumed odor source name, left column: shape dimension ratings; right column: ratings from image analysis

probably because the visible symbols prompted participants to really visualize a given odor compared to the verbally anchored dimensions.

In comparison to the dimension ratings, images tended to be rather *irregular* (8 of 10 odors and 160 of 300 cases with

higher R–I ratings for images), *simple* (10 of 10 odors and 180 of 300 cases with lower S–C ratings for images), and *organic* (9 of 10 odors and 176 of 300 cases with higher G–O ratings for images). While shape ratings correlate moderately with intensity and pleasantness scores, we found no relationship
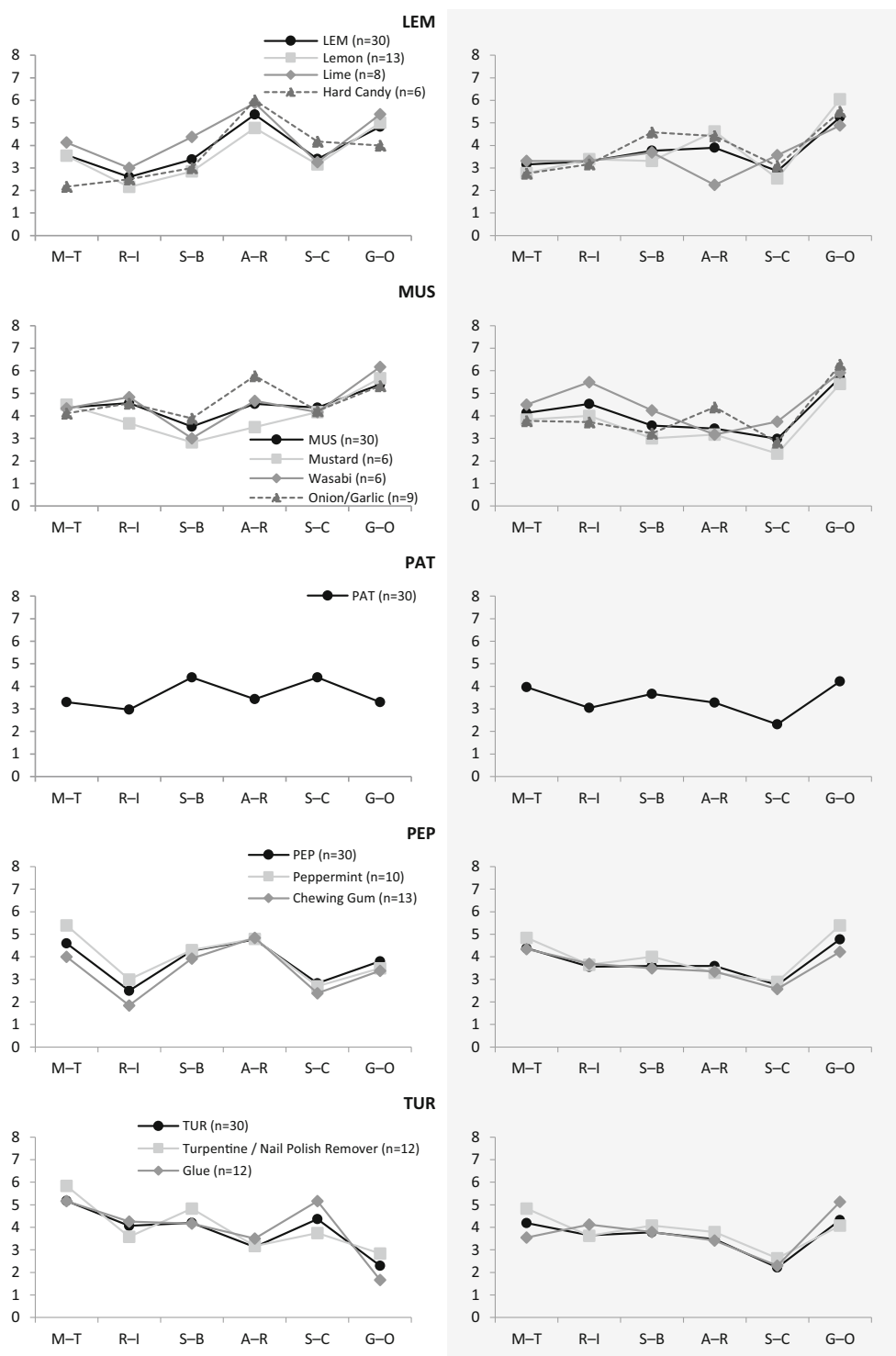
Fig. 6 (continued)

between any perceptual dimension and the image analysis results (Table 6(b)).

The image analysis revealed two basic findings: (a) drawings varied only marginally across odors when a comparison was solely based on the shape-related dimensions we applied. (b) Rating and freely drawing the shape association of an odor produced very different results when a comparison was based on the shape-related dimensions we applied. That is rating and creating a shape from an odor perception result very different things.

What can we learn from this divergence? First, we might question which aspect of odor–shape associations has been actually assessed by shape dimension ratings in previous studies

a

b

c

d
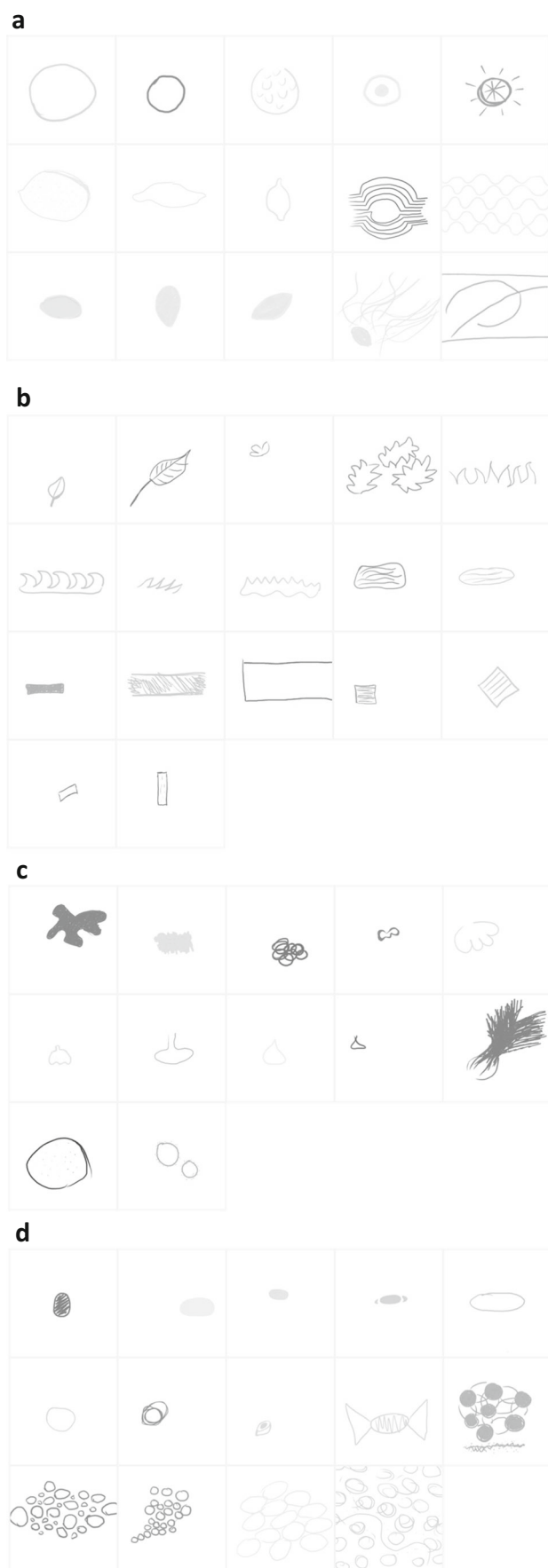
◀ **Fig. 7 a** Image examples for odor sample LEM showing lemons and limes. **b** Image examples for odor sample PEP showing leaves or chewing gum. **c** Image examples for odor sample MUS showing mustard blobs or onion and garlic bulbs. **d** Image examples for odor sample ISO showing candy

and—with respect to our approach—whether these dimensions are useful to capture shape features of free drawings in a proper sense. It appears that these dimensions focus on *how* something is visualized rather than *what* is visualized. They, hence, overlooked the content of an image and differences in its semantics. When we, however, expect that color as well as shape visualizations were strongly affected by semantic considerations, it is not surprising to find very similar shape dimension profiles for very diverse drawings of patterns and shapes. In future research, a different measurement approach, i.e., way to analyze images in terms of their content should be applied.

Discussion

The results of the present study confirm a range of previous findings on the existence of reliable crossmodal associations between smell and vision. Moreover, it supports a better understanding of the principles behind these crossmodal matchings by demonstrating how a person's considerations about an odor or more specifically about its source may affect associations with colors and shapes. Indications for the lexical–semantic nature of odor associations have been found in several empirical works on odor–color mappings (Table 1(a)). But these insights have been repeatedly discarded with reference to (a) a general difficulty of untrained subjects to name odors correctly (Cain 1979; Cain and Potts 1996; Cain et al. 1998; Desor and Beauchamp 1974; Wijk and Cain 1994) or (b) visual associations that did not reflect an odor's source one to one (Maric and Jacquot 2013). These arguments, however, disregard that a lexical–semantic involvement does not require the correct identification of an odor, but rather any kind of source consideration triggered by an odorous stimulus. Olofsson and Gottfried (2015) assumed that (source) object representations manifest on an early stage of olfactory encoding, presumably even ahead of valence encoding. This assumption has been supported by the finding that behavioral responses are slower when decisions are based on accessing the valence of an odor compared to odor object features (Olofsson 2014; Olofsson et al. 2013). That is, crossmodal associations (of any dimension) might be initiated by an olfactory sensation even along with poor odor naming. Further, crossmodal mappings may not simply mirror the visual features of a natural source but rather express real experiences with certain odors. That is, even, if we do not find a visible one to one relation to an object that emanates an odor, a matching can still reflect a source-based color matching strategy.

If mentioned, semantic principles of odor mapping have been a sideline in many publications and authors have usually called for additional empirical evidence to better understand these mechanisms. Basically, if odor–color matching depends on odor source naming, (a) colors should differ with changing labels for identical odors but (b) only in cultures and languages that classify odors with respect to their sources rather than in abstract terms. Interestingly, both assumptions have received empirical evidence: (a) Zellner et al. (2008) conducted one of the first studies to purposefully asses the influence of semantic labels attached to an odor. They asked subjects to rate six fine fragrances on the dimensions masculinity/femininity and to select appropriate colors for each odor. In agreement with our hypothesis, they reported "The choice of masculine and feminine colors as corresponding to an odor is based on thinking about the odor as masculine or feminine" (p. 220)—even though subjects were asked to rate masculinity and femininity only after color matching. (b) Valk and colleagues (2016) evaluated odor–color associations for Western European participants as well as for speakers of Maniq and Thai—two languages that use abstract terms comparably often as source-based terms to describe odors. Their findings support the assumption that color mappings are reliable and object related when a language depends on source references while associations are less consistent and object independent in abstract languages: "This suggests an important strategy for assigning colors to odors via language" (p. 8).

In accordance with these studies, our results promote the assumption of lexical–semantic principles beneath odors associations. However, considering our data, this approach may fall short in explaining both color and shape mappings.

Odor–Color Associations

Odors produce distinct and reliable color profiles. These color mappings often reflect the imagery of a natural source and—more interestingly—they change with source labels. That is, different identifications of the same sensory input go along with different color selections and these mappings are equally consistent. Color or odor terms were neither presented nor requested in any task in order to avoid an active recall of semantic associations. However, the results suggest that smelling an odor triggers identification attempts (automatically) and that odor source assumptions shape the characteristics of visual mappings. When a sample was identified as lemon, participants predominantly opted for yellow, while they preferred green when naming it lime.

Color mappings may, however, be rooted on a very abstract level. Rather than simply reflecting the imagery of a natural source they may be based on associated products and their packaging (CIN—red wrapped chewing gum) or the context of their use in everyday life, on activities or related objects (TUR—bright pink of nail polish) or on brands and how they are represented in advertising (COC—clear blue Caribbean Sea; coconut-flavored confectionery *Raffaello* has been advertised in a Caribbean beach setting for more than two decades). Meanwhile, uncommon odors produce less meaningful and inconsistent color matchings. Their color profiles provide hints (not evidence) that hue mappings might be mediated by pleasantness evaluations as it has been reported by recent studies (Fiore 1993; Hanson-Vaux et al. 2013; Jacquot et al. 2016; Kemp and Gilbert 1997; Maric and Jacquot 2013; Schifferstein and Tanudjaja 2004; Zellner et al. 2008)—when odor source information is mentally not accessible with ease. We assessed the uncommon odor samples PAT and ELD (0% correct identifications each) and contrasted the color mappings of more and less pleasant and intense odor ratings, respectively. Data was divided in two subgroups based on median split for pleasantness and intensity scores. Although samples were too small for further statistical analyses, the less and more pleasant evaluations went along with different hue profiles for PAT, but not for ELD.

We could not find a link between odor quality and color lightness or saturation, although other studies have often reported such mappings. This does, however, not indicate a missing relationship. It may rather be due to the study approach that expected untrained participants to first choose a color hue and thereafter modify saturation and lightness. It is likely that subjects were simply not able (because not used to) to vary all three-color dimensions and thus focused on color hue, leaving lightness and saturation mostly unattended. Interestingly, we found a relationship between the temperature (score) and color hue matched with a given odor. However, we did not find that this relation was based on learned color–temperature relations (blue–cold, red–hot). It rather reflected the imagined gustatory effect (cool, refreshing, hot, and spicy) of an associated food or even the imagined temperature of a related context. While PEP ($M = 1.87$; $SD = 1.33$) and ISO ($M = 2.20$; $SD = 1.81$) were rated cold, CIN ($M = 6.10$; $SD = 1.73$) was regarded warm and so was COC ($M = 5.30$; $SD = 1.93$). These relations only partly overlap with our everyday life color–temperature conjunction, for example, when product packaging is based on this learned linkage (ISO—ice drops—cooling effect—blue packaging). On the one hand, this provides another hint for our assumption of source-based crossmodal associations; on the other hand, it shows how odor identifications may prompt taste associations that additionally affect color mappings (Spence et al. 2015).

Odor–Shape Associations

The few published studies on odor–shape correspondences come to the very clear conclusion that shape mappings are predominantly mediated by hedonics and perceived intensity (presumably in the sense of trigeminal stimulation). When subjects were asked to pair abstract symbols and odors (Seo

et al. 2010) or to rate odors against an angularity dimension (Crisinel et al. 2013; Hanson-Vaux et al. 2013), pleasant odors were usually associated with round, organic forms, while unpleasant, intense odors were regarded as more angular and geometric. In these studies, shape mappings were approached by the comparison of an olfactory percept to two or more abstract symbols that varied in angularity (rather than size, complexity, abstractness etc.). While pleasantness and intensity may be indeed important factors of associations between odors and more or less angular symbols, the results additionally provide indications for the mediating role of taste qualities: odors associated with a sour taste (lemon) have been evaluated as angular, sweet tastes (vanilla) as rounded (Hanson-Vaux et al. 2013; Seo et al. 2010). Interestingly, even then, some findings in previous research suggest that these dimensions may not explain the crossmodal mappings thoroughly: in the study of Hanson-Vaux et al. (2013), for example, odors of apple, blackberry, raspberry, or apricot and, what is more, mushroom was rated as more rounded and organic than honey, caramel, or almond while they have been evaluated as more pleasant or sweet elsewhere (Chrea et al. 2004; Ferdenzi et al. 2013). In these cases, lexical–semantic principles could assist in understanding these mappings. However, these inferences are no more than speculations at this point.

In our study, we took a very different approach on shape mappings and asked subjects to rate odors on several shape-related dimensions and to create rather than match visual associations. Different to color mappings, we cannot simply attribute the results to the imagery of an odor's source, as dimensions ratings and free drawings produced very dissimilar results. At this point, we may not judge with certainty which approach-captured shape features in the proper sense. In agreement with previous studies, we found moderate relations between shape ratings, primarily the angularity scale, and pleasantness or intensity, respectively, indicating a mediating role for crossmodal mappings. Each odor produced a somewhat distinct rating pattern on shape dimensions, although differences between samples and especially for different identifications of one and the same odor were less emphasized than for color mappings. Meanwhile, in the analysis of drawings, odors did not make a difference along these dimensions. This does not indicate that images did not differ, but variance was not systematically detected between odors. In fact, we observed that participants (despite an explicit demand not to do so) often tended to visualize figurative shapes and odor objects. However, these differences in image content were not assessed by the dimension-based picture analysis: The outline of a peppermint leaf and a lemon might produce comparable scores on angularity, complexity, abstractness, etc., although—concerning semantics—they display completely different things. For now, it remains difficult to contrast results of odor–shape matchings, odor-based shape ratings, and odor-based drawings in order to understand the nature of odor associations. Future research should thus address the question of how shape association can actually be measured and find reliable means to assess the semantic content of an image and its relation to an odor source. We should, however, keep in mind, that for naive participants, source-based crossmodal associations might not automatically show in the visualization of a natural source, but will be based on related food or drinks, products or brands, contexts of personal usage, or even advertised settings.

It appears like an absurdity of odor processing: Though we are lacking an odor-specific vocabulary odor processing seems to be even more language dependent than any other sensory modality. On closer examination, this dependency is anything but absurd: as we rely on a "borrowed language" that mainly refers to an odor's source and its non-olfactory features (for a review, see Deroy et al. (2013) and Kaeppler and Mueller (2013)), these features from other sensory modalities become an integral part of odor processing and evaluation. We find the effect of this dependency in the lexical–semantic nature of crossmodal associations between odor and vision.

Future research on crossmodal associations may focus on the mediating role of both pleasantness and intensity for odors that are difficult to identify and do not elicit labels (or related context information) with ease. Further empirical work is especially needed on odor-induced shape associations as well as on the bi-directionality of associations between olfaction and vision, as it has been proven for taste qualities (Spence et al. 2015).

Compliance with Ethical Standards

References

Blackwell L (1995) Visual cues and their effects on odour assessment. Nutr Food Sci 95:24–28

Cain WS (1979) To know with the nose: keys to odor identification. Science 203:467–470

Cain WS, Potts BC (1996) Switch and bait: probing the discriminative basis of odor identification via recognition memory. Chem Senses 21:35–44

Cain WS, de WR, Lulejian C, Schiet F, See L-C (1998) Odor identification: perceptual and semantic dimensions. Chem Senses 23:309–326

Charney, S., Levitan, C.A., Palmer, S.E., &Schloss, K.B. (2015). The smell of jazz: crossmodal correspondences between music, odor, and emotion. CogSci

Chrea C, Valentin D, Sulmont-Rossé C, Ly Mai H, Hoang Nguyen D, Abdi H (2004) Culture and odor categorization: agreement between cultures depends upon the odors. Food Qual Prefer 15:669–679

Collier GL (1996) Affective synesthesia: extracting emotion space from simple perceptual stimuli. Motiv Emot 20:1–32

Crisinel A-S, Jacquier C, Deroy O, Spence C (2013) Composing with cross-modal correspondences: music and odors in concert. Chem Percept. 6:45–52

Crisinel A-S, Jones S, Spence C (2012) 'The sweet taste of maluma': crossmodal associations between tastes and words. Chem Percept. 5:266–273

Crisinel A-S, Spence C (2010) As bitter as a trombone: synesthetic correspondences in nonsynesthetes between tastes/flavors and musical notes. Atten Percept Psychophys. 72:1994–2002

Dematte ML, Sanabria D, Spence C (2006) Cross-modal associations between odors and colors. Chem Senses 31:531–538

Deroy O, Crisinel A-S, Spence C (2013) Crossmodal correspondences between odors and contingent features: odors, musical notes, and geometrical shapes. Psychon Bull Rev 20:878–896

Desor JA, Beauchamp GK (1974) The human capacity to transmit olfactory information. Percept Psychophys 16:551–556

Dubois D, Rouby C (2002) Names and categories for odors: the veridical label. In: Rouby C, Schaal B, Dubois D, Gervais R, Holley A (eds) Olfaction, taste, and cognition. Cambridge University Press, Cambridge (GB), pp 47–66

Engen T (1972) The effect of expectation on judgments of odor. Acta Psychol 36:450–458

Ferdenzi C, Roberts SC, Schirmer A, Delplanque S, Cekic S, Porcherot C, Cayeux I, Sander D, Grandjean D (2013) Variability of affective responses to odors: culture, gender, and olfactory knowledge. Chem Senses 38:175–186

Fiore AM (1993) Multisensory integration of visual, tactile, and olfactory aesthetic cues of appearance. Cloth Textiles Res J 11:45–52

Gilbert AN, Martin R, Kemp SE (1996) Cross-modal correspondence between vision and olfaction: the color of smells. Am J Psychol 109:335–351

Hanson-Vaux G, Crisinel A-S, Spence C (2013) Smelling shapes: crossmodal correspondences between odors and shapes. Chem Senses 38:161–166

Jacquot M, Noel F, Velasco C, Spence C (2016) On the colours of odours. Chem Percept. 9:79–93

Kaeppler K, Mueller F (2013) Odor classification: a review of factors influencing perception-based odor arrangements. Chem Senses 38:189–209

Kemp SE, Gilbert AN (1997) Odor intensity and color lightness are correlated sensory dimensions. Am J Psychol 110:35–46

Knöferle K, Spence C (2012) Crossmodal correspondences between sounds and tastes. Psychon Bull Rev 19:992–1006

Lavin JG, Lawless HT (1998) Effects of color and odor on judgments of sweetness among children and adults. Food Qual Prefer 9:283–289

Levitan CA, Ren J, Woods AT, Boesveldt S, Chan JS, McKenzie KJ, Dodson M, Levin JA, Leong CXR, van den Bosch JJF (2014) Cross-cultural color-odor associations. PLoS One 9:e101651

Majid A (2015) Cultural factors shape olfactory language. Trends Cogn Sci 19:629–630

Majid A, Burenhult N (2014) Odors are expressible in language, as long as you speak the right language. Cognition 130:266–270

Maric Y, Jacquot M (2013) Contribution to understanding odour–colour associations. Food Qual Prefer 27:191–195

Marks LE (1996) On perceptual metaphors. Metaphor Symb Act 11:39–66

Marks LE (2004) Cross-modal interactions in speeded classification. In: Calvert GA, Spence C, Stein BE (eds) Handbook of multisensory processes. MIT Press, Cambridge (MA), pp 85–106

Martino G, Marks LE (2000) Cross-modal interaction between vision and touch: the role of synesthetic correspondence. Perception 29:745–754

Martino G, Marks LE (2001) Synesthesia: strong and weak. Curr Direct Psychol Sci 10:61–65

Morrot G, Brochet F, Dubourdieu D (2001) The color of odors. Brain Lang 79:309–320

Nehmé L, Barbar R, Maric Y, Jacquot M (2016) Influence of odor function and color symbolism in odor–color associations: a French–Lebanese–Taiwanese cross-cultural study. Food Qual Prefer 49:33–41

Olofsson JK (2014) Time to smell: a cascade model of human olfactory perception based on response-time (RT) measurement. Front Psychol 5:33

Olofsson JK, Bowman NE, Gottfried JA (2013) High and low roads to odor valence? A choice response-time study. J Exp Psychol Hum Percept Perform 39:1205–1211

Olofsson JK, Gottfried JA (2015) The muted sense: neurocognitive limitations of olfactory language. Trends Cogn Sci 19:314–321

Österbauer RA, Matthews PM, Jenkinson M, Beckmann CF, Hansen PC, Calvert GA (2005) Color of scents: chromatic stimuli modulate odor responses in the human brain. J Neurophysiol 93:3434–3441

Pauli P, Bourne LE, Diekmann H, Birbaumer N (1999) Cross-modality priming between odors and odor-congruent words. Am J Psychol 112:175–186

Sakai N (2005) The effect of visual images on perception of odors. Chem Senses 30:i244–i245

Schifferstein HNJ, Tanudjaja I (2004) Visualising fragrances through colours: the mediating role of emotions. Perception 33:1249–1266

Seo H-S, Arshamian A, Schemmer K, Scheer I, Sander T, Ritter G, Hummel T (2010) Cross-modal integration between odors and abstract symbols. Neurosci Lett 478:175–178

Spector F, Maurer D (2012) Making sense of scents the colour and texture of odours. Seeing Perceiving 25:655–677

Spence C (2011) Crossmodal correspondences: a tutorial review. Atten Percept Psychophys 73:971–995

Spence C, Deroy O (2013) How automatic are crossmodal correspondences? Conscious Cogn 22:245–260

Spence C, Wan X, Woods A, Velasco C, Deng J, Youssef J, Deroy O (2015) On tasty colours and colourful tastes? Assessing, explaining, and utilizing crossmodal correspondences between colours and basic tastes. Flavour 4:70

Stevenson RJ, Rich A, Russell A (2012) The nature and origin of cross-modal associations to odours. Perception 41:606–619

Streeter NL, White TL (2011) Incongruent contextual information intrudes on short-term olfactory memory. Chem Percept 4:1–8

de Valk JM, Wnuk E, Huisman JLA, Majid A (2016) Odor-color associations differ with verbal descriptors for odors: a comparison of three linguistically diverse groups. Psychon Bull Rev:1–9

de Wijk RA, Cain WS (1994) Odor quality: discrimination versus free and cued identification. Percept Psychophys 56:12–18

Zellner DA (2013) Color–odor interactions areview and model. Chem Percept. 6:155–169

Zellner DA, Bartoli AM, Eckard R (1991) Influence of color on odor identification and liking ratings. Am J Psychol 104:547–561

Zellner DA, Kautz MA (1990) Color affects perceived odor intensity. J Exp Psychol Human Percept 16:391–397

Zellner DA, McGarry A, Mattern-McClory R, Abreu D (2008) Masculinity/femininity of fine fragrances affects color-odor correspondences: acase for cognitions influencing cross-modal correspondences. Chem Senses 33:211–222

Zellner DA, Whitten LA (1999) The effect of color intensity and appropriateness on color-induced odor enhancement. Am J Psychol 112:585–604