Language Mediation of Odor Processing: Impact of Verbal Codes on Olfaction

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Table of Content

Preface on Scientific Style and Format

The format of in–text citations and reference lists as well as spelling and writing style in all articles comply with standards defined by *Chemical Senses* and *Chemosensory Perception*. For the sake of consistency, this standard has been applied throughout the synopsis as well.

Synopsis

When addressing the question of how odors are processed and represented in the human perceptual system, researchers have commonly stumbled upon a very basic and particularly challenging issue: the lack of means to compare and describe odors accurately, or to estimate their degree of similarity with precision. Up until now, olfactory research has assessed the perceptual mechanisms of a sensory modality without a valid arrangement of the stimuli concerned. Guided by the conceptions in other sensory modalities, olfactory scientists have tried to establish links between perceptual qualities and the features of the sensory system, or the chemical structure of odorant molecules, respectively. While structure–odor relationships have been established successfully for basic perceptual judgements like similarity (Snitz et al. 2013) or pleasantness (Kermen et al. 2011; Khan et al. 2007; Zarzo and Stanton 2006), the general principles beneath these links have not been specified yet. Predicting the odor quality of a given molecule remains nearly impossible, not to mention any kind of classification system that defines the sensory space by mutually exclusive stimuli categories or a preferably small number of independent dimensions. The accomplishments by more recent applications of machine learning strategies have been elusive (Keller et al. 2017; Poivet et al. 2018), as a crucial question remains unanswered: What do we actually perceive? Before we can link structural properties to perceptual qualities, a consensus on just these perceptual qualities is needed.

Arranging percepts has mostly been based on perception–based odor evaluations that occupied odor research throughout the 20th century. Several systems have been proposed, some have been considered plausible, none has sustained empirical validation. The difficulties of empirical research to capture odor perceptions adequately may be a crucial factor to this lack of consent. In the paper *"Odor classification: a review of factors influencing perception–based odor arrangements"*, we assessed how basic characteristics of study design, sampling, and data analysis have been influencing the outcomes of perception–based odor classification studies over several decades. In a review of 28 studies, we identified four basic issues that have pre–defined arrangements considerably:

Subjects: The reliability of perceptual judgments across both time and individuals is crucial for the dependability of perception–based odor arrangements. While olfactory ratings are quite stable across short and moderate periods of time (Cain et al. 1998; Dravnieks 1982; Jeltema and Southwick 1986; Lawless and Glatter 1990), long–term reliability is usually affected by age–related physiological changes (Larsson et al. 2000; Wysocki and Gilbert 1989). Still, odor perception may be considered as a basically archetypic process (Carrie et al. 1999; Dawes et al. 2004), that produces comparable results under equal conditions regarding age, gender, and health status. However, a particular important influence is exerted by a non–physical peculiarity: experience. These differences are most emphasized between societies where aspects of domestic life and nutrition vary considerably (Chrea et al. 2005; Chrea et al. 2004; Ueno 1993). Beyond the percept as such, experience shapes odor–related vocabulary and thus affects how perceptions are verbally expressed. By the time of the study, research on the impact of culture on odor–specific language was sparse. Thus, we primarily considered the influence of an explicitly acquired terminology, i.e., the differences between odor experts and laymen, in verbalizing odors. While odor professionals acquire a set of domain–specific mental classes that facilitate categorical, abstract verbalization, untrained subjects rely on natural language that relates odors to objects, personal experiences, and hedonic evaluations. Therefore, odor arrangements that have been based on data of naive subjects may have likely revealed a hedonic dimension or reflected the lexical classification of odor sources (as fruit, vegetables, seasonings, cleaning compounds and so on) rather than relations of their smells.

Stimuli: The dependability of any classification system is restricted to the explanatory power of the stimuli applied in a study. When specific qualities or perceptual dimensions have been prevalent in an odor set, these features have likely appeared decisive in the arrangement of these odors as well.

Indeed, it is impossible to select a representative sample from a perceptual space when size and dimensionality of this space are unknown. Thus, the decisions on quality and quantity have been quite pragmatic in most studies: Odors have typically been mainly pleasant and related to (familiar) foods, flowers or cosmetic products – in order to facilitate an already demanding task for predominantly untrained subjects. Apart from this, perceived odor qualities depend on a number of factors and change considerably with other odor characteristics like intensity (Gross–Isseroff and Lancet 1988; Laing et al. 2003) or pleasantness (Distel et al. 1999), with contextual effects (Hulshoff Pol et al. 1998), personal experience (Ayabe–Kanamura et al. 1998; Chrea et al. 2005; Chrea et al. 2004) or verbal cues (Herz and Clef 2001).

Method of data collection: In most cases, data has been collected by asking subjects to rate odors against either a list of attributes (verbal) or other odors (non–verbal). Each approach is rooted in distinct premises that have affected the meaningfulness of data: While verbal references leave little room for interpretation by defining comparison criteria explicitly, they may also over– and underrepresent quality aspects, or restrict subjects to features that might not appropriately reflect their perceptual impression. In non–verbal approaches, subjects define relevant criteria for similarity ratings implicitly: these may change with every new pair of odors and reflect particularly outstanding characteristics. Findings on the interrater reliability of both approaches have been inconsistent (Berglund et al. 1973; Dravnieks 1982; Higuchi et al. 2004; Stevens and O'Connell 1996).

Method of data analysis: A classification of odors has been commonly considered as an *n*–dimensional space where odors can be described and compared by their position within this arrangement and to each other, respectively. Researchers have typically applied analysis approaches that uncover the underlying structure of complex data sets: multidimensional scaling (MDS), principal component analysis (PCA) and exploratory factor analysis (EFA). All methods are meant to establish a preferably small number of orthogonal dimensions that explain a maximum of variance in the data. As each technique is, however, based on distinct mathematical assumptions, they are not equally appropriate in providing meaningful results for odor classifications. Especially a preference for applying PCA instead of EFA has not been reasonable.

In general, each method leaves room for numerous substantial decisions that produce different result even on the same data (Boelens and Haring 1981; Khan et al. 2007; Zarzo 2008; Zarzo and Stanton 2009). These decisions have been documented and justified in many classification studies only sparsely and thus complicated the assessment of their adequacy.

The list of influencing variables we have identified may not even be comprehensive. Still, it illustrates how perception–based odor arrangements have typically reflected the relations of perceptual qualities as well as the conditions under which these have been assessed. Remarkably, many of the difficulties in establishing these systems have been rooted in one underlying issue: the puzzling relationship between language and olfaction in general. Language has been a recurring aspect among all influencing variables we identified: in the terminology of subjects as well as researchers, in assumed identities of the odors presented, the explicit or implicit verbal demands of different data collection methods and in the interpretation of mathematically derived dimensions or clusters. What is more, the fundamental assumption of any perception–based classification approach has been that (verbally expressed) odor perceptions reliably reflect sensory properties. Interestingly, works from diverse domains of odor research have repeatedly shown that this relationship is rather fragile, and anything but reliable (for a review, see Olofsson and Gottfried 2015; Speed and Majid 2018). The gap between odor sensation and verbal expression is often hard to bridge: While the reference from odors to language is (at least in Western societies) weak (Cain 1979; Engen 1987; Levinson and Majid 2014; Majid 2015; Majid and Burenhult 2014; Olofsson and Gottfried 2015; San Roque et al. 2015; Valk et al. 2017; Wnuk et al. 2017), the reverse impact of verbal processing on olfaction seems powerful (Bensafi et al. 2007; Distel and Hudson 2001; Djordjevic et al. 2008; Herz 2003; Herz and Clef 2001, 2001; Lorig and Roberts 1990; Lundström et al. 2006; Moskowitz 1979; Rolls et al. 2003; Stevenson and Mahmut 2013). Herz (2005) proposed a mechanism of dual coding and argued that effects of language on odor processing are depending on the availability of explicit contextual odor source information. When cues on an odor's identity are not available from the perceptual setting, olfaction may be considered as primarily sensation–driven. Interestingly, in several empirical settings including perception–based classification attempts, odor evaluations have been affected by linguistic or semantic arrangements – even without overt source references or a requirement of odor naming (Carrasco and Ridout 1993; Chastrette et al. 1988; Chrea et al. 2005; Lawless 1989; Prost et al. 2001; Urdapilleta et al. 2006). When fruit odors have been grouped with other fruit odors or flowers with flowers – despite sensory varying codes – these systems have likely reflected the lexical categories of assumed odor sources rather than actual sensory (dis)similarities. That is, language may exert an impact on odor processing also without verbal cues being explicitly provided or visual indications of an odor's source. People may not only react on verbal or visual source cues, they may also search for them in the perceptual context and their memories. As long as we are unable to "think olfactory" (Valk et al. 2017; Wilson and Stevenson 2003, 2006), we need to apply some kind of mental translation. Without abstract concepts, this translation will rely on concrete language and thus initiate odor identification. That is, odor naming might be a crucial step in odor processing – not as an end in itself, but because concrete object concepts permit to mentally process odors beyond basic hedonic or functional judgments (Auvray and Spence 2008; Holley 2002; Sugiyama et al. 2006).

In the paper *"How differences in ratings of odors and odor labels are associated with identification mechanisms"*, I assessed if language effects occur despite the absence of verbal cues and how expectations about an odor's identity shape odor evaluations. More precisely, I investigated whether differences in odor and odor label ratings may be attributed to identification mechanisms, rather than differences in processing of odor sensations and odor names, respectively. I adopted an approach of odor–label comparisons that has been used in several studies to assess the nature of mental odor representations (Breckler and Fried 1993; Carrasco and Ridout 1993; Chrea et al. 2005; Herz 2003). These works have usually substantiated Herz' hypothesis of dual coding as they found significant differences in ratings of odors and ratings of associated odor labels. These dissimilarities have been considered as an evidence for the sensation–driven processing of odors when verbal cues are absent. I was curious if this approach of comparing odors to their true labels had possibly exemplified a comparison of two actually unrelated stimuli. I assumed that subjects would build hypotheses about an odor's identity when rating odors. Given our poor naming ability, these mentally assigned labels would be incorrect in many cases and thus relate to different odorous objects and mental concepts, respectively. Participants (n=56) were asked to rate 20 odor samples on general perceptual dimensions as well as 40 odor quality attributes and to eventually provide an odor source name. In a subsequent session, the same subjects performed the same rating tasks on a set of written (verbal) odor labels. As I wanted to control for incorrect identifications, this set was compiled individually for each participant. It included both the 20 correct odor names (true labels) and – in any case of false odor identification in the first session – the self–assigned labels (identified labels). In the analysis, each odor was related to both its correct and identified label.

In line with earlier studies, ratings of odors and their true labels displayed considerable differences. When these odor ratings were, however, matched to ratings of identified labels, agreement increased substantially. No matter, whether identifications were correct or incorrect, these odor–label pairs showed higher correlations than pairs of odors and their correct (yet not associated) labels in terms of intensity, edibility, and pleasantness ratings. For odor quality descriptions, the impact of odor identification was even stronger. These results indicate that a language–based coding of odors may not be limited to settings where source cues are overtly available. Odor processing is affected by assumptions of an odor's identity and this identity remains tied to an odor's source – a defined, consistent object (Berglund and Höglund 2012; Holley 2002; Majid 2015; Majid and Burenhult 2014; Wijk et al. 1995).

Speaking and thinking of odors refer to a mental representation of episodic and semantic memory content including an object label, that may include a quite volatile olfactory image (Arshamian and Larsson 2014) and relate to further multimodal properties of the source. That is, associations between odors and stimuli from other sensory modalities should not only be stable, but these mappings should be mediated by an odor's identity. I was interested in the mechanisms underlying these crossmodal correspondences. In the paper *"Crossmodal associations between olfaction and vision: color and shape visualizations of odors"*, I assessed linguistic–semantic effects on olfaction from a further research perspective, namely color and shape associations of odors. An extensive body of research has demonstrated consistent mappings between odors and specific stimuli, classes or dimensions of other sensory modalities, especially vision. I assumed that crossmodal mappings of odors would be language–mediated, that is, visual associations would primarily reflect visible features of assumed source objects and vary with different identifications of the very same smell.

To assess crossmodal visual mappings, researchers have typically asked participants to match odors to a given set of colors or shapes. I wanted to introduce a novel approach to obtain a more holistic impression of visual odor matches. I asked a total of 30 participants to display their visual associations on a drawing tablet, freely deciding on color and shape. Additionally, subjects rated odors on general as well as shape–related dimensions and eventually provided a verbal label for each of the ten odors. In line with a range of previous studies, the results demonstrated the existence of stable mappings between olfaction and vision. Moreover, they suggested that expectations about an odor's identity and the multisensory knowledge we have acquired on it, affect the visual associations of an odor.

Color selection was non–random for easy–to–label odors and resembled the appearance of their assumed source, independent from the accuracy of this label. For less familiar odors, color mappings were rather inconsistent but still then reflected features of objects or typical contexts of application. Color matching was not mediated by pleasantness or intensity ratings. Thus, a repeatedly reported hedonic principle beneath crossmodal associations could not be confirmed for this odor set.

Results of shape associations were less conclusive. In order to compare shape ratings and shape drawings on a joint metric, I asked three raters to judge each image on the shape dimensions of the rating task. While shape ratings varied with odor identity, the shape profiles established from images displayed very similar patterns across odors. Correlations between both shape measures were, at most, moderate and raised the question whether each approach had actually captured very distinct aspects of shape. Images often displayed concrete objects. But quantifying these semantic concepts by ratings on shape–related dimensions left a major part of the differences between drawings unnoticed.

These findings, once again, exemplified how psychological phenomena have been susceptible to the methods scientists have applied to investigate them. A thorough reflection on these aspects may not only allow for a better control in study settings; it will also improve the understanding of the constructs under consideration and more fundamental issues. The link between language and olfaction is one of these fundamental issues. The critical importance of linguistic–semantic effects that I found in the review of perception–based classification studies has drawn my attention to this topic. The two subsequent empirical articles have been devoted to the mediating role of language in different domains of odor processing. I generally assumed that verbal codes have a major impact on odor processing, that the mental processing of odors is commonly related to their language–based identity and semantic conceptualizations. According to this assumption, the processing of odors should generate percepts that are identity–matching, rather than sensation–matching. That is, judgements of odors should be rooted in the concept of a specific object, that could be accessed by an odor label as well. Further, visual associations of odors should reflect features of an identity–related entity and change when a different identity is matched to the very same sensation, independent of its accuracy. The results of the two studies I conducted provide empirical evidence for these hypotheses. They improve our understanding of odor evaluations and crossmodal correspondences of odors, and thus provide important insights on the principles of odor processing in general. Furthermore, the research reported here raises awareness for the method dependability of scientific findings and facilitates the understanding of some contradicting results in previous studies. Not least, these works contribute to the field of olfactory research by introducing new approaches for assessing different aspects of odor perception.

It has been repeatedly suggested that odors are ineffable: perceptual concepts that resist linguistic coding (Henning 1916; Levinson and Majid 2014; Majid and Kruspe 2018). Per definition, this ineffability comprises low amenability for language in general. Taken together all findings on language effects I have reported, I do not consider olfaction as a non–linguistic cognition. However, these findings also illustrate a highly asymmetric relationship between language and olfaction. Odor processing appears as a perceptual domain of two extremes: language resistance and language dependability. These extremes are not mutually exclusive, but reciprocally conditional. The influence of verbal identity codes on quality ratings or crossmodal mappings is rooted in the very same problem that perception–based classification systems have tried to solve – a terminology that relates to abstract mental categories. The less specific we communicate, the more we need to resort to source–related analogies – in scientific endeavors and everyday life alike.

To define the position of distinct aspects of the olfactory process relative to these extremes is challenging, deeply interesting and not yet resolved. Recently, a growing body of cross–cultural research has increased the complexity of these questions by demonstrating that a poor odor naming found for untrained subjects may not be not universal (Majid 2015; Majid and Burenhult 2014; Majid et al. 2018; Valk et al. 2017; Wnuk et al. 2017). Studies in distinct language areas like the hunter–gatherer communities Jahai and Maniq have demonstrated how superior olfactory performance is associated with a dedicated abstract vocabulary. At the same time, these studies have not yet addressed the reverse direction of this relationship. Cross–cultural research on the influence of verbal codes on odor ratings or crossmodal associations could help us to understand how definite mental concepts moderate the impact of language on perception in comparison to other sensory modalities. Not least, this would advance the discussion on the role and significance of olfaction among the human senses.

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ODOR CLASSIFICATION: A REVIEW OF FACTORS INFLUENCING PERCEPTION–BASED ODOR ARRANGEMENTS

Reference

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

Abstract

Decoding the psychological dimensions of human odor perception has long been a central issue of olfactory research. Odor scientists as well as fragrance professionals have tried to establish comprehensive standards for the description, measurement and prediction of odor quality characteristics. As odor percepts could not be linked to a few measurable physicochemical features of odorous compounds or physiological characteristics of the olfactory system, odor qualities have often been assessed by perception–based ratings. Although they have been applied for more than 5 decades, these psychological approaches have not yielded a comprehensive or generally accepted classification system yet. We assumed that design and methodology of these studies have largely prevented the development of unbiased odor arrangements. To address this issue, we reviewed 28 perception–based classification studies and found that their outcome has been largely determined by 4 influencing factors: (1) interindividual differences in perceptual and verbal abilities of subjects, (2) stimuli characteristics, (3) approaches of data collection, and (4) methods of data analysis. We discuss the effects of each factor in detail and illustrate how odor systems have reflected perceptual qualities as well as the conditions under which these have been assessed.

Introduction

For decades scientists from various disciplines have been searching for an olfactory classification system to define a perceptual space and facilitate objective communication about odors. However, none of the yet proposed odor arrangements has gained wide acceptance or empirical confirmation. There is a lack of means to compare and describe odors accurately or estimate their degree of similarity with precision.

Fallacy of Color Analogy

To illustrate the aims of olfactory classification systems, researchers have often drawn an analogy to color perception, where classes, dimensions and the perception space have been widely studied and well–defined (Chastrette 1998; Haddad et al. 2008b; Harper 1966; Harper et al. 1968; Madany Mamlouk and Martinetz 2004). The dependency of perceived color quality on the wavelength of light and the color specific sensibility of 3 receptor types in the human eye have facilitated the development of low–dimensional, neatly arranged color models. However, the assumption of a single comprehensive color system that is rooted in a natural arrangement of stimuli is a fallacy. A great number of color systems has been developed to accomplish distinct tasks at different levels of detail (for an overview, see Kuehni and Schwarz 2008). These systems have defined (1) color classes and appropriate labels, (2) color dimensions that characterize stimuli by their position on independent measures or (3) color spaces that comprise an assumed entirety of perceivable colors along with meaningful dimensions to distinguish them. The structure of these systems has been anything but axiomatic: The number and character of dimensions or classes has varied with the purpose of each arrangement. While a single, universal color scheme has not been established, nor sought after, the work of many odor researchers has been guided by this ideal conception. However, the potential purposes of odor systems are diverse: They range from the allocation of odors in classes with appropriate labels over the identification of (hierarchical) relations between these classes and the features by which they may be distinguished to the establishing of an appropriate terminology, the depiction of blending rules, perceptual similarities and finally the relations to physical, chemical or functional criteria. Remarkably, in odor research these aims have very often been specified only vaguely. While numerous investigators have tried to establish classification systems to facilitate "differentiation, recognition, and identification" (Harper et al. 1968), most of them have in fact pursued different aims without stating them explicitly. Not surprisingly, neither an accepted system nor a reliable consensus on the basic principles of this arrangement has been reached. In order to attain meaningful outcomes, odor researchers are thus required to carefully address and define the functions of odor systems initially. The work of odor professionals and perfumers has shown how clearly defined tasks can yield valuable schemes of fragrance qualities (Köster 2002).

General Approaches to Olfactory Classification

Given that an association between percepts and a single or a few physical parameters has not yet been found in olfaction (Turin and Yoshii 2003), odor scientists have relied on more subjective attempts in arranging odors. Early odor classification systems were largely based on individual expertise of botanists, chemists or perfumers and have mainly ruled out experimental confirmation (for a review, see Billot and Wells 1975; Chastrette 1998; Chastrette 2002; Harper et al. 1968). The first empirical classifications were only published in the 20th century and were based on 3 main approaches:

1. **Features of the sensory organ:** Several researchers have linked odor qualities to the function of olfactory receptors. Amoore (1967; 1977) assumed an increased detection threshold for specific odorants along with otherwise normal olfactory sensitivity as indication for the malfunction of a particular receptor type. He screened subjects for specific types of anosmia and defined a classification system based on 7 primary odors, each related to a distinct receptor type. Other studies used empirical cross–adaptation approaches to investigate the relation between odor classes and receptor types (Cain 1970; Cain and Polak 1992; Pierce et al. 1993; Pierce et al. 1995; Todrank et al. 1991). However, with the discovery of not less

than 320 odor receptor types in humans (Glusman et al. 2001; Malnic 2004; Zozulya et al. 2001) the idea of a manageable system of primary odors has been largely discarded along with the attempt to establish olfactory classifications from physiological features of the olfactory system.

2. **Features of the sensory stimulus:** The chemical structure of an odorous compound strongly determines its perceived quality. There have been attempts to establish reliable structure–odor relationships (SOR) by linking perceptual properties to molecular vibration (Dyson 1938; Wright 1954; Wright and Michels 1964; Wright and Serenius 1954), molecular weight (Schiffman 1974b), functional group type and position (Goeke 2002; Uchida et al. 2000), molecule shape (Amoore 1963), electron donor (McGill and Kowalski 1977), acid–base character (Brower and Schafer 1975), chain length (Døving 1966), and other physicochemical parameters (for a review, see Rossiter 1996). However, all single measures have failed to reliably predict odor sensations or systematically explain odor perception so far. To address this issue, recent studies have revived early approaches (Amoore et al. 1967; Schiffman 1974a, 1974b; Schiffman et al. 1977) and attempted to include hundreds of physicochemical features in a single measure (Haddad et al. 2008a; Haddad et al. 2008b; Khan et al. 2007). With this approach, Khan et al. (2007) successfully estimated odor pleasantness from a metric of 1664 structural characteristics. Remarkably, Amoore (1971) was able to predict a single quality dimension from structural features already 30 years earlier. Hence, even modern computational approaches and the access to thousands of physicochemical odor attributes has not moved odor researchers closer to meaningful odor arrangements. This is little surprising: To provide valid outcomes, SOR approaches require what is actually under investigation – a reliable system of odor perceptions. SOR may actually benefit from the availability of perceptual odor spaces, while they are little promising in the development of basic classifications.

3. **Features of the sensory percept:** Henning (1916) was the first who directly classified olfactory percepts by arranging verbal odor descriptions. He presented 415 odorants to 6 participants and asked them to freely verbalize their perceptions.

Based on a subjective summary of these verbal reports, Henning proposed 6 odor qualities and arranged them as corners of a prism. Although Henning's model has been repeatedly tested and falsified (Dimmick 1922; Findley 1924; Hazzard 1930; MacDonald 1922), many studies have followed his approach and applied verbal reports of odor perception to established odor classifications. These studies have been largely based on the assumption that odors can be located in an *n*–dimensional space where their position illustrates their similarity to each other. To reveal the nature of these dimensions, odor scientists have collected data on the relation between odors and searched for an underlying structure by the means of multivariate statistical methods.

Several authors have raised the question whether these perception–based efforts have been more successful than physiological or stimulus–centered approaches. Chastrette (1998; 2002) and Wise et al. (2000) reviewed a large body of research and reported that many of the proposed perception–based classification systems are vague or even contradictory. From 5 decades of empirical classification research, Chastrette (1998; 2002) reported merely 4 basic conclusions: (1) the olfactory perception space is probably not hierarchically structured – its structure is generally weak, (2) it is rather high–dimensional, (3) the labels of these odor dimensions remain arbitrary, and (4) odor classes may partly overlap. Wise et al. (2000) ascribed this lack of reliable insights to the subjective character of perception–based data collection methods, which "makes them anachronistic with modern methodology in experimental behavioral science" (p. 429). We assumed additional factors that have caused the conflicting results of classification studies. This paper reviews psychological classification studies published in the last 50 years to analyze the impact of 4 factors: (1) subjects, (2) stimuli characteristics, (3) approaches of data collection, and (4) methods of data analysis. Although several studies have addressed the impact of particular variables on odor arrangements (Chastrette et al. 1991; Davis 1979; Higuchi et al. 2004; Jeltema and Southwick 1986; Schiffman and Dackis 1976; Yoshida 1975), these effects have not been reported systematically so far. We examined papers listed in psychological data bases that applied a perception–based approach to odor classification. Non–English publications, grey literature and abstracts of symposia or conferences were excluded from a detailed review. Papers addressing methodological issues were not considered as classification studies. We identified 28 studies that complied with these criteria. Basic characteristics of these studies are summarized in Table 1. Their results clearly indicate that the proposed odor arrangements have varied considerably with respect to number and nature of olfactory dimensions. This paper discusses 4 possible factors that have affected the outcome of these studies and illustrates why consistency for olfactory systems has not been reached so far.

Table 1 Overview of psychological classification studies

		Subjects		Classification					Results		
Study	Analysis of	n	Knowledge status	Number of test odors	Method	Number of attributes	Number of reference odors	Method for data analysis	Number of dimensions	Pleasantness as primary dimension	Number of clusters
Wright and Michels (1964)	–	84	N/a	45	RefO	–	9	EFA	8	No	–
Woskow (1968)	–	20	Laymen	25	PSim	–	–	MDS	3	Yes	–
Døving (1970)	Woskow (1964)	20	Laymen	25	PSim	–	–	MDS	4	No interpretation	–
	Wright and Michels (1964)	84	N/a	45	RefO	–	9	MDS	3	No interpretation	–
	Wright and Michels (1964)	84	N/a	46	RefO	–	10	CLA	–	–	3
Cunningham and Crady (1971)	–	20	N/a	14	SemD	24	–	EFA	4	Yes	–
Berglund et al. (1973)	–	11	Experienced laymen	21	PSim	–	–	PCA	3	Yes	–
Schiffman (1974a, 1974b)	Wright and Michels (1964)	84	N/a	45	RefO	–	9	MDS	2	Yes	–
	Woskow (1964)	20	Laymen	25	PSim	–	–	MDS	2	No interpretation	–
Moskowitz and Gerbers (1974)	–	15	Experienced laymen	15	PSim	–	–	MDS	2	Yes	–
Yoshida (1975)	–	20	Laymen	32	RefO	–	40	PCA	7	Yes	–
								MDS (metric)	3	Yes	–
								MDS (nonmetric)	10	Yes	–
Schiffman et al. (1977)	–	12	Laymen	19	PSim	–	–	MDS	2	Yes	–
Coxon et al. (1978)	–	60	Laymen	23	A	9	–	MDS	5	Yes	–
Boelens and Haring (1981)	–	7	Experts	309	RefO	–	30	PCA	15	No interpretation	–
Ennis et al. (1982)	Boelens and Haring (1981)	7	Experts	309	RefO	–	30	PCA	12	No	–
						–		PCA and CLA	–	No interpretation	27
								PCA and DA	–	No interpretation	27
Jeltema and Southwick (1986)	–	25	Laymen	35	A	146	–	EFA	17	No	–
	Dravnieks (1985)	507	Experts	144	A	146	–	EFA	17	No	–
Chastrette et al. (1988)	Arctander (1969)	1	Expert	2467	OProf	74	–	CLA	–	–	41
Abe et al. (1990)	Arctander (1969)	1	Expert	1573	OProf	126	–	CLA	–	–	19
Carrasco and Ridout (1993)	–	32	Laymen	16	PSim	–	–	MDS	3	Yes	–
Stevens and O'Connell (1996)	–	104	N/a	15	S	–	–	MDS	3	Yes	–
Prost et al. (2001)	–	240	Laymen	40	A	40	–	CA	4	No	–
							–	CLA	–	–	–
Madany Mamlouk et al. (2003)	Sigma–Aldrich (1996)	N/a	Experts	851	OProf	278	–	MDS (and SOM)	32	No interpretation	–
Madany Mamlouk et al. (2004)	Sigma–Aldrich (1996)	N/a	Experts	851	OProf	171	–	MDS and PCA	32	No interpretation	–
Chrea et al. (2004)	–	90	Laymen (30 France,	40	S	–	–	MDS and CLA	F: 3	Yes	F: 5
			30 USA, 30 Vietnam)						US: 3		US: 4
									VN: 3		VN: 4
Sugiyama et al. (2005)	–	25	Laymen	17	PSim	–	–	MDS	3	No	–
Zarzo and Stanton (2006)	Sigma–Aldrich (2003)	N/a	Experts	881	OProf	82	–	PCA	–	No	17
Khan et al. (2007)	Dravnieks (1985)	507	Experts	144	A	146	–	PCA	4	Yes	–
Dalton et al. (2008)	–	300	Laymen	30	SemD	50	–	PCA	3	Yes	–
Zarzo (2008a)	Chrea et al. (2005)	90	Laymen	40	A	11	–	PCA	5	Yes	10
Zarzo (2008b)	Boelens and Haring (1981)	7	Experts	309	RefO	–	30	PCA	4	No	–
Zarzo et al. (2009)	Boelens and Haring (1981)	7	Experts	309	RefO	–	30	PCA	2	No	–
	Thiboud (1991)	1	Expert	119	OProf	–	–	PCA	2	No	–

Table 1 (continued)

n/a, not available; A, attributes; RefO, reference odors; PSim, pairwise similarity; OProf, odor profile; S, sorting; EFA, exploratory factor analysis; MDS, multidimensional scaling; PCA, principal component analysis; CLA, cluster analysis; DA, discriminant analysis; CA, correspondence analysis; SOM, self–organizing maps

Factor 1: Subjects

The psychological approach to odor classification is mainly based on verbal descriptions of odor percepts. Hence, a valid olfactory classification requires the reliability of both perception and verbal expression. However, one should not simply assume (1) that olfactory perceptions are generally stable over time, (2) that different people perceive identical odorants in the same way and (3) that different people verbalize their olfactory percepts consistently.

Intra– and Interpersonal Differences in Odor Perception

Some authors have addressed the "test–retest reliability" of perceptual ratings and found high correlations for experts as well as laymen, across different data collecting approaches and over short and medium time periods (Dravnieks 1982; Jeltema and Southwick 1986; Lawless and Glatter 1990; Schutz 1964; Wright and Michels 1964). However, reliability measures of odor ratings have usually been calculated from averaged group data and hence provide only little indication on the stability of an individual's odor perception or ratings, respectively. Hence, the reproducibility of individual ratings may actually be much lower than the exceptionally high reliabilities reported by several authors (Cain et al. 1998).

Over very long time periods odor ratings may be less reliable due to age–related changes in odor perception. Although there has been little longitudinal research, several cross–sectional studies have suggested a considerable influence of age on olfaction (Corwin et al. 1995; Larsson et al. 2000; Russell et al. 1993; Wysocki and Gilbert 1989): In 4 studies participants received 6 microencapsulated odorants and were asked to describe each odor with only 1 attribute from an 11–item list. The results of almost 2.4 million panelists aged between 10 and 90 years point towards a change in odor quality perception with increasing age. However, age–related differences were found to be odor–specific: Wysocki and Gilbert (1989), for example, reported that adrostenone was identified correctly by only about 20–30% of the subjects in all age groups with a slight decrease in the sixth decade whereas the identification rate of rose strongly declined from over 80% in third decade to less than 60% for panelists aged 80 and more. The influence of age on odor perception is not at all uniform across odors and hence difficult to control in olfactory studies. Elderly subjects might be excluded from classification studies to reduce the impact of physiological impairments. This can, however, not solve the problem of interindividual differences, as these also occur within age groups. Beyond age, gender (Cain 1982; Doty et al. 1985; Keller et al. 2012; Yousem et al. 1999), several other demographic variables (Corwin et al. 1995; Keller et al. 2012; Larsson et al. 2000; Larsson et al. 2004), certain diseases (Doty 1989) and psychiatric disorders (Atanasova et al. 2008) have been found to influence olfactory performance. A particular important influence is exerted by experience. It affects (1) basic perceptual ratings as well as (2) odor classifications. Several studies stated that *odor quality perception* is substantially shaped by experience and have illustrated this relation in cross–cultural comparisons (Ayabe–Kanamura et al. 1998; Chrea et al. 2004; Pangborn et al. 1988; Seo et al. 2011; Song and Bell 1998; Wysocki et al. 1991) as well as intra–cultural studies (Distel et al. 1999; Distel and Hudson 2001; Hudson and Distel 2002). Ayabe–Kanamura et al. (1998) compared the olfactory perception of 44 German and 40 Japanese subjects. Participants were asked to smell 18 everyday odorants (6 familiar to Japanese, 6 familiar to Germans, 6 familiar to both groups) and to judge them against several perceptual characteristics. For 10 odors significant differences in familiarity ratings were found between both groups. Well–known odors were usually rated as more pleasant and more often as edible in each of the 2 populations. These results suggest that humans prefer the smells they have frequently experienced due to their culture–specific eating habits and hence demonstrate a substantial impact of cultural experience on perceptual ratings of odors. Distel et al. (1999) applied the same approach and extended the German–Japanese sample by 39 Mexican subjects. Again, ratings in pleasantness and familiarity were found to correlate. Distel and Hudson (Distel and Hudson 2001; Hudson and Distel 2002) could replicate these cross–cultural findings in 2 German samples: To control for prior experience, subjects were either tested with odors they had rated as familiar or unfamiliar in an earlier session (Hudson and Distel 2002) or they were asked to identify the presented odorants (Distel and Hudson 2001). Similar to the cross–cultural studies, subjects' knowledge of an odor yielded increased pleasantness and intensity ratings, confirming the experience–dependency of odor quality judgments. Effects of experience have also been shown for the *classification of odors* (Chrea et al. 2005; Chrea et al. 2004; Ueno 1993). Ueno (1993) asked 20 Japanese and 20 Nepalese (Sherpa) participants to sort 20 Japanese food flavors based on their perceived similarity. The data analysis revealed that different from the Japanese sample, Sherpa did not apply a distinct category for "fishy" odorants. Ueno ascribed these differences to culture specific experiences, namely, the fact that Sherpa rarely come in contact with fish odors in their daily routine. A more comprehensive study with a similar approach was performed by Chrea and colleagues (Chrea et al. 2005; Chrea et al. 2004): They investigated the perceptual categories of 3 cultural groups (USA, France, Vietnam). Participants were asked to sort 40 odorants based on their perceptual similarity in as many groups as they felt necessary. The results showed several culture specific arrangements that were explained with differences in nutrition and domestic life. However, these differences were mainly found in the assignment of single odors to classes. The general structure of the 3 olfactory spaces was similar. Chrea and colleagues (Chrea et al. 2005; Chrea et al. 2004) thus provided empirical evidence for the basic universality of odor perception that has been proposed by several authors (Carrasco and Ridout 1993; Carrie et al. 1999; Dawes et al. 2004).

In summary, olfactory ratings appear to be stable over short periods of time. Interestingly, Keller et al. (2012) reported that within–individual variability does not increase with longer time intervals. The variance between 2 measures is largely attributable to sniff–to–sniff changes, that is, processes in the range of seconds or minutes.

However, across the life span, olfactory perception may alter with physiological changes and cause intra– as well as interpersonal differences. In addition to physiological effects, experience accounts for interpersonal differences in odor perception or evaluation, respectively. Nevertheless, one can assume a basic universality in odor perception for people at comparable ages, with similar cultural backgrounds, and without olfactory deficiencies. Inter–cultural research has shown that culturally acquired experience mainly affects the evaluation of familiar versus unfamiliar odors rather than perceptual processes in general.

Not surprisingly, intra– and interindividual variance has also been observed for basic perceptual ratings in other sensory modalities, as in color vision (Alfvin and Fairchild 1997; North and Fairchild 1993; Viénot 1980). Nevertheless, color systems have often been based on perceptual data. An example is the widely applied color metric established by the International Commission on Illumination (CIE) in 1931 (CIE 1932) and 1964 (1964), respectively. Both CIE color spaces were established from color matching experiments conducted by Wright (1929), Guild (Guild 1931), Stiles and Burch (1959) and Speranskaya (1959). Remarkably, Wright (1929) as well as Stiles and Burch (1959) reported considerable differences in the color matching functions of the observers they had tested. Wright (1929) discarded the results of 10 participants due to "inaccuracy and unreliability" (p. 152). This general variance in color ratings has, however, neither prevented the development of the CIE color system nor induced a general debate on the applicability and validity of perception based color systems.

Harper et al. (1968) summarized that an olfactory classification should be based on "some (specifiable) degree of agreement between different people" (p. 114) to be effective. Hence, odor researchers are advised to control for basic sources of variability, namely age, gender and culture, both in the recruitment of participants and the analysis of (group) data. Apart from this, they may accept variance as a fundamental characteristic of perception that may not be factored out in classification systems.

Interpersonal Differences in Odor Terminology

A basic requirement for language–based classifications is that people express their percepts similarly and apply verbal descriptions of odors in a similar way. Several authors who addressed the inter–rater reliability of verbal odor ratings, reported high consistencies for both panelists with the same experience level (Dravnieks 1982; Dravnieks et al. 1978) as well as between trained and naive subjects (Jeltema and Southwick 1986). However, other studies reported differences in verbal ratings of experts and laymen and indicated that linguistic expressions of odor perceptions are inconsistent: (1) When compared to laymen, experts use further and more specific descriptors to verbalize their perceptions (Lawless 1984; Solomon 1990, 1997). (2) Different from nonprofessionals, experts can give verbal descriptions for odors that are matched with an appropriate stimuli by other experts (Lawless 1984; Solomon 1990). Some authors noted that these differences should be ascribed to enhanced perceptual skills (Parr et al. 2004). Others suggested that experience primarily affects the verbal and cognitive processing of odors (Hughson and Boakes 2001, 2002; Valentin et al. 2007). Training might enhance both perceptual and verbal skills. Its impact on language is especially strong not least because of the sparse olfactory terminology of untrained subjects. Harper and colleagues (1968) characterized the language people use to capture odors as “a borrowed one” (p. 84), “a language of substances and things” (p. 167). Nonprofessionals even lack proper odor names and hence usually specify odors by their source. This may be the chemical substance (“amyl acetate”) or – more likely – the object that emanates a specific smell (“banana”) (Dubois and Rouby 2002). However, odors are poor retrieval cues for verbal labels. Laymen usually have major difficulties in naming even familiar odors correctly and identification rates rarely exceed 50% (Cain 1979; Cain and Potts 1996; Cain et al. 1998; Desor and Beauchamp 1974; Wijk and Cain 1994). At the same time odors are powerful cues for episodic memories (Chu and Downes 2000). Odor–related autobiographical memories can be recalled even without odor identification (Herz and Cupchik 1992). Thus, when people are unable to identify an odor, they normally express their olfactory perceptions by experiences they have gained with it: places or situations (“Christmas”), activities (“cleaning”, “baking”), effects (“relaxing”) or – on the most basic level – hedonic ratings (“pleasant”) (Dubois 2000; Rouby and Bensafi 2002; Schleidt et al. 1988). To facilitate a satisfactory communication despite this inaccuracy of everyday language, perfumers and fragrance companies have established a professional terminology. Along with this terminology, odor professionals have acquired cognitive categories that allow them to perceive a continuous space of odors in discrete conceptual categories. That is, experts are skilled in a categorical perception (CP) of odors. CP improves the discrimination among perceptual objects when these objects are assigned to different rather than the same categories. CP is a fundamental process in perception: It was first observed for color vision and has since been found in various perceptual domains (Harnad 1987). There has been a constant matter of scientific debate whether mental categories are innate and thus universal or learned and therefore experience dependent. Unquestionably, the perceptual classes applied by odor professionals are acquired. However, the degree to which they reflect “natural” odor categories or are completely arbitrary remains questionable. Various findings indicate that superior experience yields in odor arrangements that are distinct from the perceptional systems of nonprofessionals: (1) When data has been gathered from either experts or laymen, odor arrangements have varied with respect to the prevalence of a pleasantness factor. In the classification studies we reviewed, ratings by laymen have often yielded a hedonic dimension (Berglund et al. 1973; Carrasco and Ridout 1993; Chrea et al. 2004, 2004; Coxon et al. 1978; Moskowitz and Gerbers 1974; Schiffman et al. 1977; Woskow 1968; Yoshida 1975), while those by odor professionals have usually not applied pleasantness as comparison criterion (Ennis et al. 1982; Jeltema and Southwick 1986; Zarzo 2008b; Zarzo and Stanton 2006; Zarzo and Stanton 2009). (2) When attribute lists have been provided by experts and applied by laymen, terms have been understood and used differently by the untrained subjects (Lawless 1984; Solomon 1990, 1997). (3) In nonverbal classification procedures, professional terminology has affected the interpretation of results when researchers imposed their acquired system on the data. Nonverbal data sets lack a verbal reference frame for the interpretation. Language and expectations may hence exert a particularly strong influence. Nevertheless, we also found arbitrary interpretations in the study of Jeltema and Southwick (1986) that was based on a verbal classification approach. One of the 17 dimensions they found was related to attributes like *fresh green vegetable, crushed grass, green pepper, herbal, green, musty, earthy, moldy, celery.* Jeltema and Soutwick (1986) labeled it *green* – a term that has been commonly used in professional odor language (Edwards; Sigma–Aldrich Company 2011). The dimension could, however, be labeled with terms that refer to the semantic arrangement of the attributes like *garden*, *vegetable*, *fresh*, *organic* or *ecological*. To uncover the criteria applied by subjects, researchers might ask them to provide verbal labels for their nonverbal arrangements (Chrea et al. 2004; Stevens and O'Connell 1996). This approach can both facilitate the interpretation process and help to uncover non–perceptual strategies of odor classification.

The inappropriateness of everyday language for the description of odor perceptions has initiated the development of an expert vocabulary. This terminology has facilitated a more objective communication on odors. At the same time, it may have affected odor arrangements when the linguistic or perceptual categories of laymen have been captured and possibly blurred by professional terms.

Factor 2: Odorants

Quality and Quantity

In any study researchers determine the scope of their results by defining the sample they assess. This has also been true for olfactory classifications: The selection of odors has determined the structure and meaning of odor arrangements. Hence, odors should have been selected to represent the full extent of olfactory space. However, as the organization of this space is under investigation, the matter of representativeness is vague and classification studies have dealt differently with this issue: Several studies of the works we reviewed did not report selection criteria at all (Dalton et al. 2008; Jeltema and Southwick 1986; Stevens and O'Connell 1996; Woskow 1968; Wright and Michels 1964), others chose odors according to a specific physicochemical criterion (Coxon et al. 1978) or presented compounds as diverse as possible from a perceptual or a chemical perspective (Berglund et al. 1973; Moskowitz and Gerbers 1974; Schiffman et al. 1977). Some studies followed the approach of earlier works (Carrasco and Ridout 1993; Cunningham and Crady 1971; Yoshida 1975) or even selected odors in accordance with existing classification systems (Prost et al. 2001; Sugiyama et al. 2006). Without an objective selection criterion the presentation of qualitatively and chemically various compounds seems most reasonable. Nevertheless, most odors applied in classification studies belong to very specific quality categories, namely food (Calkin and Jellinek 1994; Gilbert and Greenberg 1992), flowers and cosmetics. Given that the presentation of familiar odors to nonprofessionals is meant to facilitate the already demanding task of odor evaluation, this is comprehensible. Odor researchers should nevertheless consider that the exclusion or under–representation of specific odor classes, especially of unpleasant odors, will yield biased classification systems. This constraint to odor arrangements has only rarely been discussed in classification studies.

In order to represent the different odor qualities appropriately, a minimum number of odors is required. The studies we reviewed usually applied around 30 odorants (Table 1). With this sample size, researchers have usually found a trade–off between methodological requirements and practicability aspects. But it may be questioned whether this number is sufficient to represent a presumably high–dimensional olfactory space. Several studies have therefore analyzed existing data sets that have been established by odor professionals and comprise between more than 100 (Dravnieks 1985; Thiboud 1991) and several thousand (Arctander 1994; Sigma–Aldrich Company 2011) odorants. However, a large number of compounds is not necessarily more representative than a well–selected smaller stimuli set.

Intensity

In many classification studies participants have been explicitly instructed to ignore potential differences in intensity when evaluating odors. This approach has been based on the assumption that intensity represents a distinct perceptual dimension – comparable, for instance, to color perception. However, in olfaction the quality and intensity of a compound interact considerably and a shift on one dimension is often accompanied by a shift in another dimension: Whereas a color keeps its basic quality (blue) with increasing or decreasing intensity (light blue, dark blue), odors often change their quality with higher or lower concentrations. Thus, subjects might have difficulties in ignoring intensity effects – simply because they directly affect the sensation of quality. Gross–Isserhoff and Lancet (1988) found quality changes for 8 odors in a study with nonprofessional panelists. Subjects were asked to decide whether pairwise presented odors were identical. While subjects were able to correctly identify pairs of the same odor in identical dilutions in over 90% of the trials, errors increased considerably when the very same odor was presented in different concentrations. In a more recent study, Laing et al. (2003) assessed 5 odorants at 7 different concentrations. They asked subjects to rate each sample against 145 descriptors and found a quality change with increasing intensity for 4 of the 5 tested odors. Hence, intensity is very likely neither a separate dimension outside a quality space nor congruent with a single quality dimension inside this space (Henion 1971). In a number of the classification studies we reviewed intensity effects were controlled. In these studies odors were presented in concentrations that had been rated as equally intense in a pretest (Berglund et al. 1973; Dalton et al. 2008; Moskowitz and Gerbers 1974; Stevens and O'Connell 1996). However, in various other studies intensity effects were considered only marginally or not at all (Carrasco and Ridout 1993; Chrea et al. 2004; Coxon et al. 1978; Cunningham and Crady 1971; Jeltema and Southwick 1986; Schiffman et al. 1977; Sugiyama et al. 2006; Woskow 1968; Wright and Michels 1964; Yoshida 1975). This lack of control might have produced variance in the data that has been falsely ascribed to odor quality (Berglund et al. 1973). For future research, scientists should not only control for intensity effects by presenting compounds at equally intense dilutions. They should also keep in mind that the quality of some odors cannot be fully represented at a single intensity level and that these odors will not have a single distinct position in an olfactory space.

Verbal Cues

Experience has been shown to influence quality perception by providing facts on the identity, function or effect of an odor. Several studies have shown that this information can also originate from contextual cues like the color (Gilbert et al. 1996; Lavin and Lawless 1998; Morrot et al. 2001; Sakai 2005; Zellner et al. 1991) or verbal label attached to an odor. Herz and Clef (2001) investigated the influence of verbal labels on odor descriptions by presenting identical odors with different labels in 2 several test sessions (violet leaf as “fresh cucumber” or “mildew”). Among other rating tasks subjects were asked to report a memory evoked by each smell, to describe its function and to generate a name for what they supposed the odors could be. Raters without knowledge of the experimental design evaluated whether these reports differed between the trials: Depending on the compound, 50– 83% of the subjects actually changed their description as a function of verbal context. However, while some odors are susceptible to verbal influences, others have distinct perceptual features that are less affected by context information. From the 5 odors presented, menthol and pine oil were considerably less affected by the different labels than violet leaf, patchouli, and a 1:1 mixture of isovaleric and butyric acid. In addition to the direct impact of labels odor quality, numerous studies have confirmed an effect of verbal information on hedonic ratings (Bensafi et al. 2007; Distel and Hudson 2001; Djordjevic et al. 2008; Herz 2003; Herz and Clef 2001; Lorig and Roberts 1990; Lundström et al. 2006; Moskowitz 1979). This, in turn, might influence intensity as well as quality features (Figure 1).

The impact of visual or verbal information has not been a methodological issue in classification studies as odors have been presented in neutral carriers without any labeling. However, along with the judgment of perceptual properties subjects have very likely made assumptions what the source of an odor is and thus attached a label to them. If these labels have been wrong or varied between subjects or trials, they have caused variance in a classification system falsely ascribed to odor quality.

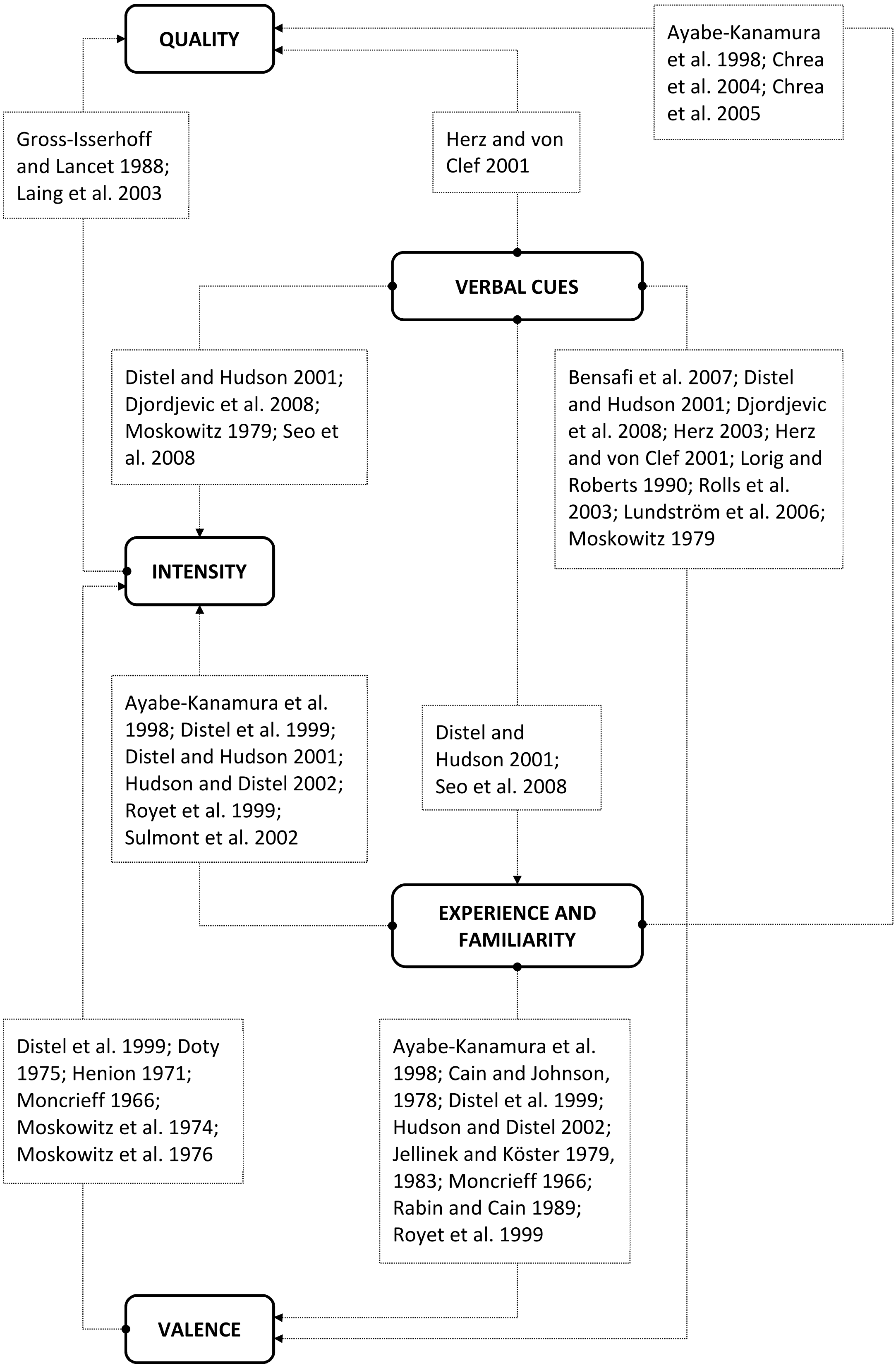

Fig. 1 Research on mutual effects of odor characteristics; arrows indicate the direction of relations assessed

Contextual Effects

In addition to visual and verbal cues the set of presented odors might act as reference frame itself and affect the evaluation of every single compound. Among various contextual biases in sensory judgments, contrast effects are probably the most common (Lawless and Heymann 2010). They occur when the perception of a stimulus characteristic is affected by the strength of this property in surrounding stimuli and shifted in the direction away from this context. Hulshoff et al. (1998) demonstrated the effect for odor intensity ratings where an odor was judged weaker in the context of stronger stimuli and stronger in the context of weaker stimuli. Lawless and associates (Lawless 1991; Lawless et al. 1991) confirmed the impact of perceptual context on quality judgments. They presented a citrus–woody odor (dihydromyrcenol) in a session with either prototypically citrus or prototypically woody odors and instructed participants to rate the stimuli against several quality descriptors. The ambiguous odor was rated as more woody in the citrus context and as being more citrus in the presence of woody compounds. Context effects also appear when only a single compound in a set is replaced: Kurtz et al. (2000) collected dissimilarity ratings for a set of 4 fixed odorants (licorice, mint, mothballs, rose) and either vinegar or rubbing alcohol. They found significant differences for ratings of the fixed compounds between both conditions with odors being rated as more similar in the presence of a very disparate smell (vinegar). Contrast effects are an ordinary mechanism of perception and appear to be unavoidable in sensory studies. However, since they decrease the reliability of judgments, they are highly undesirable for the development of comprehensive odor arrangements. To stabilize ratings, several of the reviewed classification studies have counterbalanced their stimuli sets (Berglund et al. 1973; Chrea et al. 2004; Coxon et al. 1978; Prost et al. 2001; Woskow 1968; Wright and Michels 1964) or even fully randomized the presentation order for each subject (Carrasco and Ridout 1993; Moskowitz and Gerbers 1974). These strategies have been good practice in sensory research for decades but whether they actually counteract contrast effects remains questionable. Lawless and Heymann (2010) stressed that balancing and randomization can counter order effects by changing the direct context of each odor. However, the overall context defined by the set of odorants remains unchanged.

Naturally, a classification system is determined by the quality and number of odors presented. Hence, odors have usually been considered as representative samples of the odor space. However, in many of the reviewed studies we have found an over–representation of specific quality classes that has undoubtedly yielded in fragmentary and biased odor arrangements. Remarkably, odor quality is not only a matter of the stimuli offered, but also of how these are presented and to whom. The perceived quality of an odor is anything but a fixed characteristic that can be fully controlled by a careful selection. It rather changes with other odor characteristics, contextual information and personal experiences. Even most basic aspects like an odors carrier and dilution (air, liquid) or the duration of its presentation may affect the perceptual evaluation. The entire list of interference factors is impossible to consider, but odor researchers are asked to both choose the very limited number of test odors thoroughly and to control for biases – not primarily to fully eliminate them, but to improve the understanding and valid interpretation of outcomes (Lawless and Heymann 2010).

Factor 3: Method of Data Collection

To collect perception–based data researchers have usually applied approaches based on verbal or nonverbal judgments of odor characteristics. That is, odors have either been rated against a list of attributes or against other odors. However, due to the immense effort of these direct attempts, several classifications systems have been established from odor profiles or based on the secondary analysis of previous data sets.

Verbal Profiling

In verbal profiling approaches, odors are rated against a predefined list of verbal descriptors or semantic differentials (Coxon et al. 1978; Cunningham and Crady 1971; Dalton et al. 2008; Jeltema and Southwick 1986; Prost et al. 2001). Subjects are asked to express their olfactory sensations verbally, but instead of actively generating verbal descriptions they evaluate odors against fixed references. A verbal approach restricts subjects to the qualitative aspects of an odor (that have been presented by the researcher). However, it also prevents panelists from deciding on the relevance of given attributes or applying individual comparison criteria. Several authors stressed that attribute lists should contain terms that are representative of the olfactory space as well as not associated (Civille and Lawless 1986; Gregson and Mitchell 1974). We examined the attribute lists applied in the verbal classification approaches of Pilgrim and Schutz (1957), Dravnieks (1985), Prost et al. (2001), and Zarzo (2008a). Out of 175 different descriptors, the vast majority pointed to odor sources (84.3%), 8.4% represented sense–specific qualities (fragrant, aromatic, rancid) and 6.7% described non–olfactory percepts (dry, heavy, sweet), 1 descriptor referred to pleasantness, 1 to an odor effect (full list is available from first author). From the different categories, only source labels refer to real, distinct percepts and hence seem to provide most applicable rating standards – especially for untrained panelists. However, these labels require subjects to compare an actual sensation (test odor) to an imagined odor (verbal label) and especially nonprofessionals have often reported difficulties in imaging odors (Stevenson and Case 2005). Hence, when subjects have been instructed to compare an odor to an attribute as “birch bark” (Dravnieks 1985) they might have pictured odor sources or appropriate situations (walk in the woods, collect mushrooms) rather than a distinct smell. Odor scientists should thus keep in mind how a list of verbal descriptors always provides a definition of what odor quality is (Moskowitz and Gerbers 1974). These definitions might over– or underrepresent certain perceptual dimensions and could be processed differently by different subjects.

Similarity Ratings

Pairwise Similarity

The pairwise similarity is evaluated in each possible dyadic combination of a set of odors on numerical or visual rating scales (Berglund et al. 1973; Carrasco and Ridout 1993; Gregson and Mitchell 1974; Jeltema and Southwick 1986; Moskowitz and Gerbers 1974; Schiffman and Dackis 1976; Schiffman et al. 1977; Woskow 1968). As the classification of n stimuli requires $n(n - 1)/2$ comparisons, the method is highly time–consuming and considerably restricts the selection of test compounds. Similarity ratings are independent of a verbal reference system provided by the researcher. They rather allow panelists to apply an individual definition of relevant quality features. However, these criteria usually remain unknown. Instead of evaluating odor similarities with respect to fixed and distinct criteria, ratings are rather based on a single (outstanding) characteristic or a general perceptual impression. Davis (1979) and Gregson (1972) showed that panelists actually differ in the comparison strategies they apply. Not surprisingly, several studies reported a poor agreement among subjects in pairwise ratings of odors (Berglund et al. 1973; Gregson 1972; Yoshida 1964). Hence, nonverbally established classification systems may reflect perceptual dimensions as well as a subject's lack of clear comparison criteria in the test situation.

Sorting

Lawless (1989) applied a time–efficient alternative to pairwise similarity ratings: He adopted a method used in personality research (Rosenberg and Park Kim 1975) and asked subjects to sort odorants based on their similarity in as many groups as they considered necessary. An index of similarity is derived across all panelists from counting the joint occurrence of any possible pair of odors in the same group. Hence, a gradation among similarity ratings emerges from the agreement or disagreement between subjects. However, this index is not only affected by the allocation of odors to groups but also by the number of groups created. Subjects might differ in the number of groups they form due to different mental strategies of sorting. Nevertheless, odor sorting provides important advantages: It is less time–consuming than direct similarity ratings and minimizes perceptual fatigue. For these reasons recent studies have usually collected nonverbal similarity data based on this approach (Chrea et al. 2004; Dubois 2000; Higuchi et al. 2004; Lawless and Glatter 1990; MacRae et al. 1990; MacRae et al. 1992; Stevens and O'Connell 1996). Some authors have asked participants to provide labels for the groups they had formed after completing the sorting task (Chrea et al. 2004; Stevens and O'Connell 1996). This method both helps to assess whether different subjects applied similar sorting criteria and supports the interpretation of results. Interestingly, in the study of Chrea et al. (2004) these labels mainly referred to odor sources and indicate that the sorting was at least partly determined by odor identification and the linguistic–semantic grouping of odorous objects as flowers, cosmetics, cleaning products and so on.

Reference Odors

Several of the early classification studies have applied an approach that asks subjects to evaluate the similarity between test odors and a set of reference compounds (Boelens and Haring 1981; Schutz 1964; Wright and Michels 1964; Yoshida 1975). These references odors are usually meant to represent specific perceptual qualities; that is, they act as olfactory counterpart to verbal descriptors. The procedure requires comparably few odor ratings since each odor is only evaluated against a fixed number of standards. Dravnieks et al. (1978) questioned “if an adequately universal but relatively small and manageable set of reference odorants can be developed” (p. 192). When reference compounds are expected to represent specific odor qualities, their validity is both dependent on the selection of qualities that fully cover the olfactory space and on the capability of each odor to clearly represent (only) one specific quality. However, one can doubt that subjects will agree on the dominant quality of an odor while they sometimes even differ on the meaning of verbal descriptors (Zarzo and Stanton 2009). Empirical evidence for this notion is provided by a study of Boelens and Haring (1981). They established an extensive data set based on 307 test odors and 30 standards that has been re–analyzed by several researchers (Ennis et al. 1982; Zarzo 2008b; Zarzo and Stanton 2009). Even though the study was conducted with 7 perfumers, the panel “disagreed significantly on the odor profile of certain odorants” (Boelens and Haring 1981). This indicates difficulties in identifying the primary quality of (reference) odors – especially for nonprofessionals.

Odor Profiles

Odor profiles have usually been developed by odor professionals and contain verbal descriptions for hundreds or thousands of odors. They provide information on odor similarities that are calculated from the co–occurrence of attributes on different odors. Hence, several classification system have been based on these data sets (Abe et al. 1990; Chastrette et al. 1988; Madany Mamlouk et al. 2003; Madany Mamlouk and Martinetz 2004; Zarzo and Stanton 2006; Zarzo and Stanton 2009).

One of the most comprehensive odor profiles was developed by Arctander (1969). It contains as much as 3102 odor samples that have been characterized with about 270 different attributes. However, subjectivity is a basic constraint of the data set as each odor was described by Arctander himself. Empirical evidence for the distortion of the data was provided by Pintore (2006) who found considerable disagreements between Arctander's work and a commercial database. A second catalogue that has been originated from the expertise of a single expert was established by Thiboud (1991): 119 compounds are described by 3–4 main and several secondary notes; a total of 85 different descriptors were applied. Thiboud (1991) distinguished objective (olfactory quality) from subjective attributes (individual associations on origin, function or effect). However, as all odor descriptions have been based on a single expert's opinion and lack an external validation criterion, this distinction has been rather theoretical. A third database that has been applied in several classification studies is published and regularly updated by Sigma–Aldrich. The latest version of the catalogue (Sigma–Aldrich Company 2011) comprises profiles of more than 1600 aroma raw materials that have been characterized with 82 attributes. Zarzo and Stanton (2006) noted that these profiles have been generally acquired from literature, odor expert reports or other odor profiles, respectively. Hence, it remains largely unknown how exactly each odor has been characterized and by whom. With the *Atlas of Odor Character Profiles*, Dravnieks (1985) published an extensive data base from expert ratings: He carefully developed a 146–attribute list (Dravnieks 1975; Dravnieks et al. 1978) and asked a total of 507 perfumers and odor scientists (120 – 140 experts per odor) to evaluate 160 odors against it. Given that the data set has been based on a verbal profiling approach applied by trained raters, it is not surprisingly that odor descriptions have been found to be highly reliable (Dravnieks 1982).

Several researchers have addressed the impact of data collection approaches on classification systems. Verbal approaches have sometimes been criticized for being biased by linguistic references that may be used or understood differently and hence decrease inter–rater agreement. Schiffman and colleagues (Schiffman and Dackis 1976; Schiffman et al. 1977) compared direct similarity ratings to judgments on semantic differentials. In both studies they found that the similarity data “was virtually identical for each subject” (Schiffman et al. 1977) whereas most “semantic differential ratings tended to be widely distributed over subjects across scales” (Schiffman et al. 1977). However, other studies demonstrated high inter–rater agreement for verbal ratings (Dravnieks 1982; Jeltema and Southwick 1986) and considerable interindividual variety for nonverbal techniques (Berglund et al. 1973; Gregson 1972; Yoshida 1964). Still others noted that verbal and nonverbal approaches generally yield comparable results (Higuchi et al. 2004; Moskowitz and Gerbers 1974; Stevens and O'Connell 1996). Higuchi and collaborators (2004) explained this agreement with the quality of their attribute list; high reliabilities found for Dravnieks’ extensive list support this assumption. These findings suggest that verbal approaches are highly affected by the soundness of descriptors, rather than generally inferior to nonverbal methods. It is debatable whether verbal attributes can appropriately reflect the quality features applied by non–professionals. They, however, provide a reference frame for odor evaluations that might be especially important to guide untrained subjects. Nonverbal approaches require raters to decide on comparison criteria themselves. These will reflect natural perceptual dimensions more appropriately than predefined verbal descriptors but they may change for every new pair of odors and they may remain largely unknown – to the participants as well as to the researcher. Beyond that, one might question whether similarity ratings and sorting procedures are truly free of verbal influences. Even though the verbal mediation of olfactory processes has not been definitely resolved, the comparison of 2 compounds may require the mental search through verbally represented criteria. A nonverbal odor comparison thus involves perceptual as well as verbal processes. Hence, when people differ in the perception and verbalization of odors, variance in the data set cannot be reliably attributed to an (assumed) inaccuracy of language–based methods.

Factor 4: Method of Data Analysis

Olfactory classifications have usually been based on the assumption that odors are projections in an *n*–dimensional space where their position comprehensively describes the perception they elicit. Thus, classification studies have usually applied analysis approaches that either search for a parsimonious but meaningful dimensionality of the data set, like exploratory factor analysis (EFA), principal component analysis (PCA) and multidimensional scaling (MDS), or summarize odors to more homogenous groups, like cluster analysis.

Multidimensional Scaling

MDS refers to a group of exploratory data analysis approaches that attempt to visualize the underlying structure of high–dimensional data sets. It represents objects as points of a (preferably) low–dimensional space in a way that inter–point–distances best match the measured (dis)similarities of associated objects. The more similar objects are, the closer their points are located in this space and vice versa. In classification studies these objects have usually been odors and the spatial map a representation of the olfactory space. In the studies we reviewed, similarity measures were either obtained directly from pairwise similarity ratings (Carrasco and Ridout 1993; Døving 1970; Schiffman 1974a, 1974b; Schiffman et al. 1977; Woskow 1968; Yoshida 1975), sorting tasks (Chrea et al. 2004; Stevens and O'Connell 1996; Sugiyama et al. 2006) or calculated from odor profiles (Madany Mamlouk et al. 2003; Madany Mamlouk and Martinetz 2004) and attribute ratings (Coxon et al. 1978) by correlations. When Lawless (1989) first applied a sorting task to generate MDS data, he raised the question whether different data collection approaches yield comparable olfactory spaces. Several studies addressed this issue and found differences in MDS solutions caused by different scale levels of the data (Bijmolt and Wedel 1999; Humphreys 1982; Rao and Kaltz 1971). Classification studies have usually calculated MDS spaces from averaged group data (Coxon et al. 1978; Døving 1970; Schiffman 1974a, 1974b; Woskow 1968), because inter–rater variance has been treated as noise. This assumption, however, has disregarded that there *are* differences between subjects that should manifest in some way in an odor classification. Ashby et al. (1994) assessed how averaging considerably changes the underlying structure of a data set. In a simulation study they demonstrated a good fit of averaged data to standard MDS models while these models failed to represent the data of any individual subject appropriately. They emphasized that similarity measures should be analyzed either on subject level or treated with MDS procedures like INDSCAL (Carroll and Chang 1970) that does not average data across subjects. However, only few of the classification studies we reviewed, applied an individual scaling approach to verify their group results or at least considered the impact of averaging explicitly (Carrasco and Ridout 1993; Schiffman et al. 1977; Yoshida 1975). Hence, odor arrangements have possibly factored out differences between subjects with the application of classical MDS models. In addition, the major aim of MDS to visually represent complex data sets has likely biased the results of several studies.

Although the quality of an MDS solution is usually assessed by its stress value (Kruskal 1964) or the squared correlation index (R^2), in practice both criteria have frequently been traded off against low dimensionality. Most classification studies that applied MDS actually reported 2– or 3–dimensional olfactory spaces (Table 1). However, theoretical assumptions (Chastrette 2002; Harper et al. 1968) and other methods of analysis like EFA and PCA have suggested considerably more perceptual dimensions (Table 1). Jeltema und Southwick (1986) noted that MDS might provide less useful results than PCA or EFA because “MDS dimensions cover multiple sensory dimensions which were pulled apart by factor analysis” (p. 133). Independent from their accuracy, low–dimensional solutions haven often facilitated visually driven interpretations that have been based on the (visual) allocation of odors along the displayed dimensions (Coxon et al. 1978; Moskowitz and Gerbers 1974; Schiffman 1974a; Yoshida 1975). This approach, however, lacks objective criteria and is likely biased by expectations on (over)simplified data structures. Several studies have thus attempted to minimize subjectivity by performing further analyses on the results (Chrea et al. 2004; Stevens and O'Connell 1996) or regressing MDS solutions against attribute ratings acquired in separate experimental trials (Carrasco and Ridout 1993; Higuchi et al. 2004; Schiffman et al. 1977; Woskow 1968). However, this approach requires both the soundness of applied descriptors as well as the comparability of verbal and nonverbal procedures with respect to their results. It thus remains questionable whether it has truly yielded more objective results.

Despite these constraints MDS has provided several advantages for classification studies as it processes ordinal raw data to multidimensional maps and thus yields quantitative information on odor similarities without assuming linear relations or multivariate normality.

Principal Component Analysis and Exploratory Factor Analysis

The general purpose of PCA is to reduce the dimensionality of a complex data set that comprises values for n objects on p interrelated variables. In order to reveal a simplified structure, new uncorrelated variables – the principal components (PCs) – are calculated. PCs are linear combinations of the original variables and explain the entire variance of the data in successively decreasing proportions. In other words, an original data represents n points in a p–dimensional space. PCA searches for m ($m < p$) dimensions, that provide an alternative description of the data points minus the redundancy expressed by intercorrelations between the original variables. From the studies we reviewed, 10 analyzed their data with PCA (Berglund et al. 1973; Boelens and Haring 1981; Dalton et al. 2008; Ennis et al. 1982; Khan et al. 2007; Yoshida 1975; Zarzo 2008a; Zarzo 2008b; Zarzo and Stanton 2006; Zarzo and Stanton 2009), 3 reported the application of EFA (Cunningham and Crady 1971; Jeltema and Southwick 1986; Wright and Michels 1964). This prevalence of PCA over EFA does not just apply to classification studies but has also been found in other areas of psychological research

(Conway and Huffcutt 2003; Costello and Osborne 2005; Fabrigar et al. 1999; Ford et al. 1986). This preference has not necessarily been justified. Very often, there has even been a lack of differentiation between both methods: In the literature as well as in statistical software packages, PCA has often been considered as (default) extraction method of EFA (Ford et al. 1986). However, both approaches are based on distinct mathematical assumptions even though often yield fairly similar results. EFA assumes a common factor model and searches for those latent factors that cause the correlation of original variables. Each manifest variable is expressed as linear combination of common factors that explain the shared variance plus factors of unique variance and measurement error. PCA is not based on a statistical model and uses the entire variance of the original variables to calculate PCs. These PCs account for shared variance as well as unique variance and measurement error. Hence, while EFA primarily searches for interpretable dimensions, PCA is aiming at a computational data reduction. However, in classification studies principal components have usually been interpreted as perceptual dimensions and their labels have sometimes even exceeded the meaning of the original variables. Zarzo (2008b) as well as Zarzo and Stanton (2009) labeled a dimension *feminine versus masculine* that discriminated *floral*, *fruity* from *earthy*, *dusty* odors. Although similarity ratings had been collected from odor experts, the appropriateness of these labels remains questionable. Other investigators have successfully reduced the impact of subjectivity on interpretations by underpinning their assumptions with independent criteria (Khan et al. 2007). Despite these measures, expectations remain a central issue of most classification studies: Especially the search for a pleasantness factor has considerably affected numerous odor arrangements.

To our knowledge, no study has yet compared the applicability of PCA and EFA to classification data. However, classification studies have usually not explained why they applied either method. One reason for preferring PCA over EFA may be to determine the position of odors in an olfactory space in addition to identifying its relevant dimensions. This is, however, not easily attained by EFA: For a given odor several factor scores (positions in the odor space) can be calculated that perfectly fit the factor model but vary considerably. This issue has been discussed as factor indeterminacy problem in the common factor model (for a review, see Velicer and Jackson 1990), and truly argued against applying EFA in classification studies. On the other hand, several authors have discussed that PCA tends to inflate loadings of variables and estimates of explained variance when compared to EFA (Fabrigar et al. 1999; Park et al. 2002; Widaman 1993). Empirical evidence is provided by Khan et al. (2007) who applied EFA as well as PCA on their data: While the first 4 components accounted for 56% of the data variance, the first 4 factors explained only 33% of the variance. This inflation has likely biased the structure and meaning of PCA–based olfactory spaces.

When comparing both approaches with respect to the aims of classifications studies, conceptual assumptions as well empirical evidence argue for the application of EFA in classification studies (Costello and Osborne 2005; Fabrigar et al. 1999; Gorsuch 1983, 1990; Widaman 1993): Firstly, EFA should be preferred because perception–based measures very likely contain some random error. Secondly, odor scientists have searched for meaningful perceptual dimensions. PCA, however, calculates linear combinations of original variables without regard to meaningful latent constructs and yields dimensions that not necessarily capture more than a maximum of variance.

Cluster Analysis

Cluster analysis identifies naturally occurring groups in a complex, unstructured data set by grouping objects based on their similarity on assessed variables. It seeks an arrangement where objects within a group, namely a cluster, are similar and unrelated to objects of another group. Clusterings are most commonly distinguished in partitional and hierarchical approaches: While partitional cluster analysis simply creates a set of non–overlapping subgroups, a hierarchical approach allows clusters to be nested, that is, arranged in hierarchical structures with groups and subgroups. The 4 classification studies that performed cluster analysis (Abe et al. 1990; Chastrette et al. 1988; Døving 1970; Prost et al. 2001) exclusively applied hierarchical clustering algorithms and thus assumed a hierarchical structure of the olfactory space. However, if this notion is appropriate remains questionable (Chastrette 2002).

In a cluster analysis, the final number of groups can possibly be between 1 and *n*, where *n* is the number of objects assessed. Finding the most appropriate number between these 2 extremes has been a challenge, especially when prior knowledge of the grouping and external validation criteria has been missing (Everitt 1979). Everitt (1979) reported that hierarchical clustering algorithms have been primarily established for biological questions that emphasized the hierarchical relationship of objects rather than an appropriate number of groups. Numerous criteria have been proposed (Cheong and Lee 2008; Lange et al. 2004; Takasu 1998; Tibshirani et al. 2000), but none of them have prevailed to adequately solve the problem. Most of the reviewed studies have decided on a final number of clusters (Abe et al. 1990; Chastrette et al. 1988; Døving 1970) but without reporting their decision criteria appropriately or at all.

In summary, cluster analysis has played a minor part in olfactory research. Classification studies have strongly focused on the number and character of perceptual dimensions and thus mainly applied PCA, EFA or MDS on their data. Many of the reviewed studies – especially early works – missed to report and explain their choices throughout the analysis process sufficiently. This has not only complicated the replication of these studies but also a comprehensive understanding and debate on their attempts. How substantially these decisions affect the meaningfulness of outcomes has been shown by studies that applied the same analysis approach to identical data sets and yet yielded considerably different results: Døving (1970) and Schiffman (1974a; 1974b) applied MDS to a data set established by Woskow (1964) and found a 4– and 2–dimensional olfactory space, respectively. The data set of Boelens and Haring was analyzed with PCA in several studies (Boelens and Haring 1981; Ennis et al. 1982; Zarzo 2008b; Zarzo and Stanton 2009) and yielded 2 to 15 perceptual dimensions. To allow an informed choice on the appropriateness of classification results, odor researchers are required to both provide detailed information on their analysis approaches and consider potential limitations more thoroughly.

Naturally, the use of a specific method is determined by the research question and data obtained. Interestingly, recent studies have predominantly performed PCA on their data. We have questioned the adequacy of a purely computational data reduction as an approach to meaningful perceptual dimensions. Based on the research reviewed, we give preference to MDS and EFA for the analysis of non–verbal data sets and profile data, respectively. Generally, researchers should consider that methods successfully applied in “higher senses” may not be appropriate for odor research questions. Especially, the predominant averaging of data in classification studies has ignored the specific characteristics of odor perception (Köster 2002) and yielded biased and incomplete arrangements.

Conclusion

Odor classifications – especially early studies – have often been guided by the efforts and notions of color systems, where a manageable number of receptor types and relevant physical dimensions have constituted neat, low–dimensional arrangements of stimuli and comparatively few primary colors (Harper et al. 1968). Color classifications have condensed a complex perceptual reality to a few dimensions along with a minimum loss of relevant information. Odor professionals have searched for systems with the same lucidity. But to this day none of them has sustained scientific scrutiny. Perceptual–verbal approaches of odor classification have been especially prone to errors and biases. We identified a vast number of influencing factors that can be grouped to 4 main categories with respect to interindividual differences, stimuli characteristics, methods of classification, and methods of analysis. We could neither confirm nor disprove the general findings on structure and dimensionality stated by Chastrette (2002). Especially the number and character of perceptual dimensions remains a matter of debate. While Chastrette (2002) assumed a high–dimensional olfactory space, most of the reviewed studies reported between 2 and 4 perceptual dimensions. Investigators have largely agreed that among these, one dimension reflects the pleasantness of odor perceptions: In 14 of the 28 reviewed studies pleasantness was found to be a dominant factor of odor perception.

Prevalence of Pleasantness in Classification Studies

The prevalence of a hedonic dimension in olfactory spaces may have different reasons. One might argue that pleasantness primarily reflects an inappropriateness of everyday language that causes a lack of description standards for odor perceptions (in an experimental setting). In other words: In absence of clear descriptors and ratings standards, panelists may confine themselves to the most basic attribute of an odor – its pleasantness. Evidence for this assumption has been provided by the results of nonverbal classification studies: All but one of the reviewed studies that applied pairwise similarity ratings revealed a primary pleasantness dimension while verbal methods found a hedonic factor considerably less frequent. Beyond that, experts have only rarely stated pleasantness as substantial perceptual quality of odors while studies with nonprofessionals have almost always yielded a hedonic dimension. However, whether ratings by odor professionals reflect the "true" character of an odor space more precisely than those of laymen, is questionable: On the one hand, odor experts are highly experienced in odor evaluations and barely misled by the absence of a (verbal) reference frame. On the other hand, their terminology explicitly excludes hedonic ratings; perfumers are simply trained to disregard the hedonic tone of odors. Pleasantness may have also been introduced to classification systems by researcher expectations. Many investigators have focused on confirming the existence of a hedonic factor that has been based on theoretical considerations or proposed by previous studies.

There has, however, been evidence for the assumption that pleasantness *is* a significant aspect of odor perception. Firstly, the neuronal processing of odors and emotions are partly overlapping in limbic structures (Gottfried 2006). Secondly, the close connection is rooted in a point of human evolution when odors primarily provided information on food, mates, natural predators or kinship – in other words, when they informed on what to approach and what to avoid. Herz (2005) proposed that this evolutionary meaning has caused the weak connection of odors and language. First and foremost our ancestors had to learn how to respond to odors. Names or other perceptual features did, however, not provide essential information. More recent, several studies assessed emotional response to odors more closely (Chrea et al. 2009; Delplanque et al.

2012; Ferdenzi et al. 2011) and actually provided evidence for this assumption. Affective responses to odors do not mirror basic human emotions but rather reflect the "role of olfaction in well–being, social interaction, danger prevention, arousal or relaxation sensations" (Chrea et al. 2009). These findings suggest that pleasantness is a generic factor of olfactory perception which is subdivided in more specific facets related to the functions and effects of odors on humans.

The prevalence of pleasantness in perception–based olfactory systems may be caused by the "helplessness" of (untrained) subjects in odor rating tasks, it may have been introduced to experimental settings by assumptions of odor researchers or reflect the true importance of pleasantness in odor perception. Currently, a combination of all factors is likely, but more research is needed to properly judge the role of hedonic in olfaction.

Influencing Variables

We illustrated how each perception–based odor arrangement has been determined by basic characteristics of study design, sampling and data analysis. Hence, odor systems reflect the relation of perceptual qualities as well as the conditions under which these qualities have been assessed. Even if a sufficiently representative yet relatively small set of odors can be found, the sensations of these odors are anything but accurate reflections of actual stimuli. Subjects classify a mental representation of an odor that is shaped by various interactions between odor characteristics as well as the impact of interindividual differences in age, knowledge, culture and so on. When panelists agree on their perceptions, the applied methods of classification may still overrate or underemphasize certain quality aspects. Finally, different approaches of data analysis yield in results that might not appropriately reflect the mental odor categories of laymen when they are interpreted by the means of professional terminology.

Although odor researchers have been faced with these issues for more than 5 decades, neither a debate on the general appropriateness of perception–based methods nor adjustments of the applied approaches have been initiated. Instead, the scientific interest in a perceptual arrangement of odors has decreased in the last years.

Perception–based attempts have not delivered the anticipated results and the topic of odor classification appears to be off the table. More recent studies have focused on specific domains of this space (Chrea et al. 2009; Delplanque et al. 2012; Ferdenzi et al. 2011) or applied neuroimaging techniques to eventually uncover the rules of odor coding and arrangement (Gottfried et al. 2006; Howard et al. 2009). However, the "more objective" methods are incapable of discriminating the perceptual aspects of olfaction. Psychological classifications are still needed to understand the outcomes of these studies. Odor researchers should thus not lose sight of perception–based classification and focus on new approaches for establishing them. Impulses may be provided by the evolutionary functions of odors or their effects on human behavior (Holland et al. 2005; Liljenquist et al. 2010). Beyond this, more general principles of object categorization may be applied to odor perception. The concept of CP, for example, has been useful in understanding the processing of visual and auditory stimuli. CP explains how the mental arrangement of objects in cognitive classes affects the perception of their similarity and their mental processing, respectively. With respect to odor classification, it may facilitate the identification of classes and their relations to one another. As mental classes provide information on the distinctiveness of stimuli that overrule their actual physical similarity, observers should make faster judgments and fewer mistakes in discrimination tasks for odors from different mental categories. The acuity of their answers should peak at the boundary between 2 adjacent groups. Discriminability may also vary within a category given that some odors are perceived as more typical than others (Chrea et al. 2005). Psychophysical or behavioral approaches will, however, not directly address the origin of these categories. Whether odor categories are innate or acquired depends on the influence of language on odor processing. Hence, the unique and complex interaction between language and olfaction should be assessed more thoroughly. Several authors noted that odor classifications have been particularly affected by the linguistic or semantic arrangements of (supposed) odor sources rather than the sensory characteristics of odors (Chastrette et al. 1988; Chrea et al. 2005; Lawless 1989; Prost et al. 2001). Some have argued that odors are generally processed perceptually and only arranged semantically when (verbal or visual) identifiers are available (Chrea et al. 2005; Herz 2005). However, when subjects search for criteria to compare, sort or evaluate odors, they will primarily look for information on odor sources. If this information becomes available from contextual cues or memory it will dictate perceptual ratings (Bensafi et al. 2007; Distel and Hudson 2001; Djordjevic et al. 2008; Herz 2003; Herz and Clef 2001; Lorig and Roberts 1990; Lundström et al. 2006; Rolls et al. 2003). We thus raise the question whether any olfactory system will be unbiased by the linguistic classification of odor sources, or even more so, if olfactory systems may be in fact linguistic arrangements. Hence, the linguistic taxonomy of odor sources might be a close (if not the closest) approximation to the mental–perceptual arrangement of odors. To address this assumption further research on the interdependency of semantic categorizations on perceptual ratings is certainly needed.

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HOW DIFFERENCES IN RATINGS OF ODORS AND ODOR LABELS ARE ASSOCIATED WITH IDENTIFIACTION MECHANISMS

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Abstract

Introduction: Odor perception is biased by verbal–semantic processes when cues on an odor's source are readily available from the context. At the same time, olfaction has been characterized as basically sensation driven when this information is absent. In the present study, we examined whether language effects occur when verbal cues are absent and how expectations about an odor's identity shape odor evaluations.

Methods: A total of 56 subjects were asked to rate 20 unlabeled odor samples on perceptual dimensions as well as quality attributes and to eventually provide an odor source name. In a subsequent session, they performed the same rating tasks on a set of written odor labels that was compiled individually for each participant. It included both the 20 correct odor names (true labels) and in any case of incorrect odor naming in the first session, the self–generated labels (identified labels).

Results: We compared odor ratings to ratings of both types of labels to test whether differences between odor and odor label evaluations were rooted in identification mechanisms. In cases of false identifications, we found higher consistencies between the evaluation of an odor and its identified label than between the description of an odor and its true (yet not associated) label.

Conclusions: These results indicate that odor evaluations are strongly affected by the mental image of an odor rather than the actual sensory codes and that this mental image is built spontaneously. Our findings imply that odors and odor labels are evaluated similarly for identical objects and that the differences found in similar studies may have been rooted in different mental representations being evaluated.

Implications: Odor sensations provoke odor naming without explicit demand. These self–generated hypotheses about an odor’s source exert a considerable semantic impact on odor perceptual processing, regardless of their accuracy.

Introduction

The effect of language on odor perception and processing has been a matter of scientific debate for decades. The general role of verbal processes in olfaction has been discussed controversially (for a review, see Olofsson and Gottfried 2015) and is currently not yet fully understood. Meanwhile, it has been demonstrated repeatedly that verbal context information has considerable impact on odor evaluations: Verbal cues bias pleasantness ratings (Bensafi et al. 2007; Distel and Hudson 2001; Djordjevic et al. 2008; Herz 2003; Herz and Clef 2001; Lorig and Roberts 1990; Lundström et al. 2006; Moskowitz 1979; Rolls et al. 2003) as well as quality evaluations (Herz and Clef 2001; Stevenson and Mahmut 2013) and, finally, brain activation varies with the label presented with an odor (Araujo et al. 2005; Lorig and Roberts 1990; Lundström et al. 2006). Studies in this research area have usually paid particular attention to language effects triggered by overtly available verbal or visual cues. Can comparable effects be found in the absence of explicit source information in the perceptual context? Herz (2005) took a clear position on this question and proposed two different mental processes, or more specifically, a dual–coding hypothesis: In case a verbal identifier is present, odor processing is strongly language mediated. Without, odors are processed sensation driven. Olfactory perception neither depends on verbal coding nor does an odor automatically trigger verbal equivalents. This assumption has been substantiated by works that have repeatedly demonstrated (1) a poor naming ability for even familiar odors (Cain 1979; Cain and Potts 1996; Cain et al. 1998; Desor and Beauchamp 1974; Wijk and Cain 1994a; Wijk and Cain 1994b; Wijk et al. 1995) and (2) how odor recognition is unaffected by access to verbal labels (Ayabe–Kanamura et al. 1997; Lehrner 1993; Rabin and Cain 1984). However, despite our difficulties in odor naming, smell sensations are expressed as a *feature of* an odorous object in most languages ("the smell of…" or "smells like…) rather than as a *discrete, object–independent sensation* like, for example, a color (Berglund and Höglund 2012; Holley 2002; Majid 2015; Majid and Burenhult 2014; Wijk et al. 1995). Several authors have argued that a central – if not the major – function of odor perception may be the determination of the source that emanates a specific smell (Auvray and Spence 2008; Gibson 1966; Holley 2002;

Sugiyama et al. 2006). And when source information is not readily available from the perceptual context, it may be actively retrieved from memory as well. That means, perceptual processing (1) may be regularly accompanied by verbal–semantic processing and (2) these mechanisms of odor naming may occur spontaneously, triggered by an olfactory sensation itself. These assumptions are in line with empirical findings from several areas in olfactory research:

1. **Odor classifications:** language effects have been found in empirical evaluations of odors despite missing source cues. In classification studies, odors from the same lexical category (fruits, flowers) have been arranged together regardless of apparently dissimilar sensory codes (Ayabe–Kanamura et al. 1998; Carrasco and Ridout 1993; Prost et al. 2001; Seo et al. 2011; Urdapilleta et al. 2006) and cultural differences in odor arrangements have complied with culture–specific uses of odors (Chrea et al. 2005; Chrea et al. 2004; Ueno 1993). Remarkably, these identification effects have been found although participants have neither been provided with information on an odor's source nor been instructed to name the presented smells.
2. **Crossmodal associations between olfaction and vision:** Several studies have shown how language has mediated crossmodal associations between odors and stimuli of other sensory modalities, specifically vision. That is, expectations about an odor's identity have affected associations to colors and shapes (Dematte et al. 2006; Gilbert et al. 1996; Jacquot et al. 2016; Kaeppler 2018; Maric and Jacquot 2013, 2013; Spector and Maurer 2008; Zellner et al. 2008). Interestingly, this effect has not been found in languages like Maniq, Malay, or Thai that use a more comprehensive and abstract (rather than source–based) vocabulary to describe odors (Levitan et al. 2014; Valk et al. 2017) and whose speakers have less problems in naming odors correctly (Majid 2015; Majid and Burenhult 2014).
3. **Mental processing of odors:** Olofsson and Gottfried (2015) proposed that source object representations are established on an early stage of olfactory processing, presumably even ahead of valence encoding. In a series of studies they demonstrated 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).

Taken together, these findings imply that odor sensations may elicit a verbal referent or – more general – an object representation of an assumed source and although this representation is (veridically) incorrect in many cases, it may still affect the perceptual process and odor evaluations, respectively. Thus, *we assume that subjects build hypotheses about an odor's identity and that these assumptions, whether correct or incorrect, bias perception and shape odor evaluations.* To test this hypothesis, we adopted an approach used repeatedly to investigate the nature of mental odor representations: the comparison of evaluations of odor samples and mentally visualized odors (Breckler and Fried 1993; Carrasco and Ridout 1993; Chrea et al. 2005; Herz 2003). Applying this approach, previous studies have usually found differences between odor ratings and odor label ratings. These dissimilarities have been considered as an evidence for the sensation–driven processing of odors when verbal cues are absent and thus bolstered Herz' assumption of a dual coding. Remarkably, language effects caused by spontaneous odor identifications could be found in the results of all odor–label studies. False identifications may root incongruity between the rating of an odor and the rating of its correct label. Hence, the results of previous studies could have been affected by a comparison of apples and oranges, when participants actually evaluated (imagined) odors based on falsely generated labels. Hence, differences may not be created by different processing modalities (sensory versus verbal) but by different smells being rated. In the present study, we investigated whether the disparities in the way people rate odors and odor labels can be attributed to identification mechanisms. Specifically, we aimed to probe if evaluations of odors and equivalent (rather than correct) odor labels are similar – simply by matching each odor to both its true label and the name ascribed to it by each participant, in case it was identified incorrectly. In an *odor condition*, subjects were asked to rate 20 odorants on a 40–item attribute list (evaluation task) as well as on five perceptual dimensions (perceptual rating task) and to provide a verbal label for each odor presented (naming task). In a subsequent *imagery* *condition*, the same participants performed the evaluation task and rating task on a set of written verbal odor labels. For each participant, this set comprised both the correct names of the stimuli presented in the odor condition (true labels) *and* the labels generated by them in the naming task (identified labels). We compared the ratings of each odor to both its true and its identified label in order to evaluate the potential differences between objectively and subjectively matching odor–label pairs. If the assumption about an odor's source affects odor evaluation as we expected, we should find a better agreement between ratings of an odor and its identified label than between an odor and its true label if it has not been associated with this odor before.

Materials and Methods

Material

Odorants

We wanted to assess the impact of identification mechanisms. Thus, 20 common odorants were selected to cover a broad range of familiarity and identifiability (Cain et al. 1983; Chrea et al. 2009; Doty et al. 1984; Fornazieri et al. 2010; Hummel et al. 1997; Nordin et al. 1998) as well as different levels of typicality for an equivalent semantic category (Bueno and Megherbi 2009; Storms et al. 2001; van Overschelde et al. 2004). The set was not meant to represent the human olfactory space comprehensively. Nevertheless, we paid attention to the impact the odor selection would have on the scope of our results (for a review, see Crisinel et al. 2012). Odors and abbreviations used in the text are listed in Table 1. The majority of odorants was supplied as liquid solutions by Symrise (Holzminden, Germany). For COC, LAV, and VIO natural aromatic oils were used (Aromell, Germany). 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.

Table 1 Odorants used in the odor condition

Product name / substance (supplier)	Odorant	Abbreviation
1–Methoxy–4–(1–propenyl)benzene (Symrise)	Anise	ANI
Cinnamaldehyde (Symrise)	Cinnamon	CIN
Aromatic oil "Coco" (Aromell)	Coconut	COC
Curry essence (Symrise)	Curry	CUR
Elder flavor (Symrise)	Elder	ELD
Isoamyl acetate (Symrise)	Ice Drops	ISO
Aromatic oil "Lavender" (Aromell)	Lavender	LAV
Lemon oil (Symrise)	Lemon	LEM
Licorice flavor (Symrise)	Licorice	LIC
Mango flavor (Symrise)	Mango	MAN
Mustard flavor (Symrise)	Mustard	MUS
Aromatic oil "Patchouli" (Aromell)	Patchouli	PAT
Peanut flavor (Symrise)	Peanut	PEA
Peppermint oil (Symrise)	Peppermint	PEP
Allylcapronat (Symrise)	Pineapple	PIN
Phenylethyl alcohol (Symrise)	Rose	ROS
Strawberry flavor (Symrise)	Strawberry	STR
Ethyl acetate (Symrise)	Turpentine	TUR
Vanilla flavor (Symrise)	Vanilla	VAN
Aromatic oil "Violet" (Aromell)	Violet	VIO

Attribute List

The selection of attributes in verbal profiling approaches of odors has often been arbitrary. Usually, word lists have been derived from expert literature and applied with untrained subjects, who likely understood and used the terms differently (Lawless 1984; Solomon 1990, 1997). At the same time, an approach that tries to capture natural language has to necessarily build on an insufficient and predominantly source–based olfactory vocabulary, at least in Western languages (Majid and Burenhult 2014). We therefore applied a twofold method to derive a meaningful set of verbal descriptors in a systematic approach: We initially collected a comprehensive list of odor related terms used by experts and olfactory research and eventually applied a subset that was informative to untrained subjects.

An extensive literature review including odor classification studies (Coxon et al. 1978; Cunningham and Crady 1971; Dalton et al. 2008; Dravnieks 1985; Higuchi et al. 2004; Pilgrim and Schutz 1957; Prost et al. 2001; Zarzo 2008), odor profiles, and fragrance catalogs (Arctander 1969; Boelens and Haring 1981; Sigma–Aldrich Company 2011; Thiboud 1991) yielded a temporary list of 414 English terms: These referred to odor sources (n = 252), non–olfactory qualities (n = 122), olfactory qualities (n = 15), effects (n = 11), hedonic qualities (n = 9) and perceptual context (n = 5). An overview of all terms and their sources are available in Online Resource 1. As all study parts were conducted in the subjects' native language German, the complete list was translated into German and randomly divided in two subsets. Using an online questionnaire, these sets were presented to 100 participants each. Subjects were asked to rate the applicability of each attribute for describing the perceptual quality of an unspecified odor on a five–point scale (not at all applicable–very applicable). Ninety–six of these terms were judged as relevant by the majority of the subjects (selection criteria: rated with 4 or 5 by at least 50% of the respondents *and* rated with 1 or 2 by not more than 20% of the respondents) and further consolidated. (1) In order to weight different classes of characteristics equally, terms referring to odor sources with a common core characteristic, were replaced by a single term. For example: *Lemon, lime, grapefruit, orange, mandarin, citrus, fruity (citrus)* were substituted by the term *citrus*. (2) Terms that referred to very specific odor sources (*wet dog*, *fried chicken*) were replaced by the most distinctive feature. (3) Terms that represented odor qualities not exemplified by the odor set of the main study, were removed. This resulted in a final list of 40 attributes (Table 2). Despite thorough preliminaries, the set had eventually two shortcomings: It still included a number of terms that indicated odor sources or referred to a perceptual context. Further, it was rather complex and potentially difficult to handle for untrained subjects in the main study. A further consolidation lacked a reasonable approach. Therefore, we decided to apply the list as a compromise between a comprehensive set of expert terms and a sample of odor–related vocabulary found in Western cultures, corrected for the common predominance of crossmodal and source references.

Table 2 Attributes applied in the evaluation task

Alcoholic	Exotic	Menthol, minty	Savory
Aromatic	Fermented	Musty, moldy	Sharp
Baked	Fetid	Nutty	Sickening
Balsamic	Fishy	Oriental	Smoky
Bitter	Flowery	Pleasant	Solvent–containing
Burnt	Foul	Pungent	Spicy (herbs)
Cinnamon–like	Fresh	Putrid	Spicy (seasoning)
Citrus	Fried	Rancid	Sweet
Earthy	Fruity	Roasted	Tobacco–like
Ethereal	Intense	Salty	Woody

Procedure

Participants underwent two experimental sessions that were separated by approximately 2 weeks. Both conditions were conducted in the same well–ventilated room on university campus.

Odor Condition

Participants were instructed to place each odor pen under their nostrils at a distance of approximately 0.5 in and smell the odor by breathing normally. The presentation order of odors was fully randomized for each subject. Odors were presented one at a time with a break of at least 90 s between two odors. Each session lasted approximately 120 min. Answers were recorded using a computer–based questionnaire. Participants performed three tasks on each of the 20 odorants.

Evaluation Task: Subjects were instructed to rate each odor against a 40–attribute list using a nine–point rating scale ("How applicable is each term to describe the odor?" not at all applicable–very applicable). Attributes were arranged randomly for each odor.

Naming Task: First, participants rated the familiarity of each odor on a nine–point rating scale (not at all familiar–very familiar). They were then asked to freely identify each odor by providing the most accurate source name and to judge the certainty of their answer on a nine–point rating scale ("How certain do you feel in having identified the correct odor source?" not at all–very certain). Subjects were not forced to produce a source name. If a participant could not provide a label for a given odor, this case was classified as *misidentified without label*.

Perceptual Rating Task: Eventually, respondents assessed each odor on perceptual dimensions with high descriptive ability (Moss et al. 2016) using a nine–point rating scale: (1) intensity (low–high), (2) pleasantness (very unpleasant–very pleasant), and (3) edibility (not at all edible–edible).

Participants went through the tasks in this order (evaluation–naming–perceptual rating) and completed any given task for each of the 20 odorants before receiving instructions for the subsequent task. Note that subjects performed the evaluation task for *all* odors prior to the naming task and the perceptual rating task, i.e., attribute ratings were unaffected by an explicit demand to name the presented odorants.

Imagery Condition

In the imagery condition, participants were asked to rate a set of written verbal terms, each referring to a specific odor source. This set of terms was composed of 20 labels indicating the actual source of each odor (true label) plus up to 20 terms generated by each respondent in the naming task of the odor condition (identified labels). That is, for each participant the label set was composed individually in order to compare odor ratings and label ratings for both objectively and subjectively matching samples. When, for a given odor, the identification in the naming task was correct, nothing but the true label was presented. When, however, a subject misidentified the source, both the true and the identified source name were presented (separately). If, for example, a participant was able to name all odors correctly, the label set consisted of 20 true labels. If, on the contrary, a subject misidentified each odor, the label set consisted of 20 true labels and 20 identified (but incorrect) labels. If a participant could not produce a label for a particular odor, it was classified as *misidentified without label*. As an identified label was missing, only a true label could be presented in the imagery condition. These cases were considered accordingly in the data analysis.

Odor names were presented written at the top of a computer–based rating form. Respondents were instructed to mentally imagine each odor as vivid as possible.

Evaluation Task: Subjects were instructed to rate each odor against the 40–attribute list using a nine–point rating scale. The order of attributes was fully randomized for each label. Labels were evaluated one after another in a fully randomized order.

Perceptual Rating Task: Additionally, respondents were asked to rate the odor specified by each label on intensity, pleasantness and edibility using a nine–point rating scale. Labels were evaluated one after another in a fully randomized order.

Participants went through both tasks in this order (evaluation–perceptual rating) and completed the evaluation of all labels before receiving instructions for the perceptual ratings task.

The whole experimental procedure for each participant is illustrated in Fig. 1.

Participants

In total, 56 participants (41 women; mean age = 21.73, SD = 2.64) were recruited from Leuphana University of Lueneburg and participated for course credit. They were tested individually. All respondents reported a normal sense of smell; they were free of respiratory infections or allergies at the time they were being tested. Participants were instructed not to use perfume, body lotions or odorous cosmetics at the day of testing, not to eat intensely spiced foods and not to smoke 1 h prior to the experimental session. Subjects neither had previous experience in olfactory testing nor were trained in odor evaluation or identification. The experiment was conducted in their native language German. Subjects provided verbal informed consent. They were informed that the experiment aimed to study odor perception and evaluation in general. At the end of the second session, subjects 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.

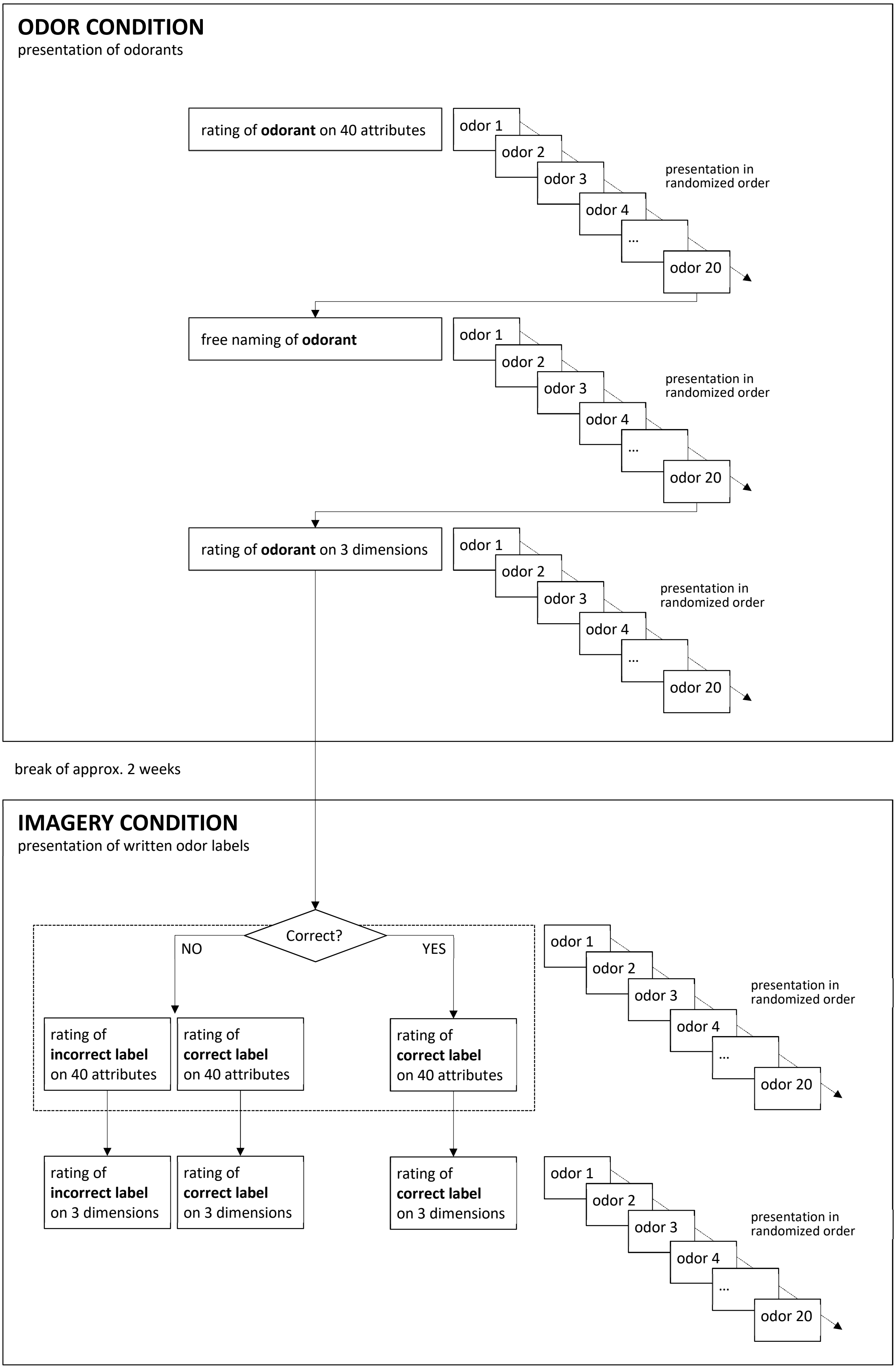

Fig. 1 Experimental procedure

Results

Based on the naming accuracy in the naming task, we distinguished three odor–label–pairings to assess the agreement between odor ratings and label ratings as a function of naming accuracy: *ideal*, *congruent* and *incongruent pair* (Table 3).

Ideal pair: An odor was identified correctly in the naming task. For this odor, only the true label was presented in the imagery condition. Hence, odor ratings were compared to the ratings of a label that was not only correct, but had also been associated with this odor by the subject before. For example: presentation of PEA in odor condition, correct identification as "peanut" by the subject, presentation of odor label "peanut" in the imagery condition. Ideal pairs required correct odor identification in the naming task. If, however, an odor was identified incorrectly, the subject was presented with two different labels in the imagery condition: the wrong label produced by the subject as well as the true label. *Congruent pair:* An odor was identified incorrectly in the naming task. The identified label was presented in the imagery condition. For example: presentation of PEA in odor condition, identification as "chocolate" by the subject, presentation of odor label "chocolate" in the imagery condition. Although they were objectively different, odor and odor label subjectively referred to the same thing. *Incongruent pair:* An odor was identified incorrectly in the naming task. The true label was presented in the imagery condition. For example: Presentation of PEA in odor condition, identification as "chocolate" by the subject, presentation of odor label "peanut" in the imagery condition. Odor and odor label factually refer to the same thing, but may still not match for the subject that named the odor differently. Usually, each incongruent pair had a corresponding congruent pair. If, however, a participant could not produce a label for a specific odor, this odor was classified as *misidentified without label*. In this case, only a true label could be presented in the imagery condition, although this had not been associated with the odor before. Odor and label made up an incongruent pair, a matching congruent odor–label pair was missing.

Table 3 Possible pairings of odor and odor label between odor and imagery condition

Odor condition		Imagery condition	Odor–label pairing
Presentation	Identification	Presentation	
A	A (correct)	A (true label)	Ideal pair
A	B (incorrect)	A (true label)	Incongruent pair
A	B (incorrect)	B (identified label)	Congruent pair

Perceptual ratings of familiarity intensity, pleasantness, and edibility of an odor were treated as metric data (cf. Seo et al. 2008). Attribute ratings were analyzed on ordinal level as they represent the degree of appropriateness of a specific term in describing an odor quality. With respect to correlations, we calculated Spearman's coefficients as data was not normally distributed (details may be requested from the author). Testing revealed no significant gender differences. Hence, data was collapsed across gender. We applied an exploratory step–by–step approach to the data. We first analyzed the whole data set and subsequently focused on subsets based on identification accuracy or ambiguity. All statistical analyses were conducted with SPSS statistics (version 24.0) for Windows.

Identifications

Rates of correct identification varied considerably across odors. Overall, odorants were identified correctly in about 37.59% of the cases (across all odorants and subjects). Given that an incorrect label might still be reasonably close to the accurate source name, we adopted a scheme proposed by Cain (1979). Following this approach, we further categorized inaccurate labels in *near misses* – names of substances that are perceptually or semantically similar to the true odor source (*melon* for *pineapple*), and *far misses* – vague category labels (*fruit* for *pineapple*) or evidently incorrect labels (*glue* for *pineapple*). Near misses may be treated as correct identifications (Sulmont–Rossé 2005) which lead to a remarkable increase in correct identifications overall (58.75%) and especially for several odors like ANI, CIN, ISO, MUS, PAT, ROS, and TUR (Fig. 2).

Note that with respect to odor–label pairs, both near and far misses were treated as incorrect identification.

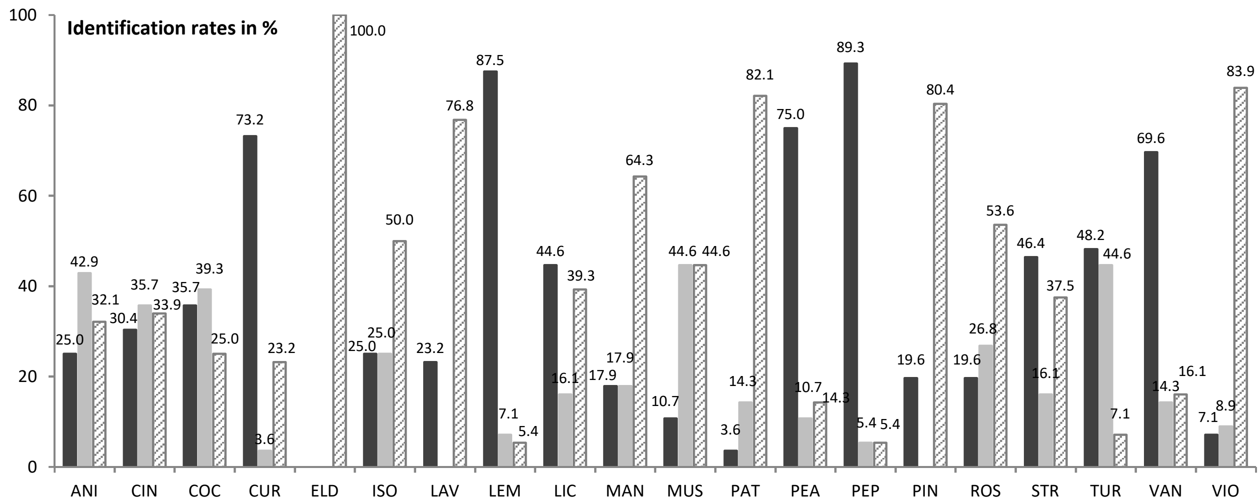

Fig. 2 Identification rates: correct identification (dark gray bars), near miss (light gray bars) and far miss (shaded bars)

A significant positive relationship was found between odor familiarity and naming certainty ($r_s = 0.732$, $p < 0.01$). Subjects were more confident in finding the correct name for odors that appeared familiar to them (Online Resource 2).

Perceptual Ratings

We first compared odors and odor labels by directly matching the ratings for odor samples and associated true labels as it has been done in previous studies (Bonfigli et al. 2002; Breckler and Fried 1993; Chrea et al. 2005). Odor–label–agreements for intensity, pleasantness, and edibility ratings were analyzed by a Mann–Whitney *U* test. Scores on all dimensions were found to vary considerably between both perceived and imagined odors: Intensity ratings differed significantly for eleven of 20 odor–label–pairs, pleasantness ratings for 16, edibility ratings for 15 (Online Resource 3). These results match the findings of previous studies that applied the same approach (Bonfigli et al. 2002; Breckler and Fried 1993; Chrea et al. 2005; Herz 2003). Interestingly, highly significant differences between odor and odor label ratings were especially found for *ambiguous odors*, i.e., odors that were repeatedly matched with either one or a very dissimilar source label across participants (for example: PIN was identified as *fruit* in 30 cases, and as *cleanser* or *solvent* in 14 cases).

Ambiguous Odors

We specified five odors as ambiguous (PIN, ELD, ISO, LAV, MUS) and further analyzed these samples to assess whether high odor–label dissimilarities could be rooted in different assumptions about an odor's source. Truly, pleasantness as well as edibility ratings were significantly higher ($p < 0.001$) for PIN when identified as a *fruit* (n = 30) than as *cleanser* or *solvent* (n = 14). A comparable pattern of significant differences was found for ELD, ISO, LAV, and MUS for pleasantness as well as edibility ratings (Table 4).

Table 4 Mean scores for pleasantness and edibility ratings in odor condition for ambiguous odors (Mann–Whitney *U* test)

					Pleasantness			Edibility		
Odorant	Identification A	n_A	Identification B	n_B	M_A	M_B		M_A	M_B	
ELD	Beverage, fruit, flower	20	Rotten fruit, organic waste	10	4.30	1.70	***	3.85	1.00	*
ISO	Candy	28	Solvent (as in paint or glue)	19	4.46	2.16	***	4.82	0.42	***
LAV	Lavender	13	Cleanser, disinfectant	8	5.15	2.31	**	2.75	0.25	*
MUS	Pungent condiment or vegetable	31	Chemicals, trash	9	3.81	0.33	***	5.06	0.00	***
PIN	Fruit	30	Cleanser, solvent	14	4.30	2.21	***	4.53	0.64	***

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Note, that these perceptual ratings *followed* the naming task. That means, the explicitly requested source labels biased these evaluations. By contrast, the evaluation of all odors on the 40 attribute terms *preceded* odor naming. However, when odor naming is triggered spontaneously, identification mechanisms would affect these ratings as well. For each ambiguous odor, attribute ratings of both assigned labels were contrasted. Results of this comparison are shown in Table 5.

Table 5 Median of attribute ratings in odor condition for ambiguous odors (Mann–Whitney *U* test)

	ELD[1]			ISO[2]			LAV[3]			MUS[4]			PIN[5]		
Attribute	Mdn_A	Mdn_B		Mdn_A	Mdn_B		Mdn_A	Mdn_B		Mdn_A	Mdn_B		Mdn_A	Mdn_B	
Alcoholic	–	–	–	2.0	5.0	***	6.0	2.5	**	–	–	–	–	–	–
Aromatic	4.0	1.5	*	3.5	0	***	0	5.0	***	4.0	0	**	4.0	0	**
Baked	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Balsamic	4.0	1.0	*	2.0	0	**	4.0	2.0	**	–	–	–	–	–	–
Bitter	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Burnt	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cinnamon–like	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Citrus	–	–	–	2.0	0	*	–	–	–	–	–	–	–	–	–
Earthy	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ethereal	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Exotic	–	–	–	1.0	0	**	–	–	–	–	–	–	5.0	1.0	**
Fermented	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fetid	0	2.5	**	0	3.0	**	0	2.0	*	2.0	7.0	***	–	–	–
Fishy	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Flowery	–	–	–	1.5	0	**	6.0	0	***	–	–	–	3.0	0	**
Foul	–	–	–	–	–	–	–	–	–	0	4.0	**	0	0	*
Fresh	4.5	1.0	*	4.5	1.0	***	–	–	–	–	–	–	–	–	–
Fried	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fruity	–	–	–	3.5	0	**	–	–	–	–	–	–	6.5	1.5	**
Intense	–	–	–	6.0	8.0	**	–	–	–	–	–	–	–	–	–
Menthol, minty	1.0	0	*	3.0	0	**	–	–	–	–	–	–	–	–	–
Musty, moldy	0	2.5	**	–	–	–	–	–	–	0	3.0	**	0	0.5	*
Nutty	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Oriental	–	–	–	0	0	**	2.0	0	*	–	–	–	2.0	0	*
Pleasant	4.0	1.0	**	3.5	1.0	***	6.0	0	***	3.0	0	**	4.0	1.5	**
Pungent	–	–	–	3.0	6.0	**	0	3.5	*	–	–	–	–	–	–
Putrid	0	5.0	**	–	–	–	–	–	–	0	3.0	**	–	–	–
Rancid	0	3.0	**	–	–	–	–	–	–	0	3.0	***	–	–	–
Roasted	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Salty	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Savory	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sharp	–	–	–	–	–	–	–	–	–	7.0	3.0	**	–	–	–
Sickening	0	2.0	*	0	2.0	**	–	–	–	1.0	6.0	***	–	–	–
Smoky	–	–	–	–	–	–	–	–	–	–	–	–	1.0	4.0	**
Solvent–containing	–	–	–	1.0	7.0	***	0	2.5	**	0	2.0	*	–	–	–
Spicy (herbs)	–	–	–	1.0	0	**	6.0	1.5	**	–	–	–	–	–	–
Spicy (seasoning)	–	–	–	0	0	**	–	–	–	–	–	–	–	–	–
Sweet	–	–	–	4.0	2.0	**	–	–	–	–	–	–	5.0	2.0	**
Tobacco–like	–	–	–	–	–	–	–	–	–	–	–	–	0	0	*
Woody	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Table 5 (continued)

[1] A = fruit (n = 20), B = organic waste (n = 10)

[2] A = candy (n = 28), B = solvent (n = 19)

[3] A = lavender (n = 13), B = disinfectant (n = 8)

[4] A = condiment (n = 31), B = chemical (n = 9)

[5] A = fruit (n = 30), B = cleanser (n = 14)

Note: median scores listed for significant differences only

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Differences could not be found for each of the 40 terms, but for those descriptors one would reasonably expect to differ between the two ambiguous odor labels. For example, ISO identified as *candy* should not differ from ISO identified as *solvent* on attributes like *baked, bitter, burnt, earthy,* etc. At the same time, both cases should differ on *alcoholic, balsamic, fresh, solvent–containing,* etc.

That means, the same odor was rated significantly different on quality attributes when it was identified differently, although the rating task preceded the naming task.

The directions of these differences varied from those we had expected in only two cases for LAV, where *lavender* received lower ratings on *aromatic* and higher ratings on *alcoholic* than *disinfectant*.

Odor–Label Associations for Perceptual Ratings

Different from previous studies, we calculated odor–label agreements separately for ideal, congruent and incongruent pairs, respectively. If differences between odor and odor–label evaluations are rooted in identification mechanisms, then false identifications should result in a better agreement for pairs of odor and identified label (i.e., congruent) than for pairs of odor and true label (i.e., incongruent). Spearman's correlation coefficients for intensity, pleasantness, and edibility ratings for each of the 20 odorants are shown in Table 6. Across all pairings, positive correlations were found for the majority of cases; 49.12% of these correlations reached significance. Average correlation coefficients were calculated by transformation of correlation scores to Fisher's Z values; 95%–confidence intervals were calculated for each score in order to compare correlations pairwise (congruent–incongruent, congruent–ideal).

For all perceptual ratings, mean correlations for congruent pairs (intensity, r_{mean} = 0.382; pleasantness, r_{mean} = 0.593; edibility, r_{mean} = 0.644) were significantly ($p < 0.05$) higher than for incongruent pairs (intensity, r_{mean} = 0.237; pleasantness, r_{mean} = 0.212; edibility, r_{mean} = 0.184). At the same time, no significant differences were found between congruent and ideal (intensity, r_{mean} = 0.421; pleasantness, r_{mean} = 0.529; edibility, r_{mean} = 0.544) odor–label pairs.

Interestingly, this pattern could be found for intensity ratings as well, though less emphasized than for pleasantness and edibility. One might question whether an untrained subject or anybody is able to rate the intensity of an imagined odor and whether the consistencies found are rooted in the congruence between odor and odor label. Interestingly, identification mechanisms can help to understand these findings: When participants inferred intensity of an odor based on what they meant, the source of the odor to be (in odor and imagery condition alike), an intensity rating may not reflect the actual (or imagined) strength of a smell. It may rather reveal associations of pleasantness or familiarity with an odor source that have in turn influence on intensity evaluations (Ayabe–Kanamura et al. 1998; Distel et al. 1999; Distel and Hudson 2001; Doty 1975; Henion 1971; Hudson and Distel 2002; Moskowitz et al. 1976; Royet et al. 1999; Sulmont et al. 2002).

Table 6 Spearman's correlation coefficients for odor and label ratings sorted by pairings

Odorant	n_I	$n_{C/IC}$	n_M	Intensity Ideal	Intensity Congruent	Intensity Incongruent	Pleasantness Ideal	Pleasantness Congruent	Pleasantness Incongruent	Edibility Ideal	Edibility Congruent	Edibility Incongruent
ANI	14	41	1	.144	.301	.267	0.491	.548 **	.580 **	.642 *	.555 **	.325 *
CIN	17	37	2	.255	.309	.533 **	0.157	.452 **	.347 *	.288	.580 **	.293
COC	20	35	1	.677 **	.217	–.100	0.614 **	.603 **	.149	.425	.414 *	.072
CUR	41	14	1	.559 **	.425	.372	0.290	.133	.261	.671 **	.344	.530
ELD	0	50	6	–[2]	.424 **	.355 *	–[2]	.569 **	–.120	–[2]	.763 **	–.025
ISO	14	40	2	.349	.587 **	–.014	0.689 **	.540 **	.292	.685 **	.738 **	–.109
LAV	13	42	1	.073	.480 **	.187	0.585 *	.724 **	.073	.251	.597 **	.318 *
LEM	49	7	0	.053	–.365	.671	0.499 **	.685	.766 *	.608 **	.548	.404
LIC	25	29	2	.169	.184	.275	0.645 **	.774 **	.566 **	.685 **	.462 *	.154
MAN	10	41	5	.139	.350 *	.131	0.453	.502 **	.032	.298	.734 **	.175
MUS	6	44	6	.492	.556 **	.403 **	–0.079	.644 **	.412 *	.857 *	.867 **	.350 *
PAT	2	51	3	–[2]	.367 **	.390 **	–[2]	.675 **	–.117	–[2]	.466 **	.235
PEA	42	13	1	.732 **	.497	.455	0.407 **	.731 **	.251	.424 **	.897 **	.405
PEP	50	6	0	.511 **	.671	.612	0.582 **	.940 **	.761	.393 **	.794	.216
PIN	11	40	5	.514	.144	.066	0.915 **	.559 **	.180	.654 *	.760 **	–.005
ROS	11	45	0	.174	.369 *	.337 *	0.263	.651 **	.224	.793 **	.727 **	.243
STR	26	29	1	.622 **	–.022	.033	0.629 **	.617 **	.296	.348	.378 *	.340
TUR	27	28	1	.387 *	.326	–.088	0.723 **	.448 *	.043	.636 **	.219	.068
VAN	39	17	0	.304	.518 *	.370	0.495 **	.448	.140	.580 **	.667 **	–.150
	4	47	5	–[1]	.620 **	.144	–[1]	.501 **	.173	–[1]	.622 **	.185

Table 6 (continued)

n_I: number of cases considered for ideal pairs

$n_{C/IC}$: number of cases considered for congruent and incongruent pairs

n_M: number of excluded cases; If a subject could not produce a label for a specific odor in the naming task, this odor was classified as misidentified without label. In this case, only a true label could be presented in the imagery condition, although it had not been associated with the odor before. The odor–label–pair was incongruent, the corresponding congruent pair was missing. These cases were excluded pairwise.

[1] No correlation coefficient calculated for n < 5

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Odor–Label Associations for Attribute Ratings

To assess odor–label agreements for attribute ratings, Euclidean distances between odors and related labels were calculated across all 40 attributes, separately for each odor sample. For this purpose, attribute values were converted to normalized rank scores (between 0 and 1) that can be treated as interval–scaled data. The calculated Euclidean distances were again re–scaled into a 0–1 range, where a score of 0 indicates identical ratings of an odor and its corresponding label across all attributes and 1 indicates the maximum difference in ratings. Euclidean distance scores were averaged for ideal, congruent and incongruent pairs, respectively (Table 7).

As expected, averaged distances were found to be significantly smaller for congruent (M = 0.219, SD = 0.026) than for incongruent odor–label pairs (M = 0.251, SD = 0.042), $t(19) = –4.57$, $p < 0.001$. A significant difference was also found between ideal (M = 0.174, SD = 0.047) and incongruent odor–label pairs, $t(19) = –5.09$, $p < 0.001$.

Table 7 Double–scaled Euclidean distances of attributes ratings averaged across all subjects

	Euclidean distances of attribute ratings		
Odorant	Ideal	Congruent	Incongruent
ANI	0.211	0.233	0.253
CIN	0.209	0.221	0.284
COC	0.203	0.200	0.236
CUR	0.175	0.281	0.273
ELD	– [1]	0.249	0.294
ISO	0.177	0.207	0.294
LAV	0.213	0.210	0.289
LEM	0.172	0.222	0.193
LIC	0.198	0.211	0.244
MAN	0.184	0.180	0.202
MUS	0.156	0.239	0.260
PAT	0.165	0.243	0.330
PEA	0.189	0.238	0.290
PEP	0.178	0.175	0.190
PIN	0.180	0.232	0.285
ROS	0.131	0.226	0.263
STR	0.166	0.183	0.181
TUR	0.164	0.200	0.209
VAN	0.177	0.224	0.220
VIO	0.224	0.197	0.231
Mean Score	0.174	0.219	0.251

[1] No correct identifications

Discussion

The major aim of the study was to assess if subjects (1) build hypotheses about an odor’s identity and (2) whether these assumptions – correct or incorrect – bias perceptual processes. We specifically investigated how differences between odor ratings and odor–label ratings might be attributed to odor identification mechanisms. We found a generally better agreement between the evaluation of an odor and its identified label than between the evaluation of an odor and its true (yet not associated) label. Our results indicate that basic perceptual as well as attribute–related odor ratings are affected by the mental image of an odor. Further, this mental image is probably built upon an explicit request and a spontaneous identification attempt alike.

More specifically, our findings provide an alternative explanation to the results of previous studies that have applied a comparable approach and substantiated the Herz' idea of dual coding in olfaction (Herz 2003; 2003; 2005) proposed that people willingly gather information on an odor's source from the external context and that these cues exert a considerable influence on mental odor processing. They may be equally willing to retrieve this information from memory with the help of self–generated source labels and without an explicit invitation to do so. Although these labels are incorrect in many cases, they may overwrite sensory information just as contextual cues can do. Thus, a language–based coding of odors might not be limited to situations where source cues are evidently available. This conclusion is supported by our data and previous research alike. Although comparable studies typically concluded that odors and odor labels induce different mental representations, they usually also found consistencies that could have been caused by unprompted identifications and subsequent language effects (Breckler and Fried 1993; Carrasco and Ridout 1993; Chrea et al. 2005; Herz 2003). Specific empirical evidence for the assumption that people build ideas about an odor's identity spontaneously has been provided by Zellner et al. (2008). In a series of experiments, they asked subjects to (among other tasks) choose appropriate colors for six fine fragrances and to rate the odors on the dimensions masculinity and femininity. They found that the categorizations of an odor as masculine or feminine significantly affected the matching of colors to these fragrances – even if subjects were asked to rate masculinity and femininity only after the color matching task. Zellner and colleagues concluded that a (gender) categorization of fragrances might be triggered automatically as fine fragrances are usually explicitly marketed as masculine or feminine. The impact of odor labels on perceptual ratings has been addressed by Stevenson and Mahmut (2013). They assessed the consistency of perceptual ratings (familiarity, intensity, edibility, pleasantness, activity, potency) over two test occasions separated by a 20–min intermission: Evaluations remained stable (in comparison to chance level) when odors were named consistently in both stages, with highest reliability scores for edibility and pleasantness ratings.

Our results suggest a generally lower impact of odor names on perceptual ratings (pleasantness, edibility, and particularly intensity) than on odor quality descriptions (attributes). This effect may be rooted in a process of preverbal identification (Herz and Eich 1995) or recognition without identification (Cleary et al. 2010) – the access to episodic memory content such as familiarity, likeability, or general source category ahead of odor naming. From an evolutionary perspective, it seems reasonable that basic olfactory assessments are quick and affected by semantic criteria to a lesser extent (Yeshurun and Sobel 2010). Olofsson and Gottfried (2015) contradicted this proposition and provided evidence that odor object representations are built very early in mental odor processing. Remarkably, these configural odor objects are a blending of single perceptual qualities where distinctive features become inaccessible as soon as an object representation is created. That means, although olfactory sensations are very likely classified instantly in order to reveal the presence of a source object (Holley 2002), in terms of an evolutionary survival strategy, these classifications could be narrowed to a judgment on familiarity, attraction or rejection, respectively (Köster 2002; Köster 2005). Hence, the specific odor source might or might not be relevant in the very first stages (or the whole) perceptual process. Whether this is true for odor perception in general or limited to the specific context of an odor study remains to be answered.

Limitations

We are aware of several limitations of the study: First, due to a complex setting, the study sample was rather small. Considering subsets of the data in an exploratory approach resulted in sometimes too few cases for a proper analysis or statements of practical significance.

Second, across all subjects and odors the most frequently applied rating on attributes was “0” (“not at all applicable”). This might express that an odor sample did not at all smell *fruity, earthy, bitter,* etc. to a rater’s mind. However, when running the experiments, we observed that subjects frequently rated attributes with “not at all applicable” when they expressed general problems in verbalizing their olfactory sensations. In this case, a “0” may reveal a rater’s insecurity rather than an odor quality. These artifacts certainly increase the ambiguity of the data and reduce its explanatory power. The subjects’ uncertainty may be rooted in the general difficulty of untrained subjects to verbally describe odors (Lawless 1984; Levinson and Majid 2014; Solomon 1990, 1997, for a review, see Crisinel et al. 2012). Beyond that, the large number of attributes might have hampered the rating process. As a result, the differences between odor and label ratings were found to be rather small for all types of pairings: The highest calculated Euclidean score was 0.330 on 0–1 range. That means, that completely different items (incongruent odors and labels) are still described rather similarly and not completely different from identical items (ideal and congruent odor–label pairs) on verbal attributes. Additionally, Euclidean distance scores turned out to be a generally weak measure of (dis)similarity as they relied on a substantial und unweighted aggregation of data across attributes and subjects. While an assessment on attribute–level provided meaningful insights, this approach was limited to ambiguous odors with a sufficient number of cases.

Third, non–experts are not only limited in verbalizing odor sensation. They often have difficulties in building olfactory mental images (Arshamian and Larsson 2014), especially when odors are hard to identify (Stevenson et al. 2007). Thus, we cannot determine with certainty which kind of object participants actually rated in the imagery condition. While some respondents might have generated vivid mental representations of olfactory events as requested, others may have relied on their crossmodal associations of a given source label.

Finally, we need to consider the universality of our findings carefully. The shown effects may strongly depend on the specific cultural context of the odor study in general as well as the odor lexicon of the participants. Our conclusions were drawn from a German sample and may (if at all) be generalized only to languages that rely on a comparable source–based odor vocabulary. Further research on cultural groups with more abstract odor languages is needed. Considering previous cross–cultural research (Levitan et al. 2014; Majid 2015; Majid and Burenhult 2014; Valk et al. 2017), it is questionable that, for example Thai, Maniq, or Jahai participants would show a similar propensity towards instant odor naming and comparable effects of identification mechanisms.

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CROSSMODAL ASSOCIATIONS BETWEEN OLFACTION AND VISION: COLOR AND SHAPE VISUALIZATIONS OF ODORS

Reference

Kaeppler K (2018) Crossmodal associations between olfaction and vision: color and shape visualizations of odors. Chem Percept 11:95–111

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.

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 (Tables 1a, 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 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 1a). 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. 2017).

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.

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

		Odors				Results		
Study (chronological order)	Dimension	Number	Qualities	Crossmodal stimuli	Matching approach	LI[1]	CM[2]	SM[3]
Fiore (1993)	Color (lightness)	3	Floral, chypre, oriental	30 fabric swatches varying in color, texture, shape	Rating of fit on a seven–point scale	x		
Gilbert et al. (1996)	Color	20	Aldehyde C–16, bergamot oil, birch tar oil, caramel lactone, cinnamic aldehyde, civet artifical, 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		x	x
				1 565 color chips varying in hue, saturation and brightness	Matching of one color to each odor		x	x
Kemp & Gilbert (1997)	Color (lightness)	15	Five odors in three concentrations each: caramel lactone, cinnamic aldehyde, aldehyde C–16, galbanum oil, methyl anthranilate	1 565 color chips varying in hue, saturation and brightness	Matching of one color to each odor	x		
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	17 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	x	x	
Demattè et al. (2006)	Color (hue)	6	Caramel, cucumber, leather, lemon, spearmint, strawberry	10 color patches: red, orange, yellow, green, turquoise, blue, purple, pink, brown, gray	Matching of one color to each odor		x	x
Zellner et al. (2008)	Color (hue terms)	6	Three feminine fragrances: Beautiful, Calyx, Tresor three masculine fragrances: Ralph Lauren Polo, Hugo Boss, Drakkar Noir	11 color terms: red, orange, yellow, green, blue, purple, brown, white, pink, gray, black	Rating of fit by distributing five points across color terms		x	x
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	12 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		x	x
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		x	x

Table 1 (continued)

Levitan et al. (2014)[4]	Color	14	Burnt, candy, fish, flower, fruity, hazelnut, meat, musty, plastic, rice, soap, vegetable, vinegar, woody	36 color patches varying in hue, saturation and brightness	Selection of three most congruent and three most incongruent colors for each odor		x	x
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	24 color patches varying in hue, saturation and brightness	Matching of one color to each odor		x	x
Valk et al. (2017)[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, galangal; 5 odors common in both cultures: banana, tobacco, garlic, canned fish, cooked rice	84 color chips varying in hue, saturation and brightness	Matching of one color to each odor		x	x

b

		Odors				Results		
Study (chronological order)	Dimension	Number	Qualities	Crossmodal stimuli	Matching approach	AI[5]	AP[6]	AT[7]
Fiore (1993)	Shape (angularity)	3	Floral, chypre, oriental	30 fabric swatches varying in color, texture, 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	18 abstract symbols varying in shape, complexity, 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	

Table 1 (continued)

[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)

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.

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 (Symrise)	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

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 naïve 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.

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, highest naming accuracy was found for LEM (86.67%) and PEP (80%), 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.

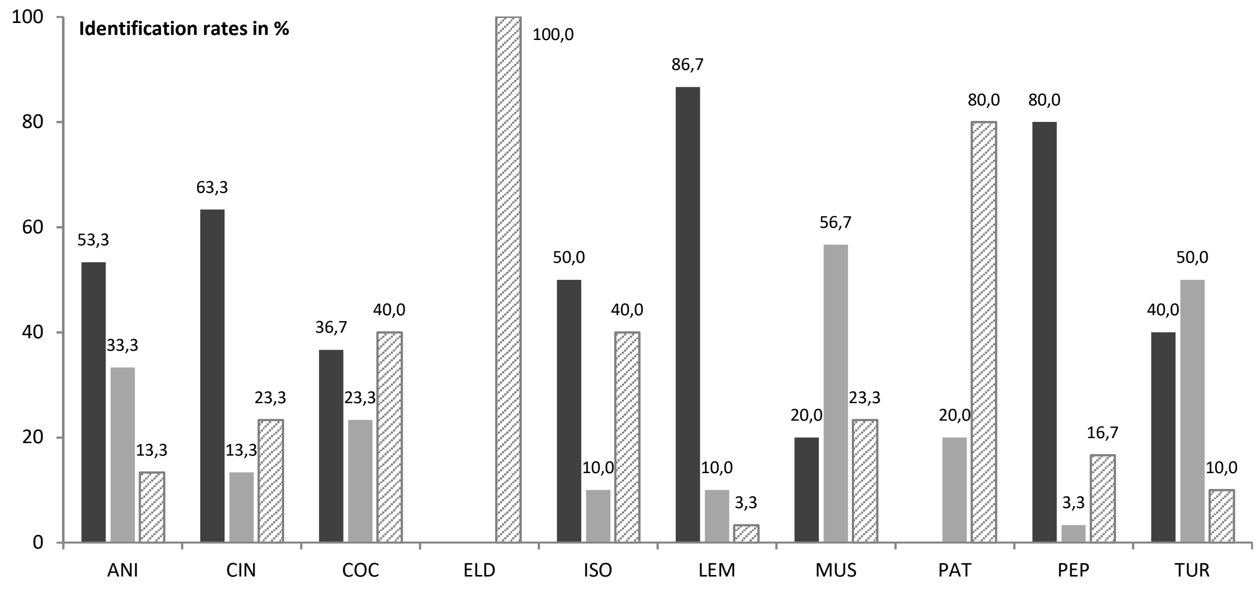

Fig. 1 Identification rates: correct identification (dark gray bars), near miss (light gray bars) and far miss (shaded bars)

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).

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.

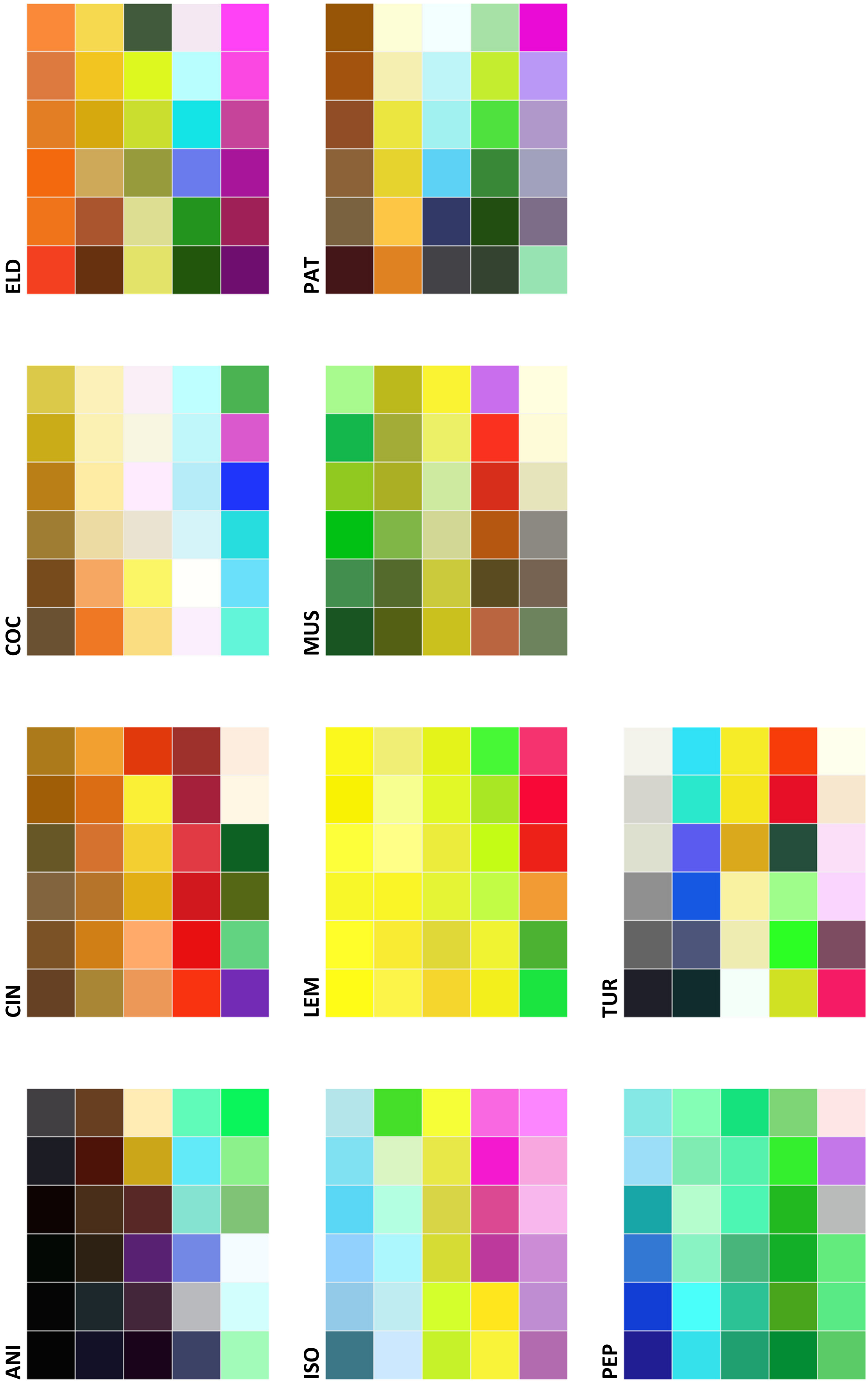

Fig. 2 Color matching for each odor. Patches are sorted by color, not by subject

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.

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°)

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.

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

*$p < 0.05$; **$p < 0.01$

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

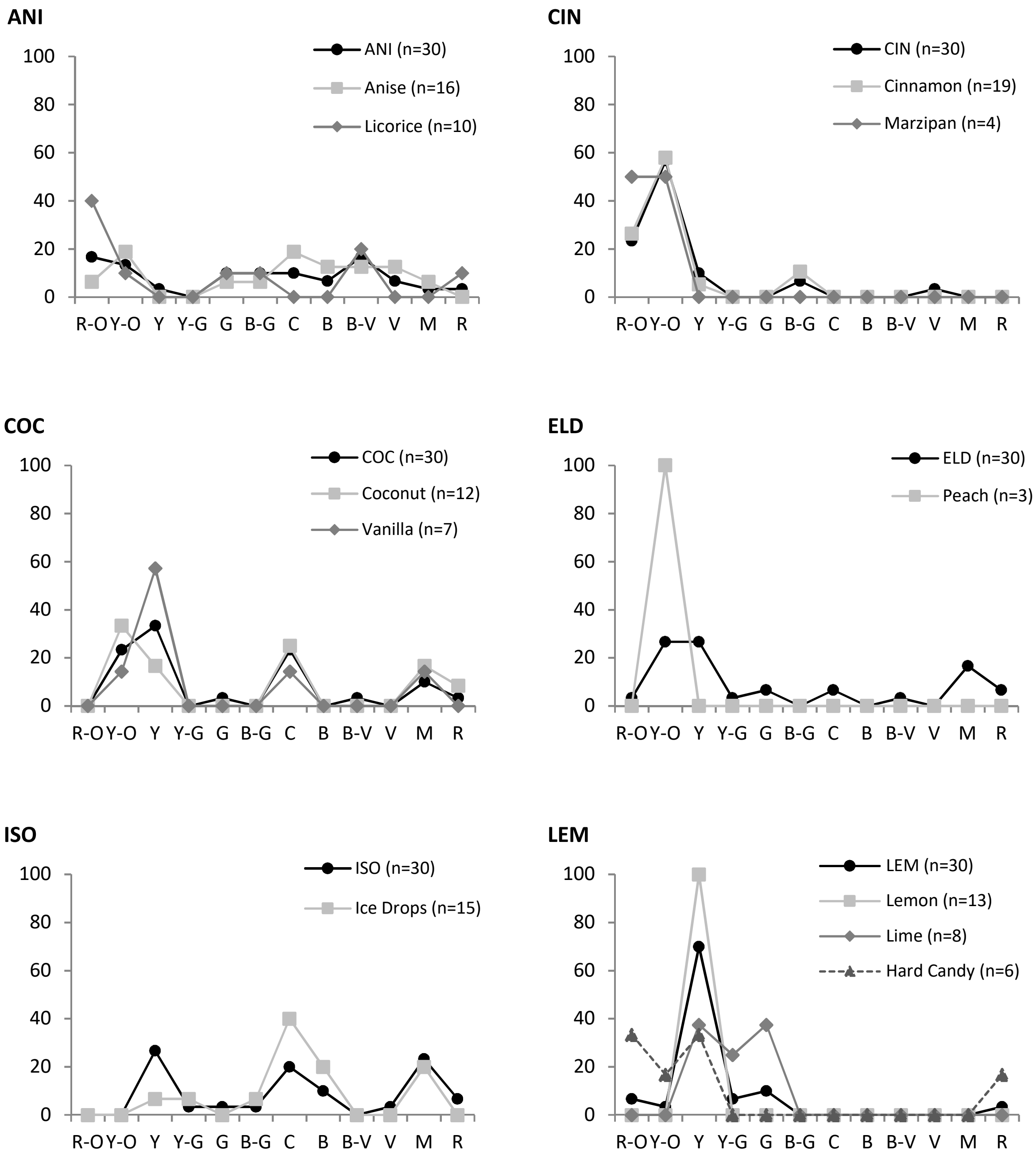

Fig. 3 Color hue profiles for each odor across all judgments and as a function of assumed odor source name; x–axis: R–O red–orange (346°–15°); Y–O yellow–orange (16°–45°); Y yellow (46°–75°); Y–G yellow–green (76°–105°); G green (106°–135°); B–G blue–green (136°–165°); C cyan (166°–195°); B blue (196°–225°); 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 %)

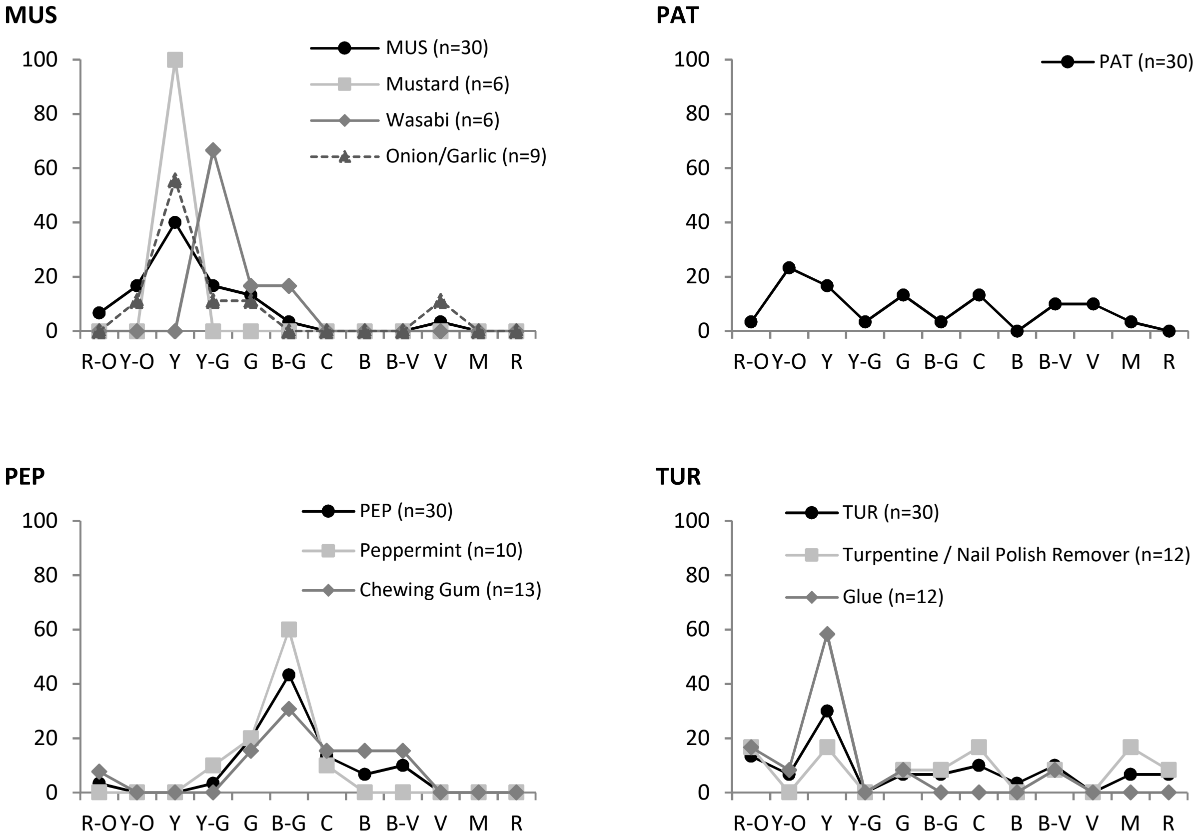

Fig. 3 (continued)

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.

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

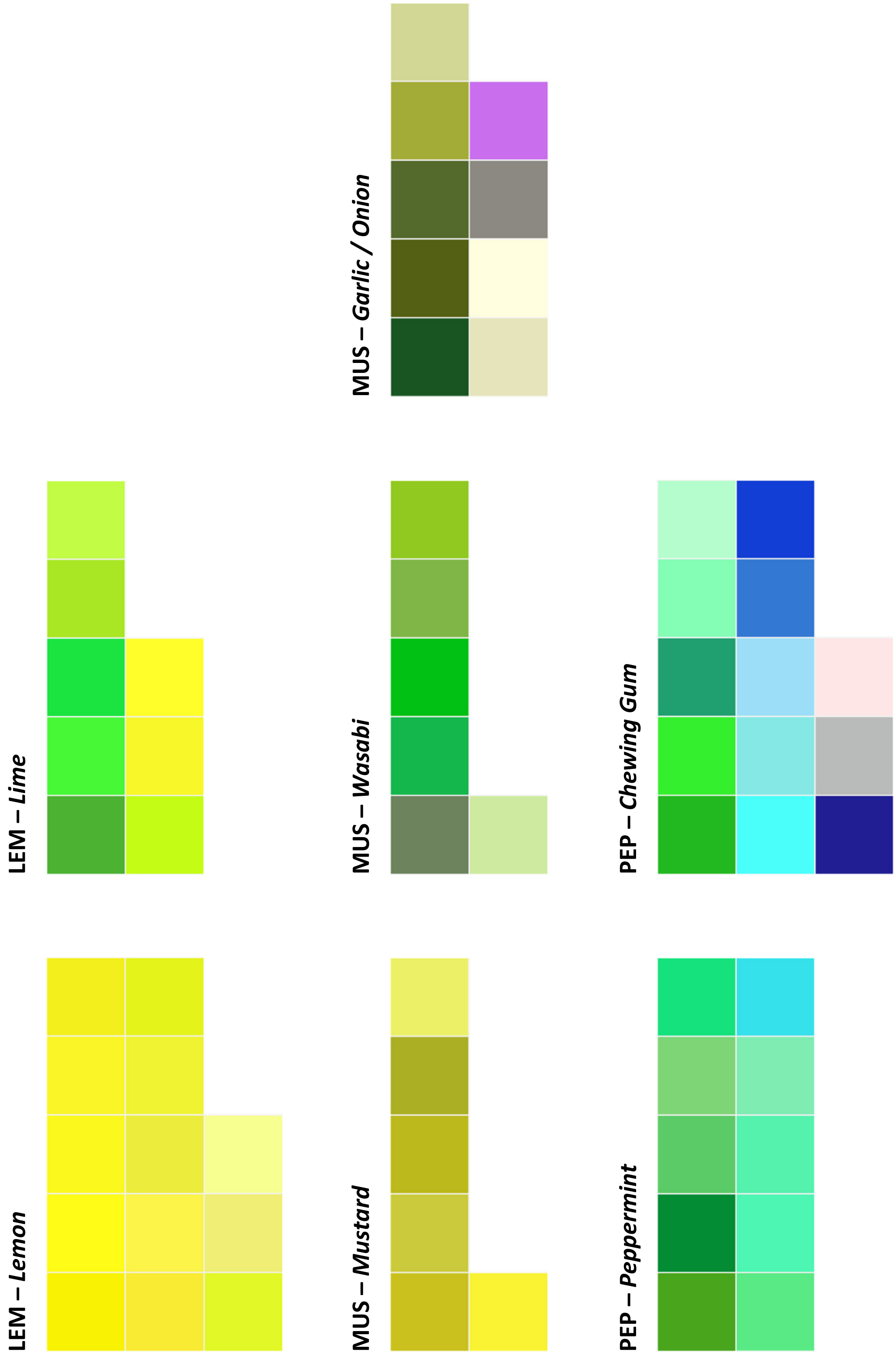


Fig. 4 Color matching as function of associated odor source: exemplary color patches for three odors. Patches are sorted by color, not by subject

Shape Analysis

Shape associations were assessed in two approaches: (1) in the visualization task, subjects were asked to draw any shape or pattern that best matched a given odor; (2) 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.

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

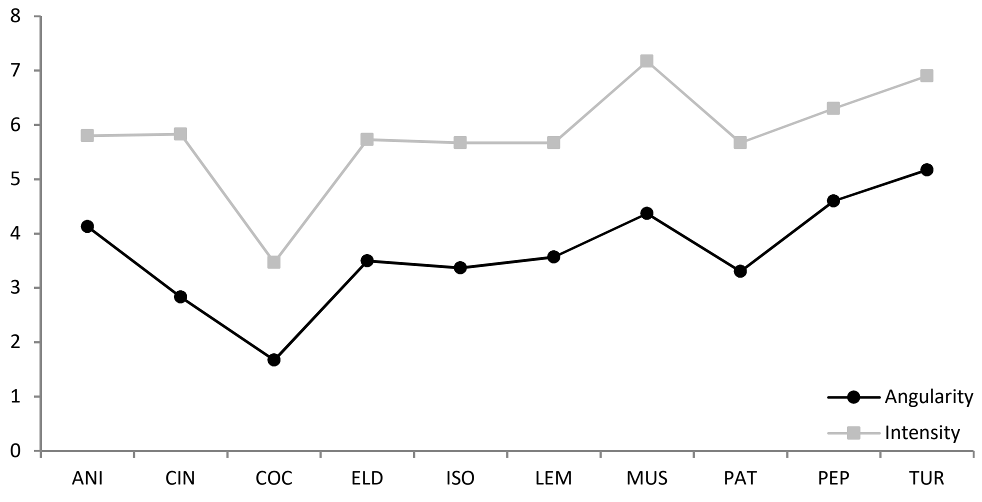
	Subjects' ratings		Image analysis	
Dimension	F	p	F	p
"Maluma"–"Takete"	4.353	<0.001	2.646	0.014
Regular–irregular	3.510	0.003	2.925	0.009
Small–big	1.590	0.144	1.067	0.385
Abstract–realistic	4.084	<0.001	0.510	0.800
Simple–complex	3.029	0.007	1.222	0.296
Geometric–organic	8.044	<0.001	2.206	0.046

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 1b) 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): odors rated as rather unpleasant or intense were regarded as more  while pleasant or less intense samples were more likely matched to the rounded, organic  shape (Fig. 5a, b).

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 *

a



b

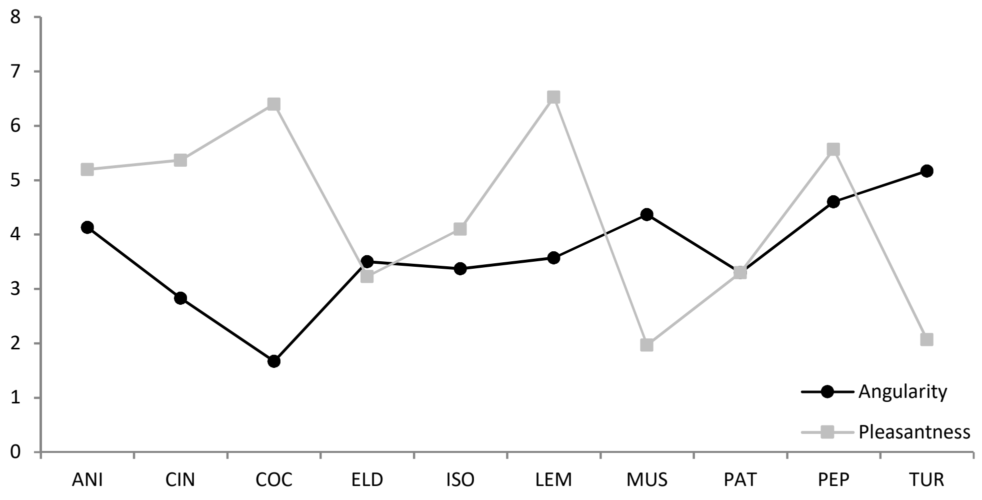


Fig. 5 **a** Mean scores of angularity and intensity ratings across odors. **b** Mean scores of angularity and pleasantness ratings across odors

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).

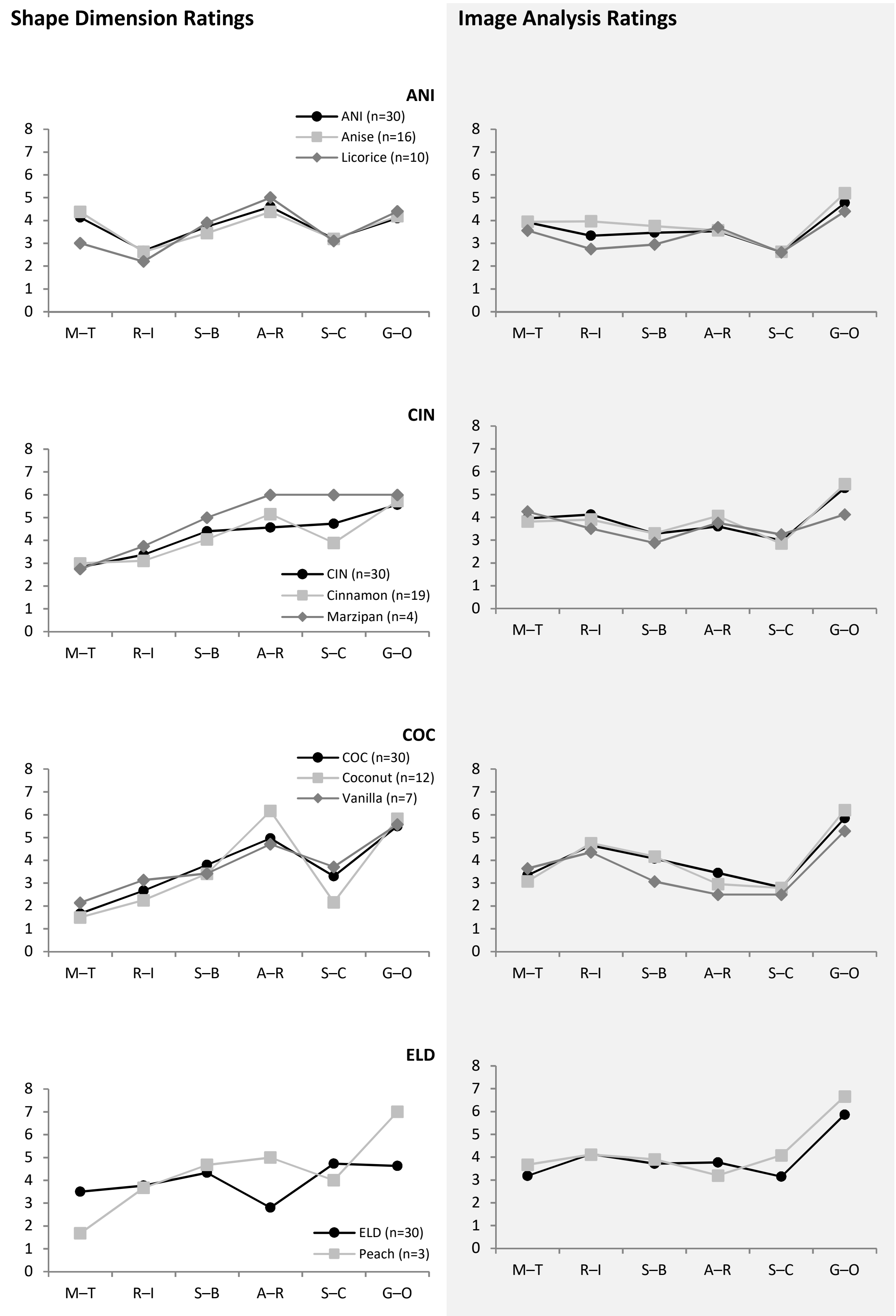


Fig. 6 Shape profiles for each odor across all judgments and as a function of assumed odor source name, left column: shape dimension ratings; right column: ratings from image analysis

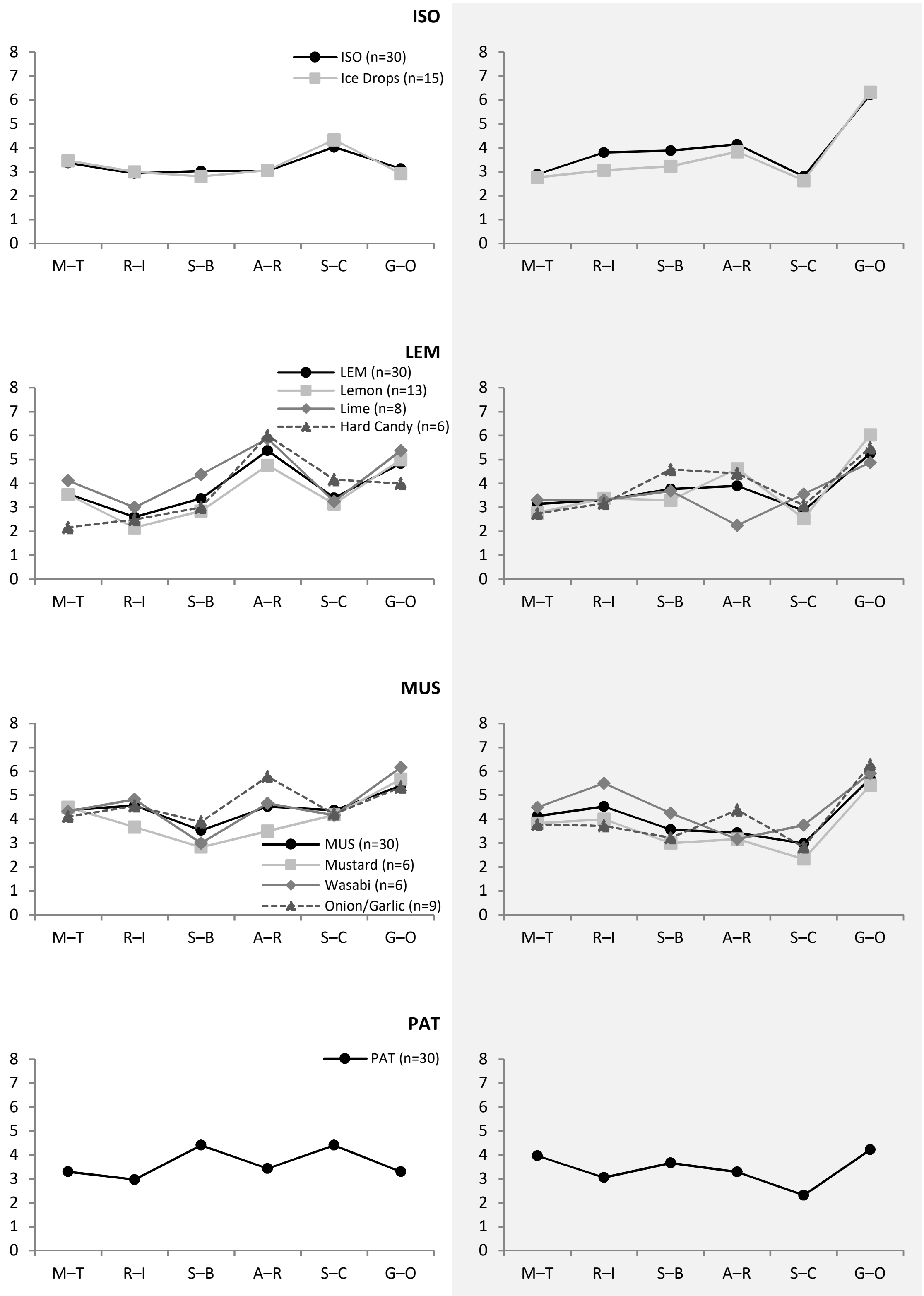


Fig. 6 (continued)

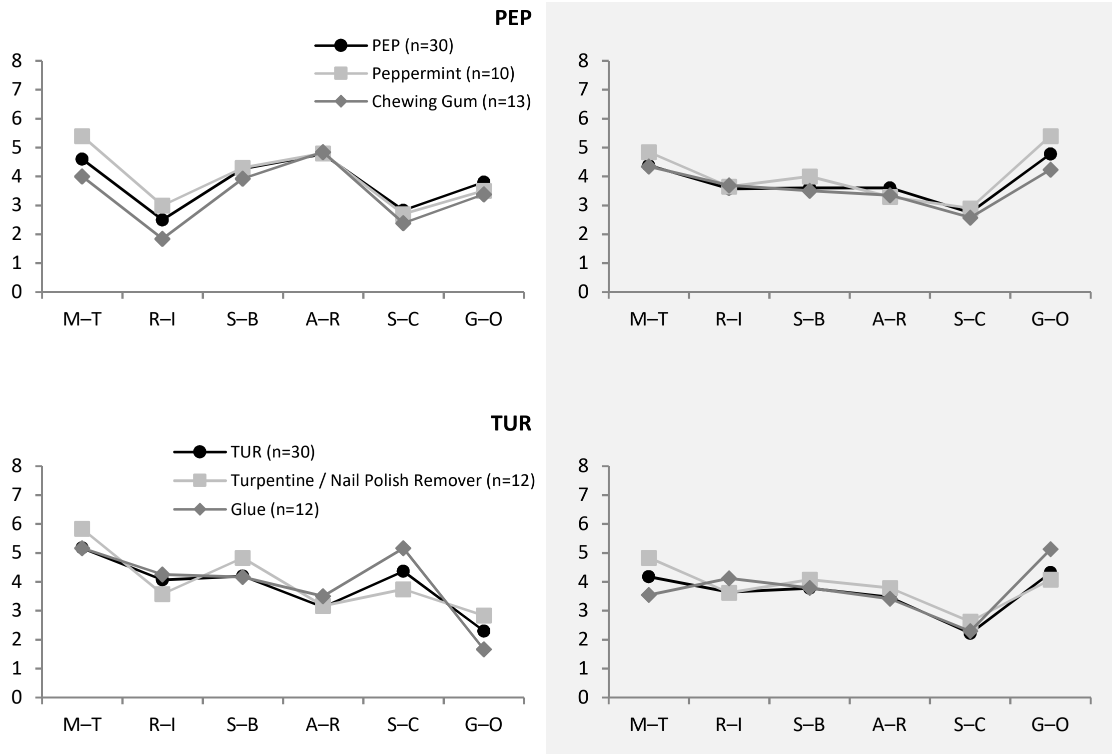


Fig. 6 (continued)

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, LEM) varied significantly from the scales midpoint and the influence of different source names was marginal.

These results may indicate that (1) shape (different from color) associations are generally less affected by semantic principles. However, it may imply as well that (2) 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 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 naïve 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).

a

b

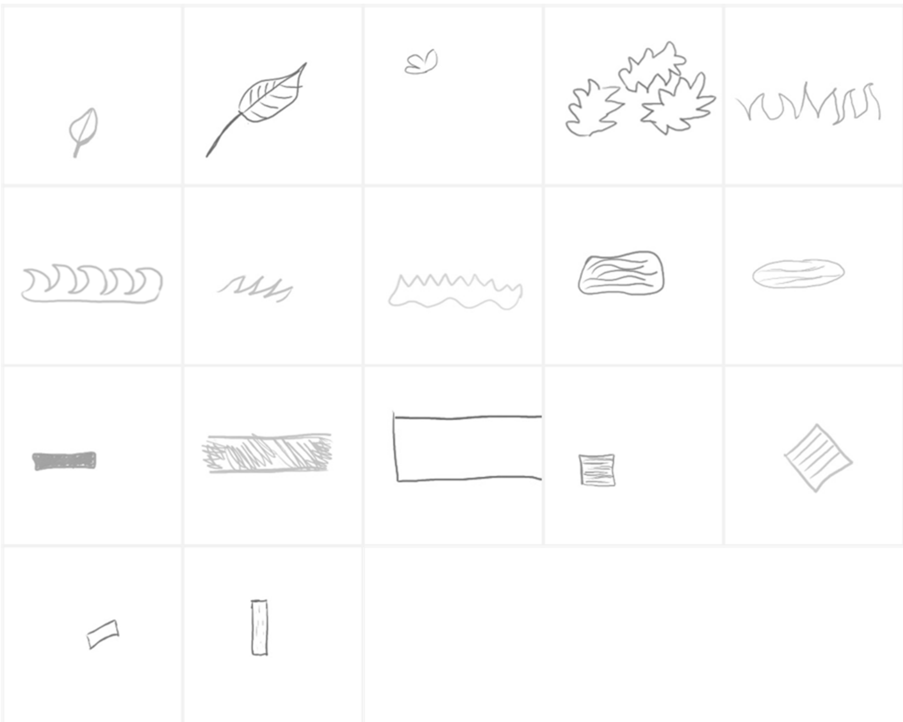
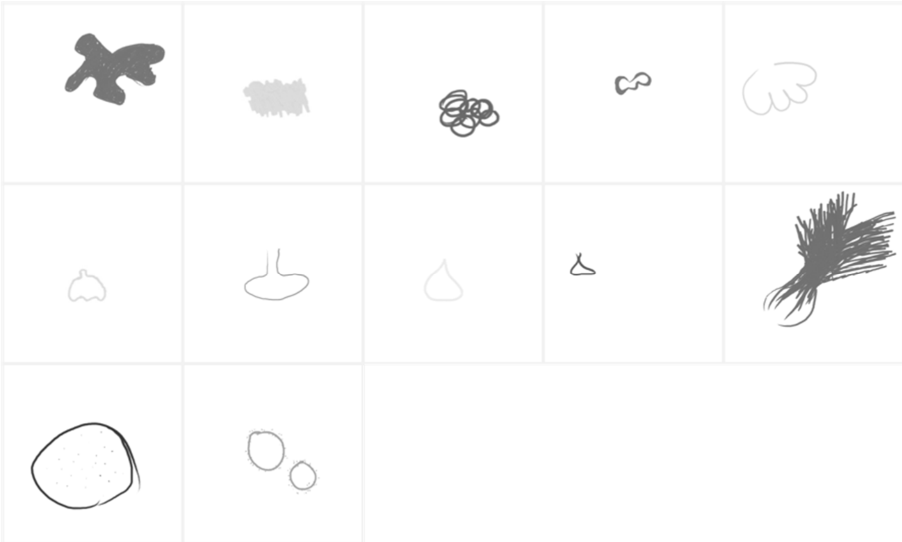


Fig. 7 **a** Image examples for odor sample LEM showing lemons and limes. **b** Image examples for odor sample PEP showing leaves or chewing gum. **c** Image examples for odor sample MUS showing mustard blobs or onion and garlic bulbs. **d** Image examples for odor sample ISO showing candy

c



d

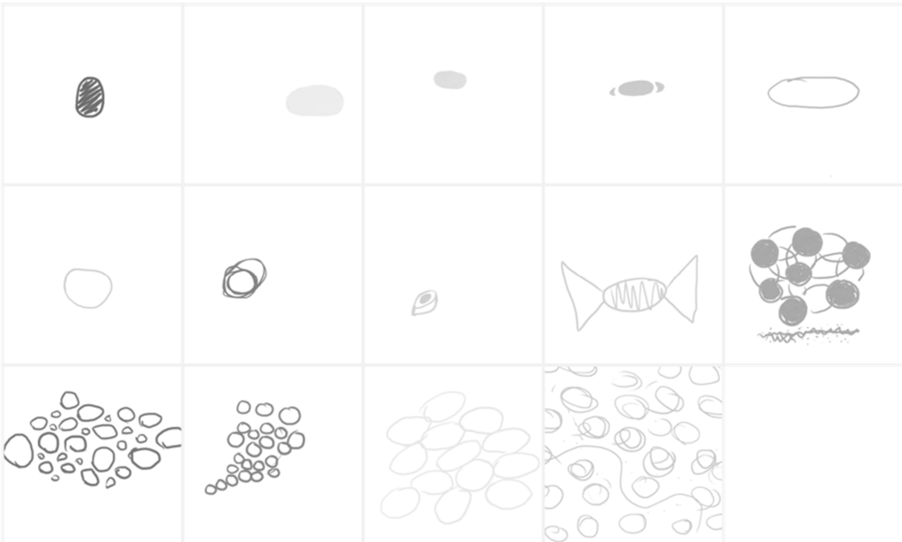


Fig. 7 (continued)

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) 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, $p = 0.028$)

and *geometric–organic* (ISO–TUR, p = 0.067). Also, when directly comparing the results of 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 ($r_s = 0.319$; $p < 0.01$), 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 between any perceptual dimension and the image analysis results (Table 6(b)).

The image analysis revealed two basic findings: (1) drawings varied only marginally across odors when a comparison was solely based on the shape–related dimensions we applied. (2) 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.

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 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 1a). But these insights have been repeatedly discarded with reference to (1) 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 (2) 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, (1) colors should differ with changing labels for identical odors but (2) 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: (1) 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. (2) Valk and colleagues (2017) 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 used 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 were 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. 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; 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).

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