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Review

Olfactory illusions: Where are they?

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ABSTRACT

It has been suggested that there maybe no olfactory illusions. This manuscript examines this claim and argues that it arises because olfactory illusions are not typically accompanied by an awareness of their illusory nature. To demonstrate that olfactory illusions do occur, the relevant empirical literature is reviewed, by examining instances of where the same stimulus results in different percepts, and of where different stimuli result in the same percept. The final part of the manuscript evaluates the evidence favoring the existence of olfactory illusions, and then examines why they may not typically be accompanied by awareness. Three contributory mechanisms are discussed, relating to difficulty of verification and paucity of olfactory knowledge, the role of change blindness, and restricted access consciousness in this sense.

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1. Introduction

A number of authors have suggested that there maybe no olfactory illusions (e.g., Batty, 2010; Lycan, 2000). This assumed absence seems to reflect a broader view held by experimental psychologists. For example, when consulting the index and content of various popular perception textbooks (e.g. Goldstein, 2002; Sekuler & Blake, 2002) or indeed, recent specialist books on olfaction (e.g. Brewer, Castle, & Pantelis, 2006; Doty, 2003; Hawkins & Doty, 2009; Wilson & Stevenson, 2006) – none of these contain a mention of olfactory illusions. This would seem to suggest that there are either no olfactory illusions or they somehow escape notice. Either conclusion would have interesting implications, both specific to current philosophical debates about the status of olfactory experience (e.g. Batty, 2010; Lycan, 2000), and relatedly to the apparent psychological

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and neural uniqueness of olfaction relative to the other senses (Stevenson, 2009; Smythies, 1997; Verhagen, 2006; Zucco, 2003). More broadly, considerations of human consciousness are highly visuo-centric, but if olfaction is somehow unique, then visually centered approaches may founder when applied to this sense. As this manuscript will show there is good experimental evidence that there are olfactory illusions, but what emerges from this literature is that olfactory illusions seem to lack an interesting feature, which is present for many, but not all illusions in other modalities. This feature concerns awareness of having experienced an illusion.

To evaluate whether there are olfactory illusions and whether we typically lack awareness of them – the manuscript is organized into three parts. The first deals with issues of definition. Unless there is some agreement over what is and what is not meant by the term 'illusion', it becomes problematic to determine which senses may demonstrate them. The second part of the manuscript presents an overview of the main classes of illusion that have been documented for olfaction. Items are included here on the basis of definition and on the grounds of similarity with phenomena categorized as illusions in the other sensory systems (e.g. see, Gregory, 1997, 2005; Hawkins, 2010; Hayward, 2008). The third part of the manuscript examines why olfactory illusions may be qualitatively different from those experienced in other modalities, especially with regard to awareness. This difference, so it is argued, relates to issues of verification (i.e. ones capacity to independently confirm what one is smelling), variation in olfactory perceptual ability and knowledge, the phenomenon of change blindness, and that access consciousness may be absent or restricted in olfaction. The specific and broader implications of this 'lack of awareness' account are then considered.

The word illusion derives from the Latin *illusio*, meaning "deceit, to mock or make sport with, the saying of the opposite of what is meant" (Glare, 1982). This Latin meaning suggests two concepts, which seem to be relevant to the use of the term illusion – an *objective* disparity or contradiction, and perhaps less apparently, a potential for *subjective* awareness of this disparity. This two-fold root to the word illusion is not always apparent in contemporary psychological definitions. Table 1 presents six definitions taken from current dictionaries of psychology that were available in the reference section of the University library (several of the authors here are distinguished experts in perception so these entries are likely to be representative). With the exception of Reber (1985), they define an illusion as a misperception or error – that is a disparity between some objective state of the world and ones perception of it. Reber's definition is consistent with this interpretation, except that he avoids terming it an error. Perhaps more importantly, with the possible exception of Coleman (2003), and the probable exception of Gregory and Zanwill (1987) – see Table 1 – these definitions do not allude to the issue of a subjective awareness of the disparity or error. On this basis, one could make a consensus definition that an illusion is a misperception, namely a disparity between objective reality and perception. This definition would then correctly classify as illusions, most visual, auditory and somatosensory phenomena that are thought of as illusions by psychologists. However, this definition avoids the issue of subjective awareness of having experienced an illusion. This avoidance may be of no consequence for visual, auditory and tactile illusions. This is because in these senses people may be readily able to detect some illusions themselves (e.g. waterfall illusion [after staring at a waterfall if ones gaze falls upon the rocks at the side, these now appear to be moving 'up']), while most others may be detectable once they are pointed out (e.g. change blindness [not noticing the change in some central feature of the stimulus between one point in time and another]). On this basis, one could nuance the claim regarding an absence of awareness of olfactory illusions into three variants, going from: (1) they are typically not noticed but could be noticed if pointed out; to (2) even if pointed out they may be less apparent than for comparable phenomena in other modalities; and to (3) that people may be incapable of noticing them, even if pointed out.

Even if one does not agree with this consensus definition of an illusion as a misperception, it is still possible to adopt a more pragmatic stance to determining whether they exist. Several authors (Gregory, 1997, 2005; Hawkins, 2010; Hayward, 2008) have either categorized or listed illusions drawn from the various senses – although no such survey has been attempted before for olfaction. To establish whether there are olfactory illusions one could then simply look for cases that broadly parallel examples drawn from these various sources. This task is made easier by the very useful tables that Gregory (1997, 2005)) assembled of various visual illusions, and these have been used here as a pragmatic guide for inclusion. However, this approach also has its limitations. Some olfactory items are included in this manuscript (notably those in the Miscellanea section), which seem relevant here, but that are not illusions either by reference to Gregory's tables or in terms of the definition adopted above. These items are included because they assist in identifying why olfactory illusions may be

Table 1
Definitions of the term 'illusion' from recent dictionaries of psychology.

Definition (and source)
1. "…an illusion is a misinterpretation of a stimulus consistently experienced by most normal people." (Anstis, 1999)
2. "A misperception or misconception of a stimulus object, image, event, experience or problem that generates such a misperception or misconception: more generally, any misleading, deceptive or puzzling stimulus or the experience it generates." (Coleman, 2003)
3. "…illusions are discrepancies from truth …but illusions pass unnoticed except when they are strikingly inconsistent with what is accepted as true, or when there are internal inconsistencies – such as contradictory sizes or shapes, ambiguities or paradoxes…" (Gregory & Zanwill, 1987)
4. "Any stimulus situation where that which is perceived cannot be predicted, prima facie, by a simple analysis of the physical stimulus." (Reber, 1985)
5. "An error in perception, triggered by the external stimulus." (Sutherland, 1995)
6. "Illusions are misperceptions of the environment. The essential notion of an illusion is that it leads the perceiver to misjudge the stimulus, to have a non-veridical perception." (Walk, 1996)

Table 2
Olfactory illusions – and their counterparts (where relevant).

Category Name of illusion	Nature (and parallels[a])
Same stimulus – different percept	
Context	Odor quality, intensity and hedonics affected by the concurrent stimulus set (visual/auditory)
Localization	Odor location, quality and intensity affected by the mode of delivery – nose vs. mouth (no parallel)
Multimodal context	Odor quality, intensity and detection affected by stimulus color (visual)
Binaral and monorhinal rivalry	Odor quality perception fluctuates between two alternatives (visual/auditory)
Different stimulus – same percept	
Constancies	Odor quality and intensity demonstrate perceptual constancies (visual/auditory)
Perceptual learning	Changes in odor quality perception and creation of gustatory/tactile synesthesia (no direct parallels)
Miscellanea	
Naming	Notably poorer than one believes and possible name illusion albeit anecdotal (no parallels)
Flavor	Role of olfaction in flavor perception unknown to most participants (no parallel)
Imagery	Notable difficulty in imagining odor percepts unknown to most participants (no parallel)

[a] Visual parallels are based upon entries in Gregory's (2005) Table 1.

qualitatively different. In addition, not all olfactory phenomena, which parallel entries on Gregory's tables, have been included, as some are rather tangential. Notably, these consist of medically induced perceptual distortions and optical ambiguities, all of which have olfactory parallels, but which do not directly relate to the two claims evaluated here. Table 2 provides a summary list of the olfactory illusions, which are described in the next section, along with their visual analog (where relevant) as identified in Gregory's tables (1997, 2005).

2. Olfactory illusions

With no obvious or available form of categorization to organize the various examples of olfactory illusions the existing literature has been sorted according to the type of relationship, which is observed between the stimulus and the percept. On this basis two categories emerge, 'same stimulus – different percept', and 'different stimulus – same percept'. This still leaves a small number of miscellaneous effects that are relevant primarily to the issue of awareness and these are grouped together at the end of this section. No theoretical weight should be attached to this classification scheme, its principal role is organizational.

2.1. Same stimulus – different percept

Within this category come a range of contextual effects, whereby the same stimulus is reportedly perceived in a different manner – qualitatively (what it smells like), intensitively (strong/weak dimension) and hedonically – dependent upon other stimuli that are experienced concurrently. Analogous effects of context are apparent in vision, such as the Ebbinghaus and Delboeuf illusions (both being relative size illusions) and color contrast effects (see Gregory, 2005 – 'context' entry in his Table 1) as well as in audition (e.g. phoneme boundaries [categorical perception of a continuum]) and gustation (e.g. sweet tastes taste sweeter after bitter tastes).

For contextual effects on odor quality perception, one principal odorant and others chemically similar to it, have been explored in several articles (and one might expect to find further examples if a search were made). Using the odorant dihydromyrcenol as the 'target', it can be perceived as smelling more 'woody' when smelled in the context of citrus smelling odors and more 'citrusy' in the context of woody smelling odors (Lawless, 1991; Lawless, Glatter, & Hohn, 1991). These experiments were arranged so that the contextual manipulation (e.g. smelling several 'citrus' odors) occurred on either different days, or in different groups of participants, so it is not possible to tell here whether a person would notice (in a within-design) that they had experienced the same odor under two different contexts, and that it smelled different on each occasion.

Contextual effects have also been identified which affect the perceived intensity of an odorant. These effects are not simply the product of scale use but reflect actual changes in perceptual magnitude. In one procedure, participants judged the intensity of a range of odor concentrations, followed around an hour later by a biasing task involving exposure to either weaker or stronger concentrations (between participants), and then 30 min later by a repeat of the concentration range task (Pol, Hijman, Baare, & van Ree, 1998). Participants' intensity ratings diverged on the post-bias ratings, such that those experiencing the stronger biasing set now judged the concentration range as less intense (and vice versa). It is interesting to note here the contrast with the visual relative size illusions, which can be seen simultaneously (i.e. side-by-side) and where the actual size and, thus the illusory nature of the experience, can be readily and immediately ascertained with a ruler.

Olfactory intensitive context effects seem to be perceptual in origin rather than resulting from scale usage, as with examples from vision, audition and gustation (e.g. Helson, 1947; Riskey, Parducci, & Beauchamp, 1979). For olfaction, as with vision and audition, these seem to be quite low-level effects. This has been established using the 'differential context procedure', developed by Marks and colleagues (e.g. Marks & Warner, 1991). As described further below, certain odors smell 'sweet'. Stevenson and Mahmut (2010) exposed participants to a series of sweet tasting solutions and sweet smelling odors. The high degree of perceptual similarity between the two stimulus sets was established both in a pilot study and in a post-hoc test on the actual participants. On one day more intense sweet smelling odors were presented alongside weaker tasting sucrose solutions. On another day weaker sweet smelling odors were presented alongside more intense tasting sucrose solutions. The odor sets shared three common stimuli, as did the tastes – the target stimuli. Even though *together* each day's set of tastes and smells formed a perceptually similar ascending series of psychological magnitude, the intensity judgments of the odor target stimuli were only affected by the odor context, as with the tastes (and see Rankin & Marks, 2000 for a similar conclusion). Thus smelling the odor targets in the weak smelling (odor) context made them appear more intense and vice versa in the strong smelling (odor) context. This would suggest a likely sub-cortical locus for this effect, because if it were cortically mediated the perceptual similarity of the sweet tastes and smells should have eliminated any effect of context. This conclusion matches those of conceptually similar studies in vision and audition (e.g. Schneider & Parker, 1990).

Not only can context influence qualitative and intensitive judgments of the same stimulus, it can also influence affective judgments too. In one series of studies, Herz and von Clef (2001) reported that providing different verbal labels, reflecting a positive (e.g. xmas tree) or negative context (e.g. toilet cleaner) for the same odor (in this case pine), had the expected effect on participants hedonic judgments. This effect seems to be more than just experimental demand, because of the 'first label effect'. For example, pine, if experienced first as 'toilet cleaner', and then later as 'xmas tree', revealed a smaller positive shift in affective judgments, relative to reversing the order of presentation. In other words the first presentation tended to (weakly) lock in a particular hedonic perspective to the target odor. Whether this 'first label effect' reflects some form of associative learning, which is then resistant to interference when the second label is presented, is not currently known (c.f. Lawless & Engen, 1977).

Several variants of this type of name-driven affective shift have now been published demonstrating its presence in children (Bensafi, Rinck, Schaal, & Rouby, 2007) and that it has physiological correlates consistent with a change in affect (Djordjevic et al., 2008). The consistency of these effects across studies is all the more remarkable because of the notable within-subject variability in hedonic response to odors generated by associative learning (e.g. Hofmann, De Houwer, Perugini, Baeyens, & Crombez, 2010). Moreover, additional examples can also be found in the consumer science literature, in which manipulation of flavor expectancy (i.e. the context) can produce, under appropriate conditions, assimilation between the hedonic expectation and the actual experience (e.g. Cardello & Sawyer, 1992). Although of interest, these findings are not strictly relevant here because most utilize flavor (i.e. taste, smell, somatosensation) rather than just odors alone.

A further type of hedonic context effect has also been observed. In this case, presenting a target odor with a less pleasant stimulus set renders affective judgments of that odor as more positive than if the target was experienced in a more pleasant stimulus set (Beebe-Center, 1929; Sandusky & Parducci, 1965). Again, it seems unlikely that these hedonic context effects arise from scale usage. In this case, Stevenson, Tomiczek, and Oaten (2007) found that following a positive olfactory context, a hedonically ambiguous odor (durian – smelling fruity/cheesy/vomitish), presented in dilute sucrose solution to render it more palatable, was judged both to smell (and 'taste') less pleasant, than when followed, in a different group of participants, by an unpleasant olfactory context. The unusual feature of this experiment was that participants were then asked to drink the fluid, and more was drunk when durian odor had been preceded by unpleasant odors than when preceded by pleasant ones – an effect that was also obtained even when no hedonics ratings were obtained prior to drinking in a further experiment. This contextual shift did not occur in a control condition employing equally affective pleasant or unpleasant pictures. The finding of behavioral continuity would suggest that the affective change wrought by the context was probably perceptual in origin.

A further case where the same stimulus results in different percepts, but which may owe more to differences in peripheral processing than the examples reviewed so far, concerns olfactory localization. While there are only one set of olfactory receptors located at the top of the nasal cavity, these can be stimulated in two discrete ways – orthonasally, as by sniffing an odor, and retronasally, with the ascent of volatile chemicals from food or drink in the mouth via the nasopharynx (Rozin, 1982). Two types of illusion may be demonstrated here. First, the perceived location of an odor can be shifted from the tip-of-the-nose to the mouth, even when the odor is still presented orthonasally, if a taste is present in the mouth (Stevenson, Oaten, & Mahmut, 2011; von Bekesy, 1964). Second, the same odor may be perceived differently via the orthonasal and retronasal routes (Hummel, Heilmann, & Landis, 2006; Rozin, 1982; Small, Gerber, Mak, & Hummel, 2005). There are several peripheral factors that may contribute to this perceptual difference such as poorer efficiency of the retronasal route resulting in lower intensity ratings and higher thresholds (e.g. Diaz, 2004), alterations in the way that volatiles are released from food when chewing, and interactions of these volatiles with other chemicals in food, all of which may alter perception (e.g. Boland, Delahunty, & van Ruth, 2006). More importantly, the direction of airflow over the olfactory receptor sheet may generate subtle or not so subtle differences, resulting in possible shifts in perceived quality and affective reaction to the odor (Scott, Acevedo, Sherrill, & Phan, 2007).

A variety of central processing differences may also occur between orthonasal and retronasal perception, independently of any peripheral factors, and these too, so it has been argued, may serve to change the hedonic reaction to the same odor (Rozin, 1982). However, attempts to test this hypothesis have not proved fruitful when self-report methods are used (Frasnelli, Ungermann, & Hummel, 2008), although physiological and neuroimaging data do suggest affective processing differences (Bender, Hummel, Negoias, & Small, 2009; Small et al., 2005). While there must be some doubt as to whether any perceptual change resulting from these two routes constitutes an illusion (especially if any differences result solely from peripheral processing), nonetheless the same stimulus could result in different percepts, and this *might* have a central locus.

Although the issue of perceptual change then is unresolved, the shift in perceived location of an orthonasally presented odor clearly does constitute an illusion. This location change may be caused by a shift in attention from nose to mouth generated by the presence of a tastant (Stevenson & Mahmut, in press a; Stevenson et al., 2011). Notably, any such difference – in percept or location – is very likely to go unnoticed, as several lines of evidence suggest that people are not routinely aware of the role of retronasal olfaction in flavor perception (Rozin, 1982; Stevenson, 2009a).

A variety of non-olfactory cues, which serve to indicate the plausible presence of an odorant, especially color, have been shown to influence judgments of intensity, affect and quality. Engen (1972) reported that on an odor detection task, even when participants were forewarned to ignore any non-olfactory cue, the coloring of blank test solutions led participants to falsely judge these stimuli as containing an odor. A far larger number of studies have examined the impact of color on odor intensity judgments (e.g. Blackwell, 1995; Zellner & Kautz, 1990; Zellner & Whitten, 1999). Here, even under conditions designed to minimize experimental demand, significant increases in perceived odor intensity are found when the odor is presented in a colored fluid (Zellner & Kautz, 1990). While the congruency between color and odor may affect the ability of participants to correctly identify the odorant (Blackwell, 1995), and to discriminate it from other odorants (Stevenson & Oaten, 2008), congruency has no impact on odor intensity judgments (Zellner & Kautz, 1990). These various findings would suggest that the presence of color, in fluids, is a fairly reliable predictor that the fluid will smell, suggesting an associative and probably quite implicit reaction to this type of cue. This would seem to parallel examples such as the Charpentier illusion (size-weight illusion) that may rely upon interactions between visually induced expectation and proprioceptive feedback (Brayanov & Smith, 2010).

While the color studies cited above all employed orthonasal (sniffing) olfaction, an even larger set of studies have examined the impact of color on retronasal perception, typically in combination with gustatory and somatosensory cues (i.e. flavor). For flavor intensity, findings are mixed with some studies reporting increases and others not. In this regard a study by Koza, Cilmi, Dolese, and Zellner (2005) is particularly interesting, as they reported that while orthonasal intensity judgments of a colored odorized fluid demonstrated the expected increase, this increase was not observed when the fluid was sampled by mouth (i.e. retronasal olfaction). While color–flavor intensity effects may be inconsistent, the effect of color on flavor quality can be marked, even under conditions where odor is the primary flavor variable (i.e. taste and somatosensation held constant). Here, the presence of a mismatch between flavor and color is resolved in the color's favor, such that flavor characteristics typically associated with that color are reported when a flavor is miscolored (e.g. lime flavored red fluid being reported as 'tasting' of cherry; Dubose, Cardello, & Maller, 1980). DuBose et al. (1980) also found that the presence of colors in fluids not containing *any* flavorant were judged as more likely to be flavored with the color congruent flavor. A similar and more notable example concerns wine. If white wine is colored red, participants attribute to it the odor characteristics normally associated with red wine (Morrot, Brochet, & Dubourdieu, 2001). While intensity and detection effects for color are probably implicit, it is not currently known whether effects on flavor or odor quality are explicit or implicit. Thus they could represent an explicit effect of experimental demand (i.e. if the wine *appears* red, then responses are given consistent with this visual fact) or an implicit alteration in the flavor/odor percept (i.e. the red colored white wine really does smell like red wine).

The final example in this section is arguably one of the most interesting because this *may* be an illusion much more akin to those that obtain in other sensory modalities. The primary reason for suggesting this is not because it is any more or less an 'illusion' than any of the other olfactory examples above (or to come), but rather that this may be one case where the illusion could be *apparent* to the perceiver. In the visual system, several illusions occur in which the same stimulus can yield markedly different percepts. One example is binocular rivalry where two different stimuli are projected onto corresponding areas of each eye's retina (Blake, 2001). This results in periods of perceiving one stimulus, then the other, with periods in between in which the two are perceived in a 'piecemeal' fashion. Another related example are bistable percepts, where one stimulus is viewed (e.g. Necker cube, Rubin's vase/face figure) but one of two alternating percepts result (Blake & Logothetis, 2001). The unusual nature of these experiences is compelling as Blake (2001) describes… "simply observing rivalry, one is fascinated and intrigued that a highly visible complex, interesting stimulus can disappear from conscious awareness for several seconds at a time". Is this the case in olfaction?

The first empirical demonstration of an olfactory equivalent to binocular rivalry was reported by Zhou and Chen (2009), although this phenomenon may have been observed before by the physiologist Gabriel Valentin in the 1840's (see Gottfried, 2009). In Zhou and Chen's (2009) demonstration, one odorant was presented to one nostril (i.e. equivalent to one image to one eye) and another odorant was simultaneously presented to the other nostril (i.e. equivalent to a second image to the other eye) – termed binaral presentation. The parallel with binocular rivalry rests upon the assumption that each nostril and its olfactory receptors are discrete, just as with each eye and ear. Although this assumption is probably well founded it is still possible that odorants can transfer between each nostril in anterior regions. Notwithstanding this possibility, there was one notable procedural departure from the way in which rivalry experiments in other modalities have been conducted. Participants sniffed both odors approximately once every 20 s to minimize adaptation. This differs from visual and auditory examples of rivalry where the stimuli are continuously presented. Returning to the procedure, and following each sniff, participants were asked whether a smell was apparent, and if it was, they were asked to rate on a bipolar scale the extent to which the odor was similar to one target smell ('marker pen') or the other ('rose'); the center of the scale reflecting equal dissimilarity/similarity. While the two odorants were of broadly similar intensity, it should be noted that all odors also trigger activity in the trigeminal nerve (irritancy), and the extent to which differential activity here between odors might affect (or trigger) the dominance of one percept over another is not currently known.

Individual similarity ratings for the 12 participants (see Zhou & Chen's, 2009, Figure 1A) indicated a pattern of apparently random alternation between ratings favoring one odor on one sampling occasion, and the other on other occasions. This random variation is also a feature of binocular rivalry. In addition to observing binaral rivalry, Zhou and Chen (2009) also reported evidence of monorhinal switching. Here, an odor mixture was presented to both nostrils, with similarity ratings obtained every 20–30 s – termed monorhinal presentation. In this case, 10/12 participants showed evidence of alternation between similarity ratings favoring one odor over the other. Examination of participants similarity ratings on both the binaral and monorhinal experiments suggests that on most occasions what was being observed was a biased blending temporarily favoring one odor over another (Gottfried, 2009). This is notable because of its contrast with visual perception. For binocular rivalry, one image typically dominates then dissolves piecemeal, as the other image becomes dominant (Blake, 2001). For olfaction, this process would seem less extreme, and it is possible that using familiar odors (which generate the most discrete percepts) as Zhou and Chen (2009) did, may represent optimal conditions for this effect.

From the perspective of this manuscript, the most interesting question is whether participants' noticed these shifts in perception. However, to appreciate the surprise of a visual stimulus disappearing and reappearing one has to *know* that it is continuously present (as presumably Gabriel Valentin did when he self-administered one odor to one nostril and another to the other). Observers would not be surprised that a visual stimulus disappeared and reappeared if the computer monitor was switched on and off – it is the continuity of presentation contrasted with the discontinuity of perception that makes this experience so (in Blake's words) fascinating and intriguing. Unfortunately, we can not know in Zhou and Chen's (2009) experiment whether participants were aware of the unchanging nature of the stimuli, whether they were aware of their reported shifts in similarity ratings and more pertinently, whether any perceptual shift was sufficiently different (*and* knowing that the stimulus was the same) for this shift to be identified and appraised. The discontinuous nature of assessment adds to this problem, and so it begins to resemble the other olfactory phenomena above. That is perceptual shifts can occur for the same olfactory stimulus, but these are usually at two discrete points in time, making it hard to compare even if one knew that the stimulus had remained constant.

2.2. Different stimulus – same percept

The examples described in this section vary from those strictly complying with the title, notably examples of perceptual constancy, to those where the term 'similar' percept would be more accurate than 'same'. In terms of perceptual constancies, which are observed in the visual (e.g. shape, size, color, lightness, distance, location) and auditory (e.g. speech perception, identification of musical instruments) systems (Gregory, 2005), two forms are evident for olfaction. The first concerns intensity, as variations in odor flow rate over the olfactory epithelium (i.e. a big sniff vs. a little one) significantly alter the size of the neural response of the olfactory nerve (Tucker, 1963), but do not produce comparable changes in perceptual magnitude (Teghtsoonian, Teghtsoonian, Berglund, & Berglund, 1978). It would seem that the olfactory epithelium, or somatosensory receptors in the nose, are sensitive to airflow rate and this information is used to adjust the apparent magnitude of the odor (Teghtsoonian & Teghtsoonian, 1984).

The second form of constancy concerns odor quality, whereby the stability of particular classes of odor object (e.g. coffee) are retained even when there may be substantial variation in the constituent chemicals that go to make them up (Barnes, Hofacer, Zaman, Rennaker, & Wilson, 2008; Wilson & Stevenson, 2006). Perceptual stability, over varying formulations and for degraded stimuli too, may be achieved by an object-recognition based perceptual system, where 'perfect fit' between stimulus input and prior encodings of that odor object are not required to generate a suitably similar output. This may also apply, over a *limited* range, for odorants that vary in concentration (but not for more extensive ranges – see Gross-Isseroff & Lancett, 1988). Increases in stimulus concentration alter the neural pattern generated by the olfactory epithelium (Malnic, Hirono, Sato, & Buck, 1999), yet stimulus quality can remain similar over some of this range (Stevenson, 2011).

While the constancies are accurately represented by the title of this section, a further set of phenomena, are more loosely tied, although these may, as with quality constancy, result from the same set of processes (i.e. object recognition). These effects relate directly to basic features of olfactory perception, namely they rely upon recognizing complex spatial and temporal neural patterns that arise from the hundreds of different olfactory receptors residing on the olfactory mucosa (Malnic et al., 1999). This pattern recognition process can have some curious consequences, and while surprising perhaps to read about, they, as with the constancies, do not seem to be noticed in day-to-day olfactory perception.

Several experiments have demonstrated that if a participant experiences a mixture of two odors (e.g. cherry and smoky), the consequences of this exposure are evident in the way that each odor alone is later perceived (e.g. Stevenson, 2001a, 2001b, 2001c). So, for the example above, if the participant later smells cherry odor alone, this will now be reported as smelling a bit 'smoky', and the smoky odor will now smell somewhat 'cherry-like'. These effects can be measured in many ways, using participant reports of odor quality, as in the example here, with similarity ratings (e.g. how similar do cherry and smoky odors smell) and with objective measures such as discrimination, this being poorer between odors previously experienced together in a mixture (Stevenson, 2001a, 2001b, 2001c). What these findings suggest is that the same stimulus, cherry say, can have its resulting percept made similar to a chemically unrelated odorant. This effect seems to result from the routine and apparently passive encoding of olfactory experience, in this case the encoding of an odor mixture. Presumably, the individual odorant, when smelled, acts to recover the mixture memory, resulting in the combinatorial percept. While these perceptual changes seem to be quite routine, for example passive exposure to unfamiliar odors heightens their discriminability and sharpens their perceptual quality (e.g. Mingo & Stevenson, 2007; Rabin, 1988), it does not seem that people are aware of these changes. However, people may not be aware of similar processes in the visual or auditory systems (perhaps relating to facial processing or voice recognition).

A more striking effect concerns cross-modal forms of odor learning (Stevenson & Tomiczek, 2007). While many people readily recognize the products of this learning, freely calling caramel odor 'sweet' for example, this does not seem to be accompanied by any deeper realization that 'sweetness' in the context of odor perception might be unusual. The perceptual quality referred to as 'sweetness' is usually associated with stimulation of receptors located on the surface of the tongue – gustation – by sugars. Of course it may be the use of terms like sweetness refers to some other property (e.g. liking). For example, colloquial use of 'sweetness' to describe a nice person does not mean they *actually* taste sweet. However, two decades of research suggests that sweetness 'sniffed' through the nose is perceptually akin to sweetness experienced when sucrose is placed upon the tongue (Stevenson, 2009a). This is suggested by extensive perceptual similarities (e.g. Dalton, Doolittle, Nagata, & Breslin, 2000), common physiological effects (e.g. Prescott & Wilkie, 2007), and similar neural processing (e.g. Stevenson, Miller, & Thayer, 2008).

While odor mixtures may be passively learned by smelling, odor induced tastes seem to result from the same type of process but applied to flavors in the mouth. Here, combinations of odorants, tastants and the somatosensory consequences of food itself (e.g. viscosity) seem to be encoded, and these encodings can later be accessed when the odor component is later sniffed alone (e.g. Stevenson, Boakes, & Wilson, 2000). It is this then, which seems to result in odors coming to smell of gustatory and even tactile qualities (Stevenson & Mahmut, 2011). As noted above, the unusual nature of this phenomenon is not generally noticed, but this does not seem to be the case at least for the visual and auditory systems. Here, the experience of one sensory modality generating experience typically associated with another (e.g. 'hearing' colors) is readily apparent, and most individuals who experience this or other forms of synesthesia seem to be well aware of the anomalous nature of their experience (e.g. Baron-Cohen, Burt, Smith-Laittan, Harrison, & Bolton, 1996).

2.3. Miscellanea

So far there do not appear to be any good examples of where an olfactory experience is noticed as being different to what one might expect based upon knowledge of the stimulus (i.e. a 'wow' response indicative of noticing the illusion, which seems to occur in the other senses). However, there are perhaps some situations, which if brought to participants' attention might create something akin to this – albeit of a rather weaker kind. Apart from recognizing the unusual nature of 'sweet' smells, there are three other phenomena that might have this ability to surprise. While these effects are not illusions, they do reflect another kind of paradox, this time between what one thinks one knows (metacognition) and reality. As will become apparent in the Discussion, these paradoxes may help explain the apparent lack of awareness that seems to accompany olfactory illusions.

One 'know-reality' paradox concerns odor naming. Most of the time people do not need to name odors directly because their identity is suggested by contextual cues. Oregano comes in a labeled container from the supermarket or from an oregano plant – the source is known. But the ability to name oregano and other odors too in the absence of visual cues, is generally quite poor (e.g. Cain, 1979; Desor & Beauchamp, 1974). Before considering the difference between this latter observation and what people believe about their ability to name odors, impoverished naming may also be able to create an illusion. Cain (1980) suggests that generating a name may be important for perceptual stability. If a person then smells an odor, which they cannot name they may experience an unusual perceptual transformation when the name is made available (e.g. a 'fishy-goaty-oily' smell suddenly becomes 'leather'; Cain, 1980, pg.352). Returning to odor naming, while odor naming in the absence of contextual cues is poor, people report (prior to trying) that their ability to name odors is good (Cain, 1982), suggesting an interesting – and *surprising* to participants – disparity between actual and expected performance (Jonsson & Olsson, 2003).

A further example, noted above, is the role that odor perception plays in flavor, and thus in the enjoyment of eating and drinking. It is no coincidence that linguistically, people use terms such as 'taste' to describe food, when much of the variation in flavor is actually based upon the olfactory component. Again, making this apparent by the simple expedient of pinching the nose during eating, is a surprising and revealing act to many people (Rozin, 1982). Finally, although not perhaps as surprising, is the discovery that it is hard, if not impossible, to evoke an olfactory sensation in the absence of an odor stimulus (Stevenson & Case, 2005). Again, until people are consciously made to try and enact such a task, they do not realize the mismatch between what they think they can do and what they can actually do in the olfactory modality.

3. Discussion

While there is evidence that the same stimulus can generate different percepts, and different stimuli can generate the same (or similar) percepts, do these reasonably count as illusions – misperceptions – the definition adopted by many dictionaries of psychology? A misperception assumes that there is a veridical state, in which the mind accurately reflects some objective state of the environment. When this does not hold, and a non-veridical percept arises, an illusion is said to have occurred. In many cases of visual illusions, especially ambiguous figures and binocular rivalry, it would seem that the brain can not reach a final decision as to which percept is veridical, resulting in a competition between two potential views. Although it is perhaps harder to reconcile these ambiguity type illusions with the misperception definition, the olfactory system undoubtedly demonstrates examples of both.

The presence of color, relative to no color, makes an odor appear to smell stronger, even though the odor stimulus remains constant – a clear misperception and one analogous to the Charpentier (size–weight) illusion. On the other hand, binaral rivalry, would seem to be an example of an illusion in which the brain can not reach a final decision as to which of two potential 'smells' is veridical – an example of an illusion based upon ambiguity. Moreover, even if one abandons attempts to rely upon definition, and instead rely upon broad parallels with items found on classifications or lists of visual illusions, there are as illustrated in the previous section many parallels – notably the effects of context, ambiguity and perceptual constancy. Finally, olfaction also demonstrates some apparently unique examples of illusions. In this case there are misperceptions, such as where a stimulus can be perceived as having gustatory or tactile qualities, which are objectively absent from the stimulus, and also the ambiguity, which may surround an odor when it is familiar but its name is not currently available, and which is immediately resolved upon knowing its identity. While the breadth of illusions for olfaction may be restricted relative to vision (with the caveat that this may simply be an absence of evidence not evidence of absence), and perhaps restricted in important ways (e.g. it is hard to imagine any olfactory parallel to the tri-bar or other impossible figure illusions) – the conclusion would seem inescapable that examples of olfactory illusions can be found.

The second claim made in the Introduction concerned a possible qualitative difference between the experience of illusions in the visual, auditory and somatosensory systems and those in the olfactory system. It was suggested that olfactory illusions may not typically be noticed, with a more extreme possibility being that they are more difficult to notice, and the most extreme being that they can not be noticed. It was further suggested that it was this qualitative difference in awareness that had led some authors (and perhaps experimental psychologists more broadly) to conclude that there were no olfactory illusions. In the review provided in the second part of this manuscript, it is hard to find evidence that participants are aware of any of the various illusions that were described. Ironically, the only evidence that they may be noticed is anecdotal, with Cain's (1982) claim about alterations in an odor percept when moving from a state of 'not knowing the name' to 'knowing the name' and Gabriel Valentin's self-observation of binaral rivalry. Although these are anecdotes, this should suggest a note of caution because the issue of awareness has not been explored in olfactory illusions, and so it is entirely possible that some cases will be found where the perceptual change between one state and another can be made evident or is even self-evident. This caveat takes on extra force because people can become aware that they are having an olfactory hallucination, both in conditions which do and do not disturb rational thought (Stevenson & Case, 2005; Stevenson, Langdon, & McGuire, 2011). While, this likely renders the very strong (impossible to notice olfactory illusions) and strong (harder to notice than other senses) versions of the awareness claim as currently unsupportable because the evidence is lacking and with due regard to the cautions above – it is still reasonable to claim that olfactory illusions *in general* are not typically noticed. This is interesting, especially if one compares it to the many visual and tactile examples, where the illusion is clearly *self-evident* (e.g. the waterfall or Aristotle illusion – where one is led to feel one has two noses). Such 'self-evident' examples seem to be generally absent for olfaction, and the final part of the discussion examines why this might be so and the implications this may have.

Cain and Algom (1997) noted that odorants yield a less distinct sensory impression than the other modalities. They argue, reiterating a point first made by Aristotle, that this might arise because the presence of an olfactory experience is often not confirmable by other means. So, for example, in the case of the Waterfall or Aristotle illusion, not only do we know (respectively) that rocks do not move 'up' the side of a waterfall and that we only have one nose, we can also readily confirm this knowledge by deploying other sensory systems (feeling the rocks or looking at our nose) to verify that we are experiencing a misperception. Olfactory stimuli, in many cases, just do not offer the means for other modality verification, and this may be confounded by three further factors. First, it would seem that there are many more sources of inter- and intra-individual variation in olfactory perceptual ability than there are for the other senses. These can relate to gender (Cain, 1982), menstrual cycle (Doty, Snyder, Huggins, & Lowry, 1981), general cognitive ability (Danthiir, Roberts, Pallier, & Stankov, 2001), and genetic differences in expressed receptor types (Knaapila et al., 2008), all of which may result in somewhat different percepts for the same odor. This type of variation may make it more difficult to identify any changes in perception wrought by an olfactory illusion. Second, the same odor may differ in emotional salience across individuals, thus leading the same odor to be potentially attention demanding for one person but not for another. This may arise because odors acquire emotional salience principally via associative learning (e.g. Degel & Koster, 1999) resulting again in significant individual differences in responsiveness, and thus disposing some participants to attend to certain odors (and perhaps notice changes wrought by illusions) and not others. Third, people often lack basic general knowledge about their olfactory sensory system. This lack of knowledge can be readily seen in the Miscellanea section above, and is sufficiently poor for many people not to know that a nose is needed to experience flavor, or that taste sensations are anomalous in the context of olfactory perception. So, a combination of lack of knowledge, stimulus variation and salience, along with difficulty in actually verifying through the other senses that a misperception has occurred, all contribute to this lack of awareness of many olfactory illusions.

While knowledge and verification may be one factor, this would not arguably prevent one *noticing* the difference between two divergent percepts, assuming that you were confident that the stimulus had remained unchanged (i.e. as presumably with Gabriel Valentin's self-experimentation with binaral smelling). Setting aside the plausible notion that even if a difference in perception were noticed for an unchanged stimulus, it would probably be attributed to some external cause – a cold, blocked nose, another odor in the environment etc – there are at least two grounds for thinking that normal healthy participants would not be very good at noticing the change. Even in the visual system, where most people have a high degree of confidence in their ability to know what is going on in the world around them, the phenomenon of change blindness suggests an often marked incapacity to notice quite significant stimulus alterations from one visual instant to another (Rensink, O'Regan, & Clark, 1997). Change blindness seems to occur when attention is directed to some other point in the visual array (away from the 'change'), or when some time interval separates the appraisal of two largely similar scenes. In a recent review article Sela and Sobel (2010) suggested olfaction may be especially prone to 'change blindness' because almost all olfactory percepts are discontinuous, thereby promoting a favorable environment – time interval separation – for *not* noticing a change. An additional factor here, likely to compound this further, is that many of the experiments which seem to generate alternate olfactory percepts for the same stimulus, are typically conducted on separate days (when using within-designs). To be aware of such an illusion would then require knowing that the stimulus had remained constant (raising the verification problem above) *and* knowing that the percept had changed (raising the change blindness problem).

There may be a further factor contributing to the apparent (noting the caveat stated earlier) absence of awareness of olfactory illusions. This concerns the nature of access consciousness in olfaction. In a recent article Stevenson (2009b) argued that access consciousness might be restricted or even absent in olfaction (and see Zucco, 2003 for a similar argument). The basis for this argument is the apparent absence of conscious awareness for various cognitive activities – notably short-term memory and imagery – which although present in olfaction seem to be present *without* conscious access. This lack of access may make it difficult to reflect upon olfactory experience in the way that people can about visual experience (e.g. for Rubin's vase – 'now it's a face, while *before* it was a vase'). An additional access constraint may also apply, in that it may not be possible to obtain semantic memories relating to particular odors without knowing the odor's name, and naming as described above is particularly hard in olfaction when other cues are absent. So if it is hard to form a conscious image of an odor one has experienced before, if it is hard to name that odor and thus know what it might mean, then this is likely to provide a further obstacle to serially comparing two olfactory experiences, in the way that we can for many visual experiences (e.g. our ability to flip back and forth between two scenes and [eventually] spot the difference – see the example in Sela & Sobel, 2010). Finally, the difficulty in accessing olfactory semantic knowledge, and its apparent paucity, might preclude 'impossible' type illusions in this modality. To know the impossible surely requires an understanding of the plausible and this may be limited in olfaction.

Both philosophers and experimental psychologists have started to converge in identifying both differences in the nature and processing of olfactory percepts and in the implications this may have for contemporary models of consciousness, which are largely based upon the visual system (e.g. Batty, 2010; Lycan, 2000; Stevenson, 2009; Smythies, 1997; Verhagen, 2006; Zucco, 2003). In the context of this manuscript, the apparent actuality of olfactory illusions would seem to call into question Batty's (2010) claim that olfactory experience lacks object status. Batty (2010) argues that the same visual object can have varying properties under different conditions, and this variance can constitute an illusion and that as odors appear to lack object status they hence lack illusions. This manuscript would suggest that there are olfactory illusions but these seem to pass unnoticed. This raises two issues, one relating to awareness and the other relating to the object status of olfactory percepts. In relation to awareness, olfaction again is something of an exception. While examples of associative learning utilizing other sensory domains seem to require conscious awareness of the experimental contingencies (e.g. Hofmann et al., 2010), this does not appear to be the case for olfaction (e.g. Degel & Koster, 1999; Stevenson et al., 2000). Indeed, some recent evidence would suggest that conscious attempts to learn may actively interfere with successful performance (Stevenson & Mahmut, in press b), and this propensity for implicit learning may reflect the fundamentally different neural architecture of the olfactory system (e.g. Smythies, 1997). The implication here is that the lack of awareness surrounding olfactory illusions may reflect a broader lack of awareness of olfactory processing, which in other senses requires awareness.

The second issue concerns the object status of olfactory percepts. Several authors have suggested that odors do constitute objects (e.g. Bower, 1991; Haberly & Bower, 1989; Hopfield, 1999; Lynch, 1986; Malnic et al., 1999; Plailly et al., 2005; Stevenson & Boakes, 2003). They do so because odors are psychological constructions that reflect recognition of complex chemical blends (e.g. 'coffee' odor has 600 or so different volatile (i.e. smellable) chemical components), which *together* have become associated with some salient feature of the environment (e.g. 'predator', 'prey', 'mate', 'disease' or… coffee). This is a perspective on olfactory perception, which is driven primarily by functional and ecological considerations (Stevenson, 2010; Stevenson & Wilson, 2007). From a functional perspective, there is little need for a *consciously* accessible system able to compare one stimulus with the next because the olfactory system achieves this via rapid cortical adaptation to an existing event (Best & Wilson, 2004). Thus a failure to notice illusions may be an arguable consequence of function. More broadly, if functional differences between the senses do result in different types of conscious state, capacity, and modes of processing, then this must question the generality of models of consciousness based primarily upon the visual system. Needless to say there have to be commonalities between the senses (e.g. clustering events which have common predictive properties into 'objects'), but the differences may be especially revealing, and more so for olfaction, which may be as different from vision as it is possible to get. Perhaps even more importantly, if certain forms of information processing in olfaction are not accompanied by conscious awareness, then this would imply that the presence of conscious processing for similar tasks in the other senses may itself be functional.

In conclusion, the available evidence suggests that we can experience olfactory illusions, but that these phenomena *may* not be noticed. This inability to notice olfactory illusions arguably contributes to the feeling that these experiences (illusions) are of a qualitatively different form to illusions experienced in the other senses. While this conclusion is probably correct where the comparator system is vision, audition or somatosensation, it may not be the case for gustatory illusions as these too could go unnoticed. There is even less information available about gustatory illusions than there is for olfaction and so the apparent uniqueness of olfaction in this regard remains unresolved. Several factors may contribute to our inability to recognize olfactory illusions: (1) the difficulty we may have in verifying them; (2) variation in olfactory perception and peoples lack of knowledge about the olfactory system; (3) the apparent vulnerability of olfaction to change blindness making detection of difference problematic; and (4) more generally, olfaction may lack capacities, in relation to access consciousness, that aid the identification of illusions in the other senses. It may be for these reasons that olfactory illusions do not provide the sense of fascination and amusement afforded by illusions in other sensory systems and, relatedly, why many observers have assumed that they do not exist.

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