SENSE OF SMELL INSTITUTE

A Sense of Smell Institute White Paper

INFLUENCES OF OLFACTORY EXPERIENCE AND LEARNING ON ODOR PERCEPTION AND ODOR PROCESSING IN THE HUMAN BRAIN

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Summary

There is a prevalent assumption guiding contemporary research in olfactory neuroscience: the perception of a smell is a direct outcome of its chemical and molecular properties. However, increasing behavioral evidence suggests that cognitive factors, such as learning, experience, and sensory context, play an equally important role in how humans perceive the quality or character of a smell. The purpose of this White Paper is to review recent olfactory studies from our lab and others demonstrating the role of experience and learning in modifying odor perception at both the behavioral and neural levels. Particular focus is given to our own work examining the psychological and biological interface between olfactory sensation, perception, and experience. Specifically, by using functional imaging techniques to measure brain activity non-invasively from awake, healthy human subjects, we have been able to show that (a) prolonged sensory exposure to a single odor is sufficient to enhance behavioral discrimination of odors related in perceptual quality, and (b) these learning effects are mediated by the orbitofrontal cortex and piriform cortex, limbic areas of the human brain dedicated to emotion, memory, and behavior. A concluding section considers the potential relevance and applications to the fragrance industry. For example, the research strongly suggests that human olfaction is inherently ambiguous and highly malleable, such that consumer perception of a fragrance should be enhanced under appropriate experiences and circumstances. In addition, our findings imply that fragrance professionals may be able to enhance their own olfactory skills through simple perceptual training tasks. Finally, it is worth exploring the utility of functional imaging techniques to estimate the impact of context and experience on odor responses in the human brain, as a way to determine the efficacy of different marketing strategies upon consumer learning and satisfaction of new fragrance products.

1. Introduction

There is a widespread belief in the olfactory neurosciences that if one is armed with sufficient knowledge of an odor's physical, chemical, and molecular composition, then odor intensity (how strong?), odor hedonics (how pleasant?), and odor quality (how jasmine-y? how lemon-y? and so forth) should be easy to predict. This viewpoint is largely affirmed by animal studies, primarily in rodents, showing that olfactory receptor neurons in the nose, as well as their first relay points in the olfactory bulb, are responsive to basic molecular-chemical features of an odor (for reviews see Leon and Johnson, 2003; Mori *et al.*, 2006). The robustness of this elegant research is without fault, and it has significantly advanced our biological understanding of the olfactory system. However, it remains to be seen whether the detection of odor molecular features has any direct relationship to odor perception. In other words, is our perception of odor "X" simply related to the way that olfactory information about molecular structure is organized in the olfactory bulb?

Another way to reflect on this question is to consider the visual system. For example, when lightbeams from Kirsten Dunst's face radiate onto our visual receptor neurons in the eye (otherwise known as the retina), information is split into three channels selective for red, green, and blue colors, but our visual perception of Kirsten is not tri-colored. Rather, the visual perception of her face is an integrated event involving the coordination of brain regions far removed from the retina, and likely modified by cognitive factors related to past experience, current context, and (future) expectation of the actress.

Returning to olfaction, human behavioral data suggests that odor perception is equally complicated. When a smell wafts into the nose, the perceived intensity, hedonics, and quality are partly a function of the molecular-chemical information (as mentioned above), but these perceptual characteristics are as much a function of memory, experience, and context. This idea has received increasing support in recent years, on the basis of both human psychophysical and functional imaging evidence. These studies have highlighted the fact that odor perception is critically influenced by cognition. The central implication for industry applications is that experience and learning can be used to shape the perception of a smell (or taste) product.

It is worth noting that human studies have unique advantages over those involving animals. In particular, humans have the ability to provide a *verbal report* of their perceptual experiences, in a way that animals obviously cannot. This provides a highly convenient means of investigating the effect of cognitive factors on perceptual processing, as well as correlating perception to neural processes in the brain. By contrast, animal studies are forced to rely on indirect measures of perception, such as digging time (Linster and Hasselmo, 1999), odor investigation time (Linster *et al.*, 2001) or response tunnel selection (Youngentob *et al.*, 1990; Youngentob *et al.*, 2006) to assess perceptual similarity between odor stimuli. These principles are important to bear in mind when considering what are the optimal research methods to unlock the brain mechanisms underlying olfactory perception.

The remainder of this White Paper is organized into four sections (Parts 2-5). Part 2 will review previous human behavioral and psychophysical experiments analyzing the modulatory role of context and experience on odor perception. Part 3 will provide some background on the use of functional magnetic resonance imaging (fMRI) techniques to measure brain activity from awake human participants, and will review imaging data from my laboratory (as well as that of others) characterizing which areas of the olfactory brain help mediate the effects of context and experience on odor processing. Part 4 will specifically concentrate on recent fMRI research from my lab on olfactory perceptual learning, which was a prominent focus of my presentation at the April 2007 AChemS conference. The final section (Part 5) will consider some of the unique ways that this work may inform research and development within the fragrance industry.

2. Human behavioral studies: role of context, experience, and learning

The first point to make is that there is a marked ambiguity in human olfactory discrimination, even among professionals, who have difficulty distinguishing more than 3 components in an odor mixture (Livermore and Laing, 1996). This curious feature distinguishes the olfactory system from other sensory modalities, perceptions of which (e.g., visual or auditory) tend to be more dependably anchored to the physical environment. On the other hand, the inherent ambiguity in odor perception probably makes it more susceptible to the modulatory effects of learning and experience. This is an important issue that will be taken up further in the White Paper.

On the basis of human psychophysical studies, it has been known for almost 30 years that identification of single odors is poor, but improves when relevant semantic (e.g., verbal) labels are available (Cain, 1979). Even basic aspects of olfactory processing are strongly modulated by visual, perceptual, and cognitive factors. Pamela Dalton has shown that the adaptation (fatigue) of odor perception is affected by whether subjects are told the odor is healthy or hazardous (Dalton, 1996). Color has been found to interact with perceived odor intensity (Zellner and Kautz, 1990; Gilbert *et al.*, 1996; Zellner and Whitten, 1999). Odor intensity and pleasantness are enhanced by cultural experience (Ayabe-Kanamura *et al.*, 1998) and by knowledge of the odor's source (Distel and Hudson, 2001). In a clever study by Herz and von Clef (Herz and von Clef, 2001), subjects were presented a series of odors in combination with either positive or negative labels. As an example, the odor of violet-leaf was paired on alternate trials with the word "cucumber" or with the word "mildew." Pleasantness ratings of these odors were significantly and profoundly affected by the attached verbal context. From these studies one is tempted to infer that the ambiguous nature of odor perception helps to place the sense of smell under the powerful sway of both external (sensory) and internal (cognitive) factors.

One of the more scandalous experiments was a wine-tasting study conducted at the University of Bordeaux (Morrot *et al.*, 2001), where 54 enology students provided a series of odor descriptions for red wines (e.g., chicory, prune, cherry) and white wines (e.g., honey, grapefruit, lemon). Following this part of the study, a white wine was surreptitiously colored with odorless, tasteless red dye, without the subjects' knowledge. As a result, subjects consistently described the "red" white wine using language typically reserved for red wine and avoided the use of white wine terms. Thus, in the absence of appropriate visual information, wine odor had minimal impact on olfactory discrimination, and despite "expertise" among the wine students, the visual contextual cue dominated. These examples suggest that interactions between olfactory and other sensory modalities may contribute to effective odor perception, and that the experience of a smell is heavily regulated by accompanying sensory, semantic, and verbal cues.

The power of suggestion (as a contextual cue) also plays an equally important role in odor perception. A classroom of students was convinced that a bottle filled with distilled water actually contained a "strong and peculiar" odor that slowly spread from the front to the back of the room (Slosson, 1899). When a radio station informed its listeners that a certain auditory tone would recreate the physiological experience of a “pleasant country smell,” many people reported perceiving such an odor (O'Mahony, 1978). Learning and experience are also critical in olfactory identification and discrimination (reviewed in Wilson and Stevenson, 2003). Taken together, these findings indicate that an individual’s olfactory viewpoint is profoundly shaped by higher-order operations, likely to be mediated via central olfactory processes. It is even fair to say that context and experience effectively weave olfactory illusions, whereby one’s perception of a odor can be altered depending on the surrounding circumstances.

Often sensory exposure, even in the absence of explicit training, is sufficient to modify odor perception. There is a phenomenon known as “perceptual learning,” described over a century ago by William James, the father of American psychology, in which sensory experience induces meaningful changes in behavior and brain function (James, 1890; Gibson and Walk, 1956; Gibson, 1991; Goldstone, 1998; Gilbert *et al.*, 2001; Fahle and Poggio, 2002). Perceptual learning has been studied most commonly in the visual system,[1] but the same principles have been found to hold in the olfactory domain. Repeated presentations of an odor reduce olfactory detection thresholds (Stevens and O'Connell, 1995; Dalton *et al.*, 2002) and can even boost olfactory sensitivity in seemingly anosmic subjects (Wysocki *et al.*, 1989; Mainland *et al.*, 2002). Exposure to wine (Owen and Machamer, 1979) or beer (Peron and Allen, 1988) is sufficient to improve sensitivity toward stimuli whose chief sensory property is olfactory. Experience and familiarity significantly enhance odor perception and odor quality discrimination of odor mixtures (Rabin, 1988; Rabin and Cain, 1989; Jehl *et al.*, 1995), while exposure to odor mixtures alters the perceived quality of the individual components (Stevenson, 2001b). Many of these studies provide examples of stimulus ‘‘differentiation,’’ an important mechanism of perceptual learning in which experience refines sensory perception through differentiation of stimulus features, dimensions, or categories (Gibson, 1991; Goldstone, 1998; Schyns *et al.*, 1998). Notably, despite growing behavioral evidence for olfactory perceptual learning, how this form of learning updates odor quality codes in the human brain is unknown. This issue will be a focus of Part 4.

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[1] For example, mere visual exposure to scribbled pictures (‘‘doodles’’) results in subjects being better able to differentiate among related pictures, generating doodle ‘‘expertise’’ (Gibson and Walk, 1956).

3. Human fMRI studies: role of context, experience, and learning

Before discussing the olfactory fMRI data, it would be useful to provide a brief overview of the technique itself. Formerly, most of our neurobiological understanding of human olfaction was based on patient lesion studies (reviewed in Gottfried, 2006). Typically patients with tumors or intractable epilepsy would undergo surgical resections of the compromised brain tissue, resulting in removal of medial temporal or basal frontal lobes. Behavioral testing would show that odor detection thresholds, odor memory, and odor identification were often impaired in such patients (e.g., Rausch and Serafetinides, 1975; Henkin *et al.*, 1977; Potter and Butters, 1980; Eichenbaum *et al.*, 1983; Eskenazi *et al.*, 1983; Jones-Gotman and Zatorre, 1993). However, it was always challenging to correlate these functions with precise brain regions, because the size of the lesion resections was usually quite large, and the comparable size of the olfactory areas (e.g., piriform cortex, olfactory tubercle, amygdala) is quite small.

In the last 15 years, the advent of modern neuroimaging techniques, such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), has led to important advances in our understanding of central olfactory function in the normal human brain. fMRI has several important advantages: it is safe and noninvasive (not requiring the intravenous injection of radioactive tracers), is easily repeated within subjects across different sessions, and is ideal for complex experiments involving the delivery of multiple different odors. It is important to note that the fMRI signal is not a direct measurement of neuron activity, but reflects hemodynamic (blood flow) changes induced by brain activity (Ogawa *et al.*, 1990; Kwong *et al.*, 1992), providing a surrogate marker of neural responses with a time lag of a few seconds. Beginning with the landmark (PET) study of Zatorre et al. (Zatorre *et al.*, 1992), human neuroimaging research has begun to identify a network of brain structures important for olfactory processing (reviewed in Gottfried, 2006). The recent introduction of event-related designs to limit the duration of odor exposure (reviewed in Gottfried, 2006), as well as the development of specialized fMRI protocols (Deichmann *et al.*, 2003; Wilson and Jezzard, 2003), have helped improve fMRI signal detection in olfactory cortex.

Initial human imaging studies were designed to delineate which areas of the brain are responsive to different odors. These investigations confirmed much of what had been established from animal and human (lesion) studies, that when subjects smell an odor, brain activity is triggered in the primary olfactory (piriform) cortex and the amygdala in the temporal lobes, and in the orbitofrontal cortex (OFC), which as its name implies is positioned in the frontal part of the brain, just above the orbits (eyes). Interestingly, each of these areas including piriform, amygdala, and OFC is considered to be part of the extended “reptilian” brain or limbic cortex, critical for controlling emotion, memory, and behavior. Thus, the anatomical and functional evidence support the idea that odors engage those very brain regions that are essential to survival.

An increasing number of fMRI studies has begun to show that odor processing in the human brain is powerfully modified by sensory, emotional, associative, and cognitive experience. Put differently, one and the same odor may provoke a different brain response, depending on the surrounding events. In one of the first fMRI studies of this kind, O’Doherty and colleagues (O'Doherty *et al.*, 2000) showed that appetite and motivational state could influence sensory-specific odor representations in human OFC. On alternating fMRI blocks, healthy participants were presented with banana or vanilla odor, both before and after a lunch of bananas until they became sated for this item. As a result of this manipulation, the neural activity evoked by the banana odor (but not the vanilla odor) was selectively diminished in OFC, indicating that this brain region was sensitive to how rewarding the banana stimulus was at any given time. Other studies in the gustatory domain have shown similar effects. Responses in human OFC decrease as chocolate (a complex food stimulus with prominent olfactory components) is consumed to satiety (Small *et al.*, 2001), and also occur when subjects drink a flavorful food liquid (either tomato juice or chocolate milk) until they are sated (Kringelbach *et al.*, 2003).

Odor responses in the brain are also highly malleable when smells are presented with other sensory cues. An early PET study by Small et al. (Small *et al.*, 1997) evaluated sensory processing in response to odors, tastes, and combinations of odors and tastes that either matched (e.g., strawberry odorant with a sweet sucrose tastant) or mismatched (e.g., strawberry odorant with a salty sodium chloride tastant). These investigators found that combined odor-taste stimuli elicited reduced PET activity in olfactory and gustatory brain regions. Moreover, they found greater brain activity in the amygdala and the basal forebrain when these combinations mismatched (vs. matched) in quality. These results provided early evidence that multi-sensory context can influence the neural processing of smells. An fMRI variation of this study (Small *et al.*, 2004) in which smells were delivered retronasally (via the mouth) rather than orthonasally (via the nose) also demonstrated multi-sensory odor-taste integration within OFC and nearby regions in the insula and anterior cingulate cortex.

Using a different fMRI paradigm, Gottfried and Dolan (Gottfried and Dolan, 2003) showed that visual information also modifies odor coding in OFC. The primary aim of this study was to characterize mechanisms underlying visual modulation of olfactory perception. Using a simple odor detection task, we demonstrated that olfactory detection was faster and more accurate when odors appeared in the context of semantically congruent visual cues. So for example, subjects were able to detect the smell of rose more quickly and more accurately when it was presented in combination with a congruent image (e.g., the picture of a flower), as opposed to an incongruent image (e.g., the picture of a bus). Then, by comparing fMRI data between the congruent and incongruent smell-picture conditions, we identified the neural basis of this behavioral effect: activity was increased in OFC and in hippocampus, a region classically associated with memory functions. These data confirm that the exact same sensory input can evoke different brain responses depending on whether it was experienced in a semantically appropriate context.

Similar results of sensory context on odor processing in OFC have been demonstrated with combinations of odors and tastes, as mentioned above (Small *et al.*, 2004), and with combinations of odors and verbal labels (de Araujo *et al.*, 2005). In this latter study, the perceived pleasantness of a test odor (combination of sweaty-smelling isovaleric acid + cheddar cheese flavor) was rated higher when accompanied by the visual word label, “cheddar cheese,” than when accompanied by the word label, “body odor.” Analysis of the fMRI data revealed activation in OFC and cingulate cortex to the test odor when it was labeled “cheddar cheese” than when it was labeled “body odor,” and this effect correlated with pleasantness ratings to the test odor. Together the 2003 odor-picture study by Gottfried and Dolan, and the 2005 odor-word study by de Araujo et al., help to underscore the idea that prior experience and sensory context can profoundly modulate the central processing of olfactory information. Such mechanisms may also help to resolve the inherent ambiguity in olfactory perception and optimize odor-directed behaviors.

4. Learning to smell the roses: olfactory perceptual learning in the human brain

As discussed in Part 2, the phenomenon of "perceptual learning" refers to a *perceptual* improvement in sensory discrimination as a result of *learning* (Gibson, 1991; Goldstone, 1998). While perceptual learning is commonly achieved through explicit training or behavioral reinforcement, this is not a necessity, and enhancement of sensory perception may follow simply from passive exposure and experience to the stimulus of interest. This form of plasticity has been well documented in numerous non-olfactory brain systems including vision (Crist *et al.*, 2001; Yang and Maunsell, 2004), hearing (Jenkins *et al.*, 1990; Condon and Weinberger, 1991), and touch (Kossut *et al.*, 1988). However, while olfactory perceptual learning has been demonstrated at the behavioral level (see Part 2), there is very little information available regarding which parts of the smell-brain are responsible for mediating these unique learning effects.

Recently, Dr. Wen Li, a postdoctoral fellow in my lab, and I combined fMRI techniques with an olfactory habituation paradigm (Wilson, 2000a, b, 2003) to test whether prolonged olfactory exposure (as a simple form of perceptual learning) leads to sensory plasticity within the human brain (Li *et al.*, 2006). Our main hypothesis was that prolonged sensory experience would modify neural representations of odor quality[2] in areas previously implicated in coding of this perceptual feature, including piriform cortex (Gottfried *et al.*, 2006; Kadohisa and Wilson, 2006) and OFC (Schoenbaum and Eichenbaum, 1995; Savic *et al.*, 2000; Royet *et al.*, 2001; Dade *et al.*, 2002; Gottfried *et al.*, 2006). Moreover, in parallel to the neural effects, we hypothesized that odor experience would facilitate perceptual differentiation between odorants sharing critical qualitative or molecular attributes.

During fMRI scanning, 16 healthy human volunteers (mean age, 24 years) smelled four odorants: (1) a target odorant (TG) destined for habituation; (2) an odorant related in perceptual quality to TG; (3) an odorant related in chemical characteristics to TG; and (4) a control odorant completely unrelated to TG. These odorants were smelled both before and after 3.5 minute continuous exposure (habituation) to TG. Importantly, the four odorants used in this experiment consisted of two "minty" smells (*R*-carvone; menthol)

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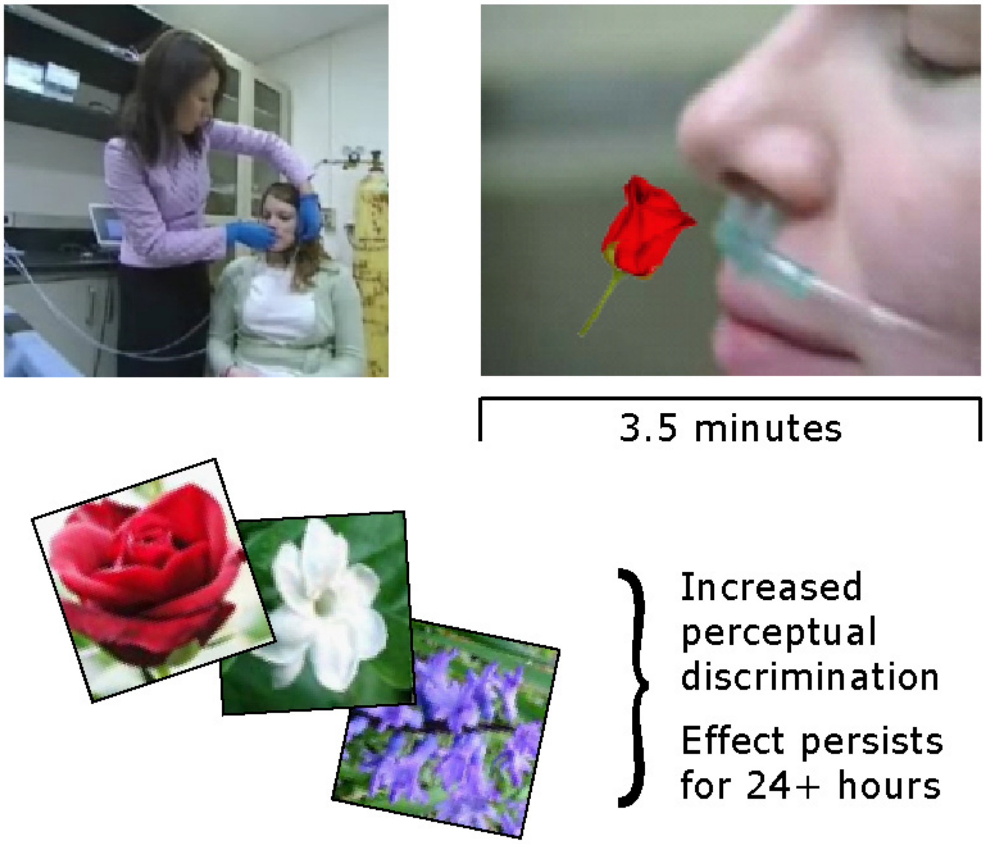
[2] Note the term "odor quality" is meant to indicate the specific character or identity of a smell emanating from an odorous object (such as its mintiness or floweriness), in contrast to other features such as intensity, pleasantness, or pungency.

and two “floral” smells (acetophenone; phenethyl alcohol), and chemically there was one ketone and one alcohol each in the minty set and the floral set. This made it possible to distinguish between the effects of perceptual quality and the chemical structure at the behavioral and neural levels. Finally, to obtain a behavioral measure of perceptual learning, we collected similarity ratings of odor quality (Stevenson, 2001a) for each pair of odorants, thirty minutes <u>before</u> and thirty minutes <u>after</u> exposure to the TG stimulus, for every subject.

Behaviorally, from pre- to post-exposure to the TG odorant, similarity ratings of odor quality decreased (indicating more *dissimilar*) for the pair of odorants related in perceptual quality, and they also decreased for the odorant pair related in chemical structure. The implication is that sensory experience with the TG odorant successfully enhanced the discriminative capacity (or expertise) for odorants similar in perceptual



This figure shows the basic layout of the experiment and a cartoon schematic depicting the influence of olfactory perceptual learning on odor discrimination. Top left, Dr. Wen Li positions the odor tubes at the entrance to the nose of a participant. Top right, the "target" odorant (in this case, rose) is inhaled continuously for 3.5 minutes during the habituation period. Bottom, as a result of prolonged odor exposure to the rose smell, the participant is better able to discriminate between different floral scents, and this learning effect lasts for at least 24 hours. See text for details.

quality or structure. For example, subjects exposed for 3.5 minutes to *R*-carvone (the minty ketone) became mint "experts," and they simultaneously became experts at distinguishing among ketone-bearing odorants. Such learning did not generalize to odorants outside of the experienced dimensions (that is, floral experts did not become mint experts, and alcohol experts did not become ketone experts), highlighting apsychological specificity that is a common characteristic of perceptual learning (Gilbert *et al.*, 2001; Fahle and Poggio, 2002). Furthermore, these effects were obtained despite the fact that subjects were completely unaware of the purpose of the study and were simply asked to rate odor intensity. As such, it is unlikely that procedural learning (performance improvements due to task rehearsal and training), which often confounds interpretations of perceptual learning (Hawkey *et al.*, 2004), contributed to the effects seen here. Finally, a complementary behavioral study on a separate group of 16 subjects revealed that these perceptual effects persisted for up to 24 hours after initial exposure and even generalized to novel odorants within the same odor category (Li *et al.*, 2006).

Analysis of the fMRI data-set was performed using the software package SPM2 (www.fil.ion.ucl.ac.uk/spm/) (Friston *et al.*, 1995a; Friston *et al.*, 1995b). Subject-specific comparisons (contrasts) between the different odor conditions, at pre- vs post-habituation, were entered into a series of statistical tests, each constituting a group-level analysis and permitting extrapolation of the results to the general population. These results demonstrated that from pre- to post-habituation, there was experience-dependent response enhancement in both piriform and orbitofrontal cortices, which even preceded the behavioral changes in odor discrimination. In posterior piriform cortex, neural activity elicited by the quality-related odorant increased from pre- to post-habituation; in olfactory OFC, increased activation was seen in response to both the quality-related and the molecular-related odorants.

The above findings provide solid evidence for behavioral and neural plasticity in response to sensory experience, but are unable to demonstrate whether there is a predictive relationship between the magnitude of response change in OFC (or piriform cortex) and the behavioral improvement in perceptual learning. To address this question, we conducted a correlation analysis by regressing subject-specific changes in neural activity (post- minus pre-habituation) against changes in odor quality similarity (post minus pre). In olfactory OFC there was a significant correlation ($R = 0.75$; $p < 0.05$ corrected for small volume) between neural and behavioral indices of learning. No such effect was observed in piriform cortex. These additional results suggest that OFC is a critical locus for guiding experience-dependent behavioral improvements in perceptual expertise.

Together our findings demonstrate that mere odor exposure is sufficient to enhance odor differentiation and elicit perceptual expertise for both odor perceptual quality and odorant functional group. These behavioral effects are paralleled (and preceded) by experience-induced neural plasticity in OFC and piriform cortex. The data suggest that experience specifically updates sensory-specific odor information in olfactory OFC, mediating subsequent improvements in odor perception.

5. Relevance of the research findings to the fragrance industry

These findings have important relevance and implications for the fragrance industry, with the possibility of several interesting applications. First, our research strongly suggests that human olfaction is inherently ambiguous and highly malleable, whereby consumer perception of a fragrance can be enhanced given the appropriate experiences and circumstances. There is every reason to think that the very same product, when marketed under a different name or contained within different packaging or linked to a different print ad, should be capable of enhancing consumer perception at both the behavioral and neural levels. Verbal and visual information have such power to modify how smells are perceived, that a fragrance may take on an entirely different meaning when associated with potent emotional cues, perhaps through advertising, provocative brand names, or visually appealing bottles.

Second, the data serve to illustrate that fragrance professionals may be able to enhance their own olfactory skills through simple perceptual training tasks. It is important to note that olfactory perceptual learning does not emerge *immediately* after continuous exposure. This is because after 3.5 minutes of smelling a single odor, there has been significant fatigue (habituation) to the smell. In our studies we allowed 20-30 minutes for the fatigue to resolve, prior to testing the effects on odor discrimination. Thus, fragrance professionals should bear this in mind to allow some time after odor exposure for the nose to recover and the discrimination effects to emerge. In our hands we have demonstrated that 3.5 minutes of exposure provides at least 24 hours of enhanced discrimination. Whether longer exposure periods might lead to more sustained odor learning is something that could easily be explored within the R&D divisions of the fragrance companies.

As further proof that odor exposure can improve one’s olfactory prowess, we have also obtained intriguing anecdotal evidence from a news anchor from WGN-TV who visited our lab early this year to cover our olfactory learning research. She was eager to see whether these perceptual learning techniques could be used to improve her sense of smell (J.A. Gottfried and W. Li, unpublished findings). Rather than using the stimuli from the original experiment (floral and minty smells), we decided to present her with real-world stimuli: three different red wine (Merlot) smells that were difficult to distinguish. Then, after 3.5-minute continuous exposure to one of the Merlots, the reporter was better able to tell apart the wine smells, on the basis of a “triangle comparison test” (in which she was asked to smell three bottles, two containing the same Merlot and a third containing a different Merlot, and then instructed to identify the one “odd” smell). This demonstration underlies the idea that humans have a great capacity for improving their odor discrimination abilities – as long as they are willing to take some time and direct their attention more carefully to the odor environment.

Finally, it is worth exploring the utility of functional imaging techniques to estimate the impact of context and experience on odor responses in the human brain. These brain-based approaches may help to determine the efficacy of different marketing strategies upon consumer learning and satisfaction of new fragrance products. Key olfactory brain regions include the orbitofrontal cortex (OFC) and piriform cortex, both key “limbic” areas that are central to emotional processing, memory, and behavior. For example, by using functional magnetic resonance imaging (fMRI) techniques to track fragrance-evoked brain responses in OFC, one might be able to assess the effectiveness of a particular marketing manipulation. From a practical point of view, it is important to emphasize that because the fMRI signal is very noisy, such studies would be best investigated at the group level (averaged across a group of subjects, e.g., 12-18), rather than at the individual level. This should not detract from the potential efficacy of the research method, but is mentioned only as to caution against attempting to make major inferences on the basis of single-subject data.

In this White Paper we have shown that simple sensory exposure is sufficient to modify how olfactory areas of the brain process smells, and that these brain changes lead to observed behavioral improvements in odor perception and discrimination. It is worth speculating that the capacity for experience-dependent neural plasticity in olfactory cortex governs the general development of human olfactory perception. This mechanism may underlie the acquisition of fine-grained percepts that distinguish, for example, the smell of Rosa damascena (Bulgarian Rose) from that of Rosa centifolia (Rose Maroc), to the point where we are able to appreciate the immense richness of aromas in everyday life. The sorts of potential industry applications described here naturally follow from basic mechanisms of odor perception and odor learning that have been closely examined in our research program.

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