

- hippocampal activity. *Hippocampus* 15, 1026–1040.
9. Takashima, A., Nieuwenhuis, I., Jensen, O., Talamini, L., and Rijpkema, M. (2009). Shift from hippocampal to neocortical centered retrieval network with consolidation. *J. Neurosci.* 29, 10087–10093.
10. Takashima, A., Nieuwenhuis, I.L., Rijpkema, M., Petersson, K.M., Jensen, O., and Fernandez, G. (2007). Memory trace stabilization leads to large-scale changes in the retrieval network: a functional MRI study on associative memory. *Learn. Mem.* 14, 472–479.
11. Slotnick, S.D. (2004). Visual memory and visual perception recruit common neural substrates. *Behav. Cogn. Neurosci. Rev.* 3, 207–221.
12. Gais, S., Albouy, G., Boly, M., Dang-Vu, T.T., Darsaud, A., Desseilles, M., Rauchs, G., Schabus, M., Sterpenich, V., Vandewalle, G., et al. (2007). Sleep transforms the cerebral trace of declarative memories. *Proc. Natl. Acad. Sci. USA* 104, 18778–18783.
13. Paz, R., Bauer, E.P., and Pare, D. (2007). Learning-related facilitation of rhinal interactions by medial prefrontal inputs. *J. Neurosci.* 27, 6542–6551.
14. Tse, D., Langston, R.F., Kakeyama, M., Bethus, I., Spooner, P.A., Wood, E.R., Witter, M.P., and Morris, R.G. (2007). Schemas and memory consolidation. *Science* 316, 76–82.
15. Born, J., Rasch, B., and Gais, S. (2006). Sleep to remember. *Neuroscientist* 12, 410–424.
16. Walker, M.P. (2009). The role of sleep in cognition and emotion. *Ann. NY Acad. Sci.* 1156, 168–197.
17. Stickgold, R. (2005). Sleep-dependent memory consolidation. *Nature* 437, 1272–1278.
18. Wilson, M.A., and McNaughton, B.L. (1994). Reactivation of hippocampal ensemble memories during sleep. *Science* 265, 676–679.
19. Yotsumoto, Y., Sasaki, Y., Chan, P., Vasios, C.E., Bonmassar, G., Ito, N., Nanez, J.E., Sr., Shimojo, S., and Watanabe, T. (2009). Location-specific cortical activation changes during sleep after training for perceptual learning. *Curr. Biol.* 19, 1278–1282.
20. Talamini, L., Nieuwenhuis, I.L.C., Takashima, A., and Jensen, O. (2008). Sleep directly following learning benefits consolidation of spatial associative memory. *Learn. Mem.* 15, 233–237.

¹School of Psychological Sciences, Zochonis Building, University of Manchester, Brunswick Street, Manchester M13 9PL, UK.
²Institute of Cognitive Neuroscience, Alexandra House, University College London, 17 Queen Square, London WC1N 3AR, UK.
E-mail: Simon.Durrant@manchester.ac.uk

DOI: 10.1016/j.cub.2009.08.019

Olfaction: When Nostrils Compete

In vision, alternating percepts occur when two different visual stimuli are presented separately to the two eyes. By analogy, simultaneous presentation of two different odorants separately to the two nostrils has now been shown to cause alternating odor percepts, an effect termed ‘binaral rivalry’.

Jay A. Gottfried

Binocular rivalry is a fascinating perceptual phenomenon that occurs when spatially incompatible images are presented to corresponding visual fields of both eyes. Rather than forming one well-blended percept, the two images compete for perceptual exclusivity, leading to alternating periods of perceptual dominance and suppression that switch abruptly every few seconds [1–3]. Scientific descriptions of this effect date back to 1760 [4], and today binocular rivalry remains a powerful method to investigate the neural bases of visual awareness. In this issue of *Current Biology*, Zhou and Chen [5] present evidence for binaral rivalry — olfactory perceptual alternations that occur when two different odorants are presented to opposite nostrils. The experimental paradigm presented here may herald a new research direction in the human sense of smell, opening up the possibility of gaining unique insights into the mechanisms of olfactory awareness.

In the main ‘binaral’ experiment, subjects were presented with dichorhnic mixtures [6,7], i.e., two different odorants delivered simultaneously to opposite nostrils. One nostril was exposed to butanol, a

straight-chain alcohol that smells like a marker pen. The other nostril was exposed to phenethyl alcohol, an aromatic alcohol that smells like roses. On each trial, subjects intermittently sampled from the two bottles, making a single sniff, and then used a bipolar rating scale (with anchors ‘marker’ and ‘rose’) to indicate how similar the odor was to marker or rose. In order to minimize sensory habituation, trials recurred every 20–30 sec. Over the course of 20 samplings, each of the subjects experienced perceptual switches between marker and rose, which varied both in the frequency of the switches as well as their magnitude: some subjects reported fairly modest effects, judging the maximal similarity of the mixture to either rose or marker between 62 and 70% (where 50% represents equal similarity to rose and marker), while others experienced more striking effects (maximal similarity, 82–94%).

Interestingly, when each subject’s ratings of whether the mixture smelled similar to either rose or marker were averaged across the 20 samplings, the mean rating across subjects was 53.9% similar to marker and 46.1% similar to rose. This analysis highlights the value of examining *trial-by-trial responses* during dichorhnic stimulation, a practice that is not

typically adopted in odor mixture studies. If one were to focus solely on group-averaged data, collapsed across trials, one would conclude that delivery of two odorants to different nostrils elicits a mixed percept that is 53.9% marker-like and 46.1% rose-like, essentially a composite odor containing roughly equal proportions of the two stimuli. Such a finding would be consistent with those observed in prior odor mixture studies [7–9]. But as shown by Zhou and Chen [5], a very different conclusion is reached when considering the data on a subject-by-subject and trial-by-trial basis. It would be valuable to reappraise the data from the earlier mixture studies to determine whether within-subject percepts fluctuated between odors across trials.

In a complementary ‘monorhinal’ experiment, the same subjects were presented with physical — rather than dichorhnic — mixtures of butanol and phenethyl alcohol. Thus, instead of separate odorant presentations to different nostrils, both odorants were presented to both nostrils. Again, each subject experienced perceptual switches, with a high degree of intersubject variability in the number of switches and the magnitude of perceptual changes. According to Zhou and Chen [5], this experiment provides evidence for a cortical basis of olfactory rivalry, relating their findings to the phenomenon of monocular rivalry — a less studied effect in which alternating visual percepts are elicited when two competing visual images are both presented to both eyes [10]. The

rationale goes as follows: because monocular rivalry is necessarily independent of eye-of-origin information (both eyes receive the same input), and because eye-of-origin is a 'low-level' effect, then perceptual alternations in this paradigm must be limited to higher-order, cortical mechanisms. How well the 'monorhinal' paradigm relates to monocular rivalry is less clear. That nostril-of-origin information is absent in this experiment nicely parallels the monocular rivalry paradigm and eliminates the possibility that nostril-specific effects are involved in this phenomenon. However, given the potential for the two odorants to compete for ligand binding at some of the same olfactory receptors in the nasal epithelium, a more peripheral basis for monorhinal rivalry cannot be excluded.

In a further effort to pinpoint the contribution of peripheral versus central factors to binaral rivalry, the authors conducted a series of olfactory adaptation studies, as previously implemented by Cain [11], from which the authors conclude that binaral rivalry involves adaptations both at peripheral sensory neurons and in the cortex. One potential difficulty with this interpretation is that the binaral rivalry effects were elicited intermittently, with a brief sniff occurring every 20–30 seconds, whereas the adaptation effects were elicited with prolonged continuous exposure to the odorants on the order of minutes. In future studies it would be important to try and equate the duration of stimulus exposure across the rivalry and adaptation paradigms in order to draw more direct inferences about the anatomical and physiological underpinnings of binaral rivalry.

As alluded to above, the current study [5] has much in common with prior psychophysical studies of odor mixture processing, but arrives at starkly different conclusions. There is a long tradition of using binary odor mixtures to approximate how humans perceive complex smells [6–9,12–16]. The use of physical odor mixtures has shown that *both odorants* in a mixture are usually perceived if the perceptual intensities of the individual odorants (in the unmixed state) are equal. On the other hand, perception of just *one odorant* within the mixture will dominate if its unmixed intensity is higher than that of the other odorant

[7,9]. While perceptual fluctuations of the type reported by Zhou and Chen [5] have not been reported, Laing and colleagues [7,9] have observed that with very small differences in odorant intensity, the perceived quality of a mixture can change dramatically from one odorant to both odorants, or from one odorant to the other. Therefore, future studies will need to ensure that trial-by-trial fluctuations in odor intensity do not account for the perceptual alternations identified in the present study [5].

One important issue raised by the new findings [5] is to clarify how well the phenomena of binaral rivalry and binocular rivalry relate to one another, if at all. To address this question it is useful to consider that binocular rivalry arises only under highly unnatural conditions, usually in the laboratory setting [1]. Under natural, real-world circumstances, the visual system is accustomed to receiving roughly identical views of an object at both eyes, which it then fuses into an integrated binocular percept. This is simply based on the fact that two different objects cannot be in the same place at the same time, and that one object cannot be in two places at the same time. In the absence of such environmental trickery, the visual system had no need of developing mechanisms to handle spatially contradictory information. Thus, binocular fusion is the default computation of the visual brain [1], failing only when spatially discordant views of an object are presented to the two eyes in the psychophysics lab. However, unlike visual objects, olfactory objects — odors emanating from odorous objects — are not tied to their sources. In the natural environment, odors are whisked away from their sources by wind currents, can travel long distances, and can defy the sorts of physical obstacles that would quench the transmission of visual information. Moreover, most natural odors are complex mixtures of dozens, if not hundreds, of different molecular constituents. It is thus possible for two different odorants to share the same physical location at one time, and for one odorant to be in two locations, or two nostrils, at the same time — quite the opposite of visual objects. Thus, the olfactory system is highly accustomed to receive conflicting 'views' of an odor object at both nostrils, blending

these inputs into an integrated olfactory percept [17].

Given that perceptual fusion of conflicting odor inputs is a default computation of the brain, it is reasonable to ask why Zhou and Chen [5] observed rivalry, rather than fusion, under conditions that should favor fusion. As mentioned earlier, whether small intensity changes across trials might contribute to the reported fluctuations will need to be considered in the future — the fact that butanol was rated more intense than phenethyl alcohol, and the fact that the intensity of both stimuli decreased with time, lends some credence to this idea. Another possibility is that there is something unique about the combination of butanol and phenethyl alcohol, such as particular chemical interactions, and replication with other stimulus pairs will be necessary to demonstrate the generalizability of the phenomenon. Finally, it is unclear whether the rivalry effect is based on genuine neural suppression of an odorant representation, making it inaccessible to conscious awareness, as suggested in binocular rivalry [1–3], or whether there is just a relative reduction in the perceived intensity of the non-dominant odorant. Inspection of the original data provides partial support for the latter possibility, which shows that some of the similarity ratings were near the midpoint between marker and rose, suggesting a blended percept with one odorant slightly more dominant than the other.

On a final historical note, it is worth mentioning that the phenomenon of binaral rivalry was actually recognized as early as the 1840s. Gabriel Valentin, an eminent German physiologist of the mid-Eighteenth Century, found "that when ether and balsam of Peru were smelled at the same time one by one nostril and the other by the other nostril, the odors are perceived not together but alternately" ([18], cited in [19], page 85). In fact Valentin believed "that there was a sensory conflict here as in vision, when one eye is directed to a field of one color and the other eye to one of another color" [19], thus forging a link to binocular rivalry. Later work by Aronsohn in 1886 [19] and Henning in 1916 [20] documented similar effects. Now with the first systematic, and certainly the most rigorous, investigation of binaral rivalry presented in this issue of *Current Biology* [5], the burgeoning olfactory

field may be poised to make new inroads into the neuroscientific basis of odor perception and awareness.

References

1. Blake, R. (1989). A neural theory of binocular rivalry. *Psychol. Rev.* **96**, 145–167.
2. Blake, R., and Logothetis, N.K. (2002). Visual competition. *Nat. Rev. Neurosci.* **3**, 13–21.
3. Tong, F., Meng, M., and Blake, R. (2006). Neural bases of binocular rivalry. *Trends Cogn. Sci.* **10**, 502–511.
4. Dutour, E.-F. (1760). Discussion d'une question d'optique [Discussion on a question of optics]. *l'Académie des Sciences. Memoires de Mathematique et de Physique Presentes par Divers Savants* **3**, 514–530.
5. Zhou, W., and Chen, D. (2009). Binocular rivalry between the nostrils and in the cortex. *Curr. Biol.* **19**, 1561–1565.
6. Cain, W.S. (1975). Odor intensity: mixtures and masking. *Chem. Senses Flav.* **1**, 339–352.
7. Laing, D.G., and Willcox, M.E. (1983). Perception of components in binary odour mixtures. *Chem. Senses* **7**, 249–264.
8. Laing, D.G., and Francis, G.W. (1989). The capacity of humans to identify odors in mixtures. *Physiol. Behav.* **46**, 809–814.
9. Laing, D.G., Panhuber, H., Willcox, M.E., and Pittman, E.A. (1984). Quality and intensity of binary odor mixtures. *Physiol. Behav.* **33**, 309–319.
10. O'Shea, R.P., Parker, A., La Rooy, D., and Alais, D. (2009). Monocular rivalry exhibits three hallmarks of binocular rivalry: evidence for common processes. *Vision Res.* **49**, 671–681.
11. Cain, W.S. (1977). Bilateral interaction in olfaction. *Nature* **268**, 50–52.
12. Berglund, B., and Olsson, M.J. (1993). Odor-intensity interaction in binary mixtures. *J. Exp. Psychol. Hum. Percept. Perform.* **19**, 302–314.
13. Engen, T. (1964). Psychophysical scaling of odor intensity and quality. *Ann. N.Y. Acad. Sci.* **116**, 504–516.
14. Jones, F.N., and Woskow, M.H. (1964). On the intensity of odor mixtures. *Ann. N.Y. Acad. Sci.* **116**, 484–494.
15. Lawless, H.T. (1977). The pleasantness of mixtures in taste and olfaction. *Sens. Processes* **1**, 227–237.
16. Moskowitz, H.R., and Barbe, C.D. (1977). Profiling of odor components and their mixtures. *Sens. Processes* **1**, 212–226.
17. Wilson, D.A., and Stevenson, R.J. (2006). *Learning to Smell: Olfactory Perception from Neurobiology to Behavior* (Baltimore, MD: The Johns Hopkins University Press).
18. Valentin, G. (1847-1850). *Lehrbuch der Physiologie des Menschen*, Bd. 2, Abt. 2. (Brunswick, 731 pp.).
19. Parker, G.H. (1922). *Monographs on Experimental Biology. Smell, Taste, and Allied Senses in the Vertebrates* (Philadelphia and London: J.B. Lippincott Company).
20. Henning, H., (1916). *Der Geruch*. (Leipzig: Barth, viii, 533 pp.).

Northwestern University Feinberg School of Medicine, Cognitive Neurology and Alzheimer's Disease Center and the Department of Neurology, 320 E. Superior St., Searle 11-453, Chicago, IL 60611, USA.
E-mail: j-gottfried@northwestern.edu

DOI: 10.1016/j.cub.2009.08.030