‘The colour difference patterns are unique molecular fingerprints that can identify specific pollutants, toxic gases, different bacteria, or even one single malt Scotch from another’

Smell-seeing

Kenneth S. Suslick (George Eastman Visiting Professor 2018–2019) has developed an optoelectronic nose that identifies smells visually

Human beings are visual creatures, but most other animals live and die by their sense of smell. Even humans, however, can discriminate among millions and millions of different odorants over a vast range of concentrations. Our olfactory system works by recognising the pattern of the responses of hundreds of different sensors (the olfactory receptors) in the uppermost part of the nasal cavity.

My students and I have developed an ‘optoelectronic nose’ that converts olfactory-like molecular interactions into visual output. We imitate olfactory pattern recognition by using the colour changes of an array of chemically responsive dyes: essentially a digital, multidimensional version of litmus paper (Figure 1), which we sometimes refer to as ‘smell-seeing’. These dyes change colour depending on their chemical interactions with odorant molecules in the air. Although no single chemically responsive pigment is specific for any one analyte, the pattern of colour change for the array proves to be a powerful method for differentiating one odour from another. The colour difference patterns are unique molecular fingerprints that can identify specific pollutants, toxic gases, different bacteria, or even one single malt Scotch from another.

The sensor array is small (less than 1 cm^2) and disposable; we generate these arrays with a robotic pin-printer or an inkjet printer. The arrays are then imaged, which can be done by an ordinary inexpensive flatbed scanner, a fancy digital camera or, just as easily, an everyday cell phone. We have also built a self-contained hand-held analyser that uses a line-imager of the sort used in business card scanners.

The chemical or industrial workplace has no equivalent of a radiation badge for monitoring individual exposure to potentially toxic gas or vapours. For the detection of volatile organic compounds (VOCs), we have demonstrated excellent discrimination with extremely high sensitivity for a wide range of toxic industrial chemicals (TICs) (Figure 2). Striking visual identifications of many TICs – for example, hydrogen sulphide, ammonia, sulphur dioxide – can be made down to part-per-billion (ppb) levels with sensitivities better than gas chromatography-mass spectrometry detection, the gold standard for gas analysis.

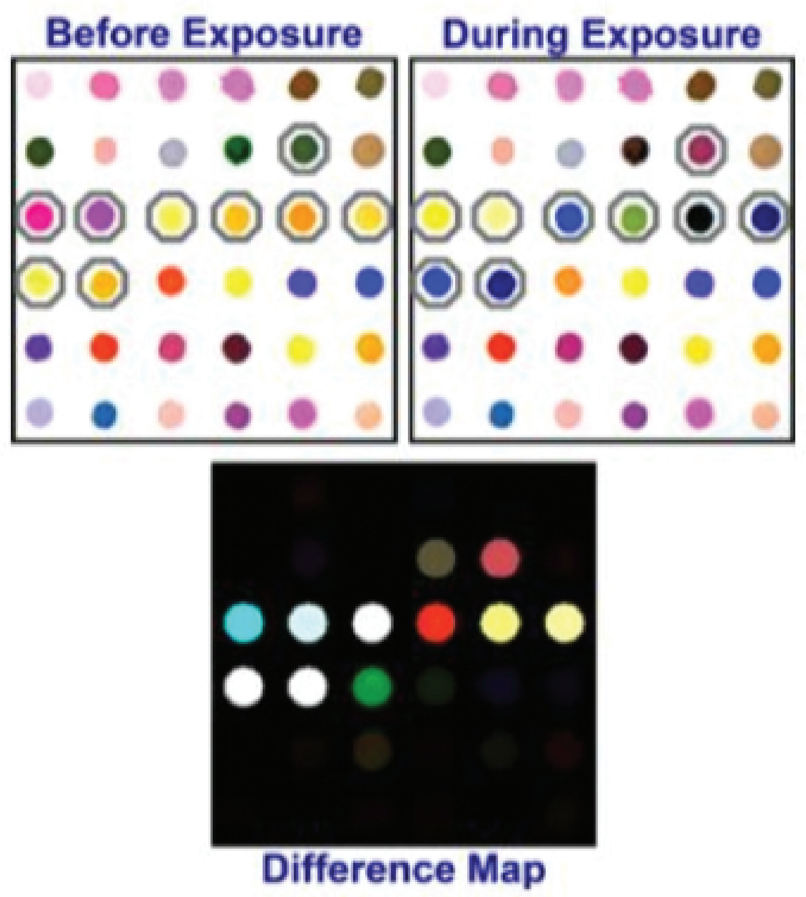

Figure 1. Smell-seeing uses the colour changes in an array (1cm^2) of chemically responsive dyes. We generate a difference map simply by subtracting red values of the image before odorant exposure from red values after exposure, green from green, and blue from blue, and so quantitatively compare the digital images before and during exposure; grey outlines mark the sensor spots with the greatest colour changes.

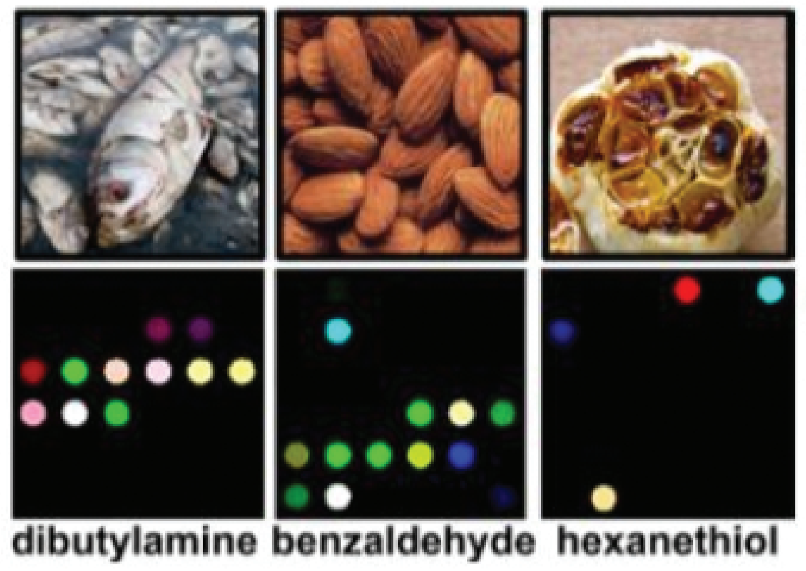

Figure 2. Difference map patterns of a few different volatile organic compounds (VOCs), shown with an everyday example of the odour of each VOC. Each pattern is a unique fingerprint for that odorant.

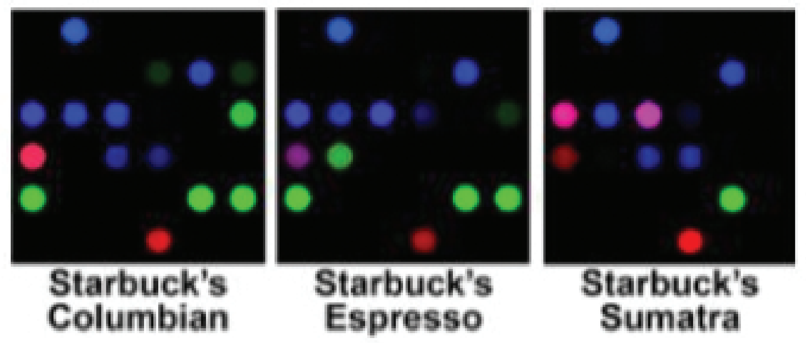

Figure 3. The sensor array can tell the differences even among individual kinds of coffee, as shown, or the roasting times and temperatures from a single batch of whole coffee beans.

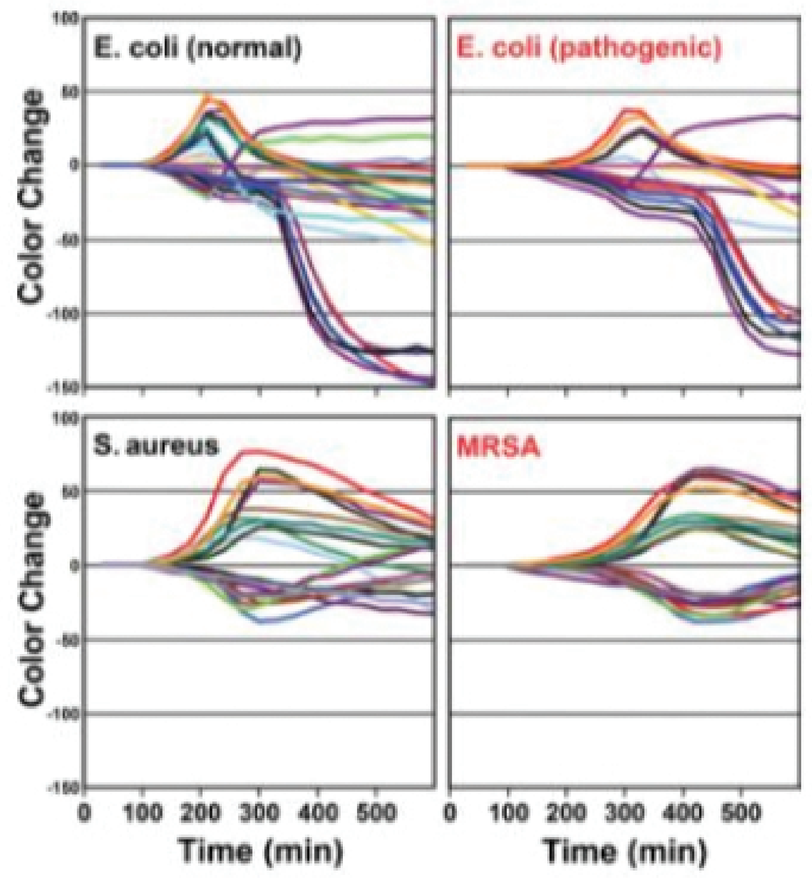

Figure 4. Rapid detection and identification of human pathogenic bacteria from blood culture is possible using the colour changes of the sensor spots versus time. In three or four hours (a clinically important time for early detection of sepsis), we can tell not only the bacterium but also indications of its antibiotic susceptibility. MRSA is the antibiotic-resistant type of *Staphylococcus aureus*.

Classification analysis (very similar to the comparison between genomes of different species) reveals that the colorimetric sensor array has an extremely high dimensionality, with the consequent ability to discriminate among a large number of TICs and explosives over a wide range of concentrations. For complex mixtures, fingerprinting through the colour difference pattern permits exquisite discrimination among very similar aromas. We can tell the differences among different brands of coffee (Figure 3), beer, soft drinks and whiskies – indeed, we can detect the watering of whisky with as little as 1% dilution.

The technology is also particularly suitable for detecting many of the most odiferous compounds produced by bacteria, for example from food spoilage or from body odour. We are able to distinguish bacterial growth at very low levels of detection and we can easily identify one pathogenic bacterium from another during growth from their smell within a petri dish or a liquid culture (Figure 4).

Our most recent project has involved monitoring artwork exposure to pollutants during exhibition. Just as people need protection from air pollution, so do cultural heritage objects, but even more so (because works of art do not heal and do not have limited lifetimes, as humans do). The desired pollutant concentration limits for sensitive artwork are generally only ~1% of the permissible exposure limits for human exposure and are at or below the low ppb regime. Monitoring pollutants at such low levels is an exceptional challenge, especially in a cost-effective fashion in a large number of locations and micro-environments.

To meet this challenge, we have used new sensor array chemistry to develop *cumulative* colorimetric sensor arrays. The resulting disposable sensor arrays are inexpensive, cross-reactive sensors using a wide range of chemical interactions with analytes. Importantly, they have been specifically engineered to be insensitive to humidity changes.

We have broadened these studies through a collaboration with the Getty Conservation Institute and the Disney Animation Research Library (DARL), both in southern California. DARL recently had its first exhibition in China of original Disney artwork, entitled ‘Drawn from Life: the Art of Disney Animation Studios’, featuring animation drawings, story sketches, layouts, backgrounds, and concept art spanning the 90 years of the Walt Disney Animation Studio's history. Naturally, there was concern about the potential effects of air pollution on the artwork during the exhibition. By using cell phone camera imaging, we were able to make field observations on pollutant exposure of sensor arrays mounted inside and outside the passepartout framed artwork during both shipping and exhibition.

Let me close by giving my deepest thanks to the Fellows and students of Balliol for a most welcoming stay as this year's Eastman Professor.

For further information:

Rakow, N.A.; Suslick, K.S. ‘A Colorimetric Sensor Array for Odor Visualization’, *Nature*, 2000, 406, 710–714.

Lim, S.H.; Feng, L.; Kemling, J.W.; Musto, C.J.; Suslick, K.S. ‘An Optoelectronic Nose for Detection of Toxic Gases’, *Nature Chemistry*, 2009, 1, 562–567.

Zheng, L.; Askim, J.R.; Suslick, K.S. ‘The Optoelectronic Nose: Colorimetric and Fluorometric Sensor Arrays’, *Chem. Rev.*, 2019, 119, 231–292.

Ken Suslick is Marvin T. Schmidt Research Professor of Chemistry at the University of Illinois at Urbana-Champaign, School of Chemical Sciences, Urbana, IL, USA (ksuslick@illinois.edu).

BOOKS AND RESEARCH