Communications Through Virtual Technology:
Identity Community and Technology in the Internet Age
Edited by *G. Riva* and *F. Davide*, IOS Press: Amsterdam, 2001 - © 2001, 2002, 2003

12 Virtual olfactory interfaces: electronic noses and olfactory displays

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Abstract. At present, in communications and virtual technologies, smell is either forgotten or improperly stimulated, because non controlled odorants present in the physical space surrounding the user. Nonetheless a controlled presentation of olfactory information can give advantages in various application fields. Therefore two enabling technologies, electronic noses and virtual olfactory displays, are reviewed. Scenarios of usage are discussed together with relevant psycho-physiological issues. End-to-end systems including virtual olfactory interfaces are quantitatively characterised under many respects: smell quality and concentration, dynamics, spatial localisation and information rate. Recent work done by the authors on fidelity is finally reported.

Contents

12.1 Principles of electronic noses

In comparison with the ear and the eye, the human nose is much more complicated, at least regarding the mechanisms responsible for the primary reaction to an external stimulus. Therefore it has been much simpler to mimic the auditory and the visual senses. In olfaction hundreds of different classes of biological receptors are involved, whereas in vision in principle only three different classes are found.

A solid state video camera can really catch an image very similar to that seen by the eye. In artificial olfaction the situation is quite different. Although several interesting developments have been made regarding so called electronic noses, their performance is far from that of our olfactory sense. They are not as sensitive as our nose to many odorous compounds. Inspite of this difference, chemical sensor arrays combined with pattern recognition are very useful in many practical applications related to the development of information technology. Electronic noses (EN) are thus emerging as new instrumentation, which can be used to measure the quality of a product or a process. They have, in that respect, a large similarity with the human nose. They also work in a way similar to the nose.

The human olfactory system is very complex, and is not yet fully understood. Some aspects have, however, been investigated [1-3]. A simple scheme of how the olfactory system works can be seen in Fig.12.1.

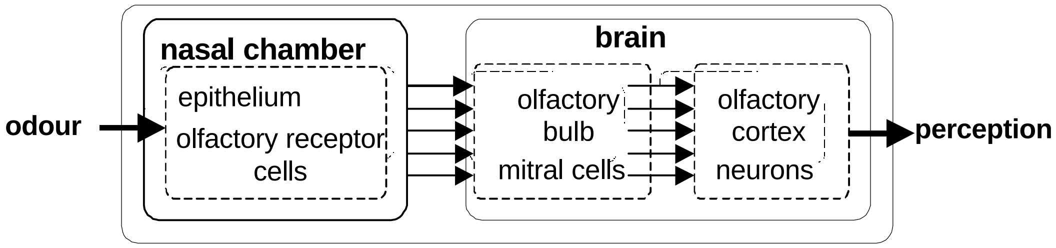

Figure 12.1. Scheme of the human olfactory system. A large number of olfactory receptor cells (»10 million) but with a limited amount of selectivity classes (~ 10-100). An odour produces a pattern of signals to the olfactory cortex via the mitral cells (~ 10 000). The brain interprets the signal pattern as a specific odour.

There are approximately ten million sensory receptor cells in the nose, each of them sensitive to a great number of compounds. The response of a receptor is due to the activation of biochemical processes in the cell and/or ion channels in the cell membrane. The response time, i.e. the time it takes for a receptor to give a significant response when exposed to a new odour, is in the order of seconds. Neighbouring receptors have similar selectivity profiles, i.e. are sensitive to almost the same molecules. Since the number of receptors is so great, the total variation in selectivity is, however, great enough to make us experience quite different sensations from different odours. Compare for instance how you react to the smell of ammonia and to freshly made bread. In order to utilise the information in the receptor signal, it has to be processed in a suitable way. Electrical signals are transferred from the receptors to the olfactory bulb through axons and dendrites. The signals then reach simple signal processing cells called neurons. A neuron has (in general) many inputs but only one output, which can either be excited or not. There will be a signal on the output if there is enough excitation on its inputs, with different importance (weight) being attached to the different inputs. These weights can be changed in a learning process, making it possible for us to learn to better recognise odours we are often exposed to. In the olfactory bulb there are many neurons, together forming a whole network. This network processes the information and then transfers the processed data to the olfactory cortex. This is where the final processing is made, by another network of neurons, and also where the communication with the rest of the brain takes place. The brain can then use this new information together with stored knowledge and tell us, e.g., to run away from or approach the odour source.

Table 12.1 Schematic comparison between human and electronic noses.

HUMAN	ELECTRONIC
~ 10 million receptors, self generated	5-100 chemical sensors manually replaced
10-100 selectivity classes	5~100 selectivity patterns
Initial reduction of number of signals (~1000 to 1)	“smart” sensor arrays can mimic this?
Adaptive	Perhaps possible
Saturates	Persistent
Signal treatment in real time	Pattern recognition hardware may do this
Identifies a large number of odours	Has to be trained for each application
Cannot detect some simple molecules	Can detect also simple molecules (H_2, H_20, $C0_2$…)
Detects some specific molecules	Not possible in general at very low concentrations
Associative with sound, vision, experience, etc	Multisensor systems possible
Can get “infected”	Can get poisoned

An electronic nose is an electronic system that, just like the human nose, tries to characterise different gas mixtures [2,4,5]. It uses currently a number of individual sensors (typically 5-100) whose selectivities towards different molecules overlap. Since the number of sensors is so small and the sensors are often carefully chosen, the overlap is usually much smaller than for the receptors in the human nose. The response from a chemical sensor is usually measured as the change of some physical parameter, e.g. conductivity or current. The response times for these devices range from seconds up to a few minutes. This is a significant drawback for these devices, and thus one of the main research topics in this field is to reduce the response time. A simple flow chart of the working principle of an electronic nose is shown in Fig.12.2. Figures 12.3 and 12.4 summarise the principle behind an electronic nose, where for simplicity we assume that we have an array of only three different sensors, with their selectivities to (classes of) molecules as shown in Fig.12.3.

If the sensor array is exposed to gas mixtures, “odours”, containing the molecules to which the devices are sensitive, different response patterns will be created as shown in Fig.12.4.

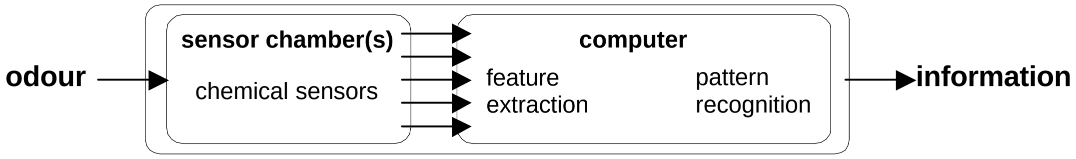

Figure 12.2 Schematic of an electronic nose. A limited amount of chemical sensors (10-100) with partly overlapping selectivity profiles. A computer is used to extract the features from the sensor signals and to recognise the patterns belonging to a given odour or gas mixture.

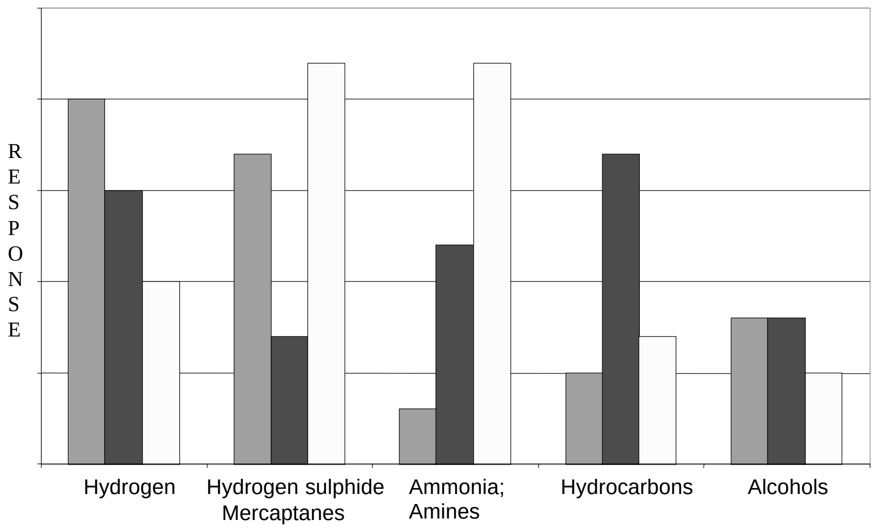

Figure 12.3 Examples of different (imagined) selectivity patterns towards different classes of molecules for a three sensor electronic nose

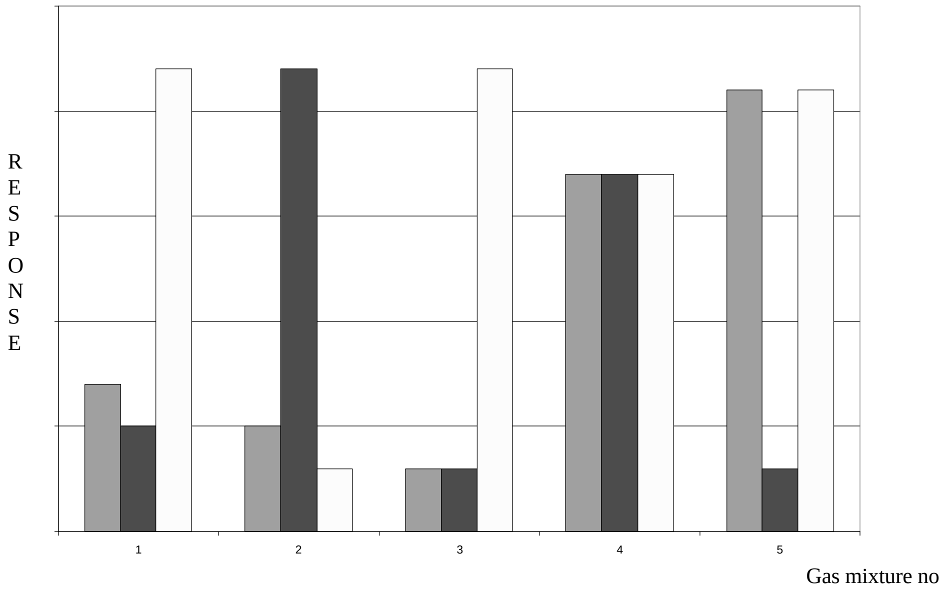

Figure 12.4 Examples of response patterns for a three sensor electronic nose towards different gas mixtures (odours).

By teaching a computer (or hardware) to recognise those patterns we have trained the electronic nose. It should now be able to classify a gas mixture belonging to the different classes of gas mixtures it has been trained to. Different levels of difficulties exist, depending on the task of the electronic nose, like identification of a gas or smell (methanol or ethanol), classification of a gaseous sample (good, bad, average), or quantification of a gas mixture (10 ppm ethanol, 2 ppm methanol, 7 ppm glycol).

One simple mathematical example shows the problems, or rather possibilities with electronic noses. If we have n sensors and use only threshold detection (i.e. "0" for low and "1" for high signals) we can obtain a maximum of :

$$N_2 = 2^n - 1 \tag{12.1}$$

different patterns if there is no redundancy among the sensors. For a three level detection we obtain:

$$N_3 = 3^n - 1 \tag{12.2}$$

If we have an array of sensors with n=12 sufficiently different selectivity patterns, we get N_2 = 4095 and N_3 = 531440. Even the primitive detection scheme above may thus provide a large amount of different response patterns. A very important part of the electronic nose is thus an efficient technique for pattern recognition. There are several methods used, some statistical which determine the clusters of data representing different classes of odours, and some based on different forms of artificial neural networks (ANNs) for classifications and quantification of gas mixtures. The development of efficient pattern recognition algorithms is therefore one of the important issues in the field of electronic noses.

One common linear method for pattern recognition is principal component analysis (PCA) [6]. We can consider this method as a way to reduce the number of dimensions of the data set. If we use 20 sensors (one measurement can thus be represented as a point in a 20-dimensional space) for our measurements, some of them probably respond in a similar (but not identical) way. This means that the number of dimensions in the data set can be reduced without any loss of information. If we look at an example with only three sensors, such co-variance between the sensors can be seen in a three-dimensional graph (with one sensor on each axis) as the data being spread out along a line, as shown in Fig.12.5.

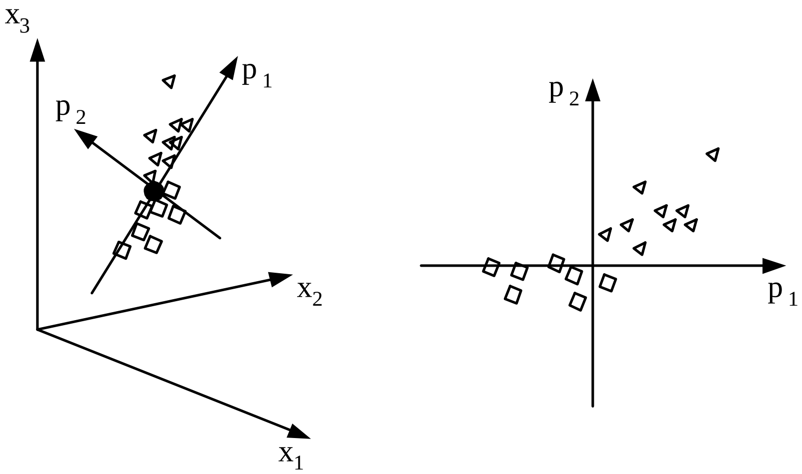

Figure 12.5 Schematic picture of how a principal component (PCA) score plot is made. The first principal component is the direction with most of the variance in the data set. The low-dimensional projection of the data can be used as a simple, but good, approximation of the data set.

If we project all data on the line drawn in the figure, we will lose only little information, so the three-dimensional problem can be reduced to two dimensions. This projection corresponds to the first principal component in a PCA, which is defined as the direction in which the data has the highest variance. The second principal component is directed in the direction, orthogonal to the first component, which has most of the remaining variance. In the case where we have several sensors, this can be repeated up to a total number of principal components equal to the number of sensors. Most variation in the sensor signals will be in the first few principal components, and we can therefore use only these to visualise the data. If we plot the first principal component as a function of the second principal component, we will be able to study most variations in the data set. This type of plot is usually called a principal component analysis score plot (PCA score plot), and can also be made using other principal components if desired. A loading plot of a PCA shows to what degree the different sensors contribute to the principal components. In this plot, sensors with similar contributions (i.e. that contain similar information) will be close together. Sensors that are close to the origin have comparably small variance, and therefore probably contain little information.

One of the most popular supervised methods to handle electronic nose data is the artificial neural network (ANN) [7], which bears a certain resemblance to the function of the human brain. In principle, an ANN is constituted of many (in the order of 50-100) artificial neurons. The artificial neurons are organised in different layers (see Fig.12.6), often three, together forming a network. An artificial neuron is a simple processing element, which in resemblance to biological neurons uses signals from several inputs to produce one output.

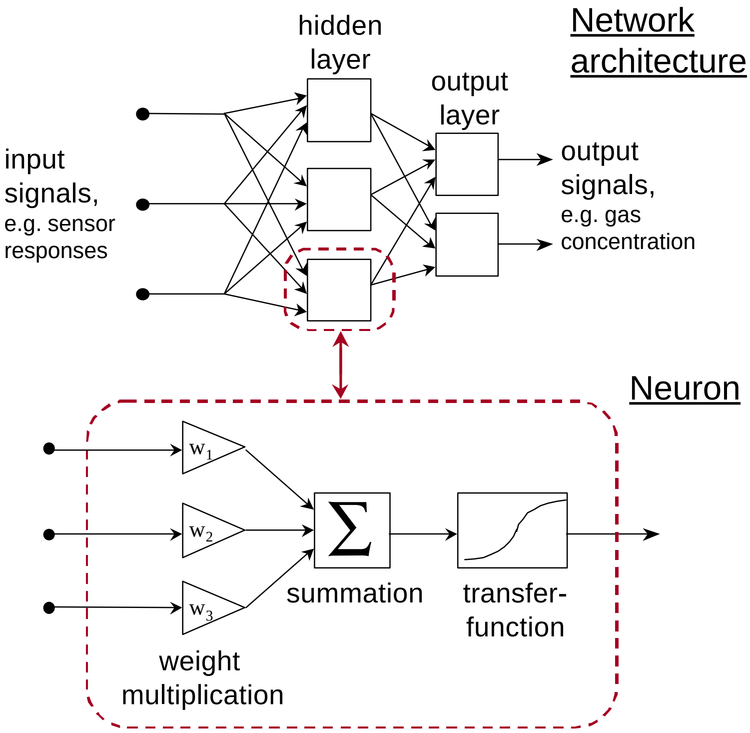

Figure 12.6 Schematic of an artificial neural network. It consists of a multilayered (often three) interconnected layers of neurons. The computing neurons (hidden and output layers) have a non-linear (often sigmoidal) transfer function. The parameters of the neurons are chosen through a minimisation of the output error for a given (known) training set.

A linear combination is taken of all the inputs, giving a single value. This value is then used in a transfer function, which could have arbitrary shape. One example is the step function, which like the biological neuron gives a non-zero value out when the calculated value from the linear combination is above a certain threshold, and zero otherwise. More common, however, is to use a smooth function, e.g. a sigmoid. The learning in an ANN is performed by changing the parameters in the linear combination, and possibly also the shape of the sigmoid. By feeding data from known odours into the network, the parameters can be adapted to recognise the sensor signals from these odours. In order to adapt the parameters, the training data has to be used many times. This is very similar to training of odour recognition for humans. After being exposed to an odour only once we seldom remember it very well, while odours we often have experienced in youth can be recognised a long time afterwards. It is important to note that an ANN, just like the human nose, cannot identify odours it has never experienced before. When confronted with the sensor signals from a new odour, the ANN can only say which of the known odours the signals are most similar to, or (even better) that it does not recognise the odour. A human can easily say if it considers an unknown odour to be pleasant or not, while an electronic nose cannot make any subjective judgement of that type.

The human olfactory system is schematically compared with electronic noses in Table 12.1. Already the olfactory receptor cells are much more complicated than any chemical sensor device constructed. They are specialised towards different classes of odourant molecules. A biochemical machinery leads to an electrical signal which is further propagated in a highly interconnected neural network. There also exists a large redundancy in the number of olfactory cells. At the first level of neural nodes in the olfactory system, the mitral cells, a reduction of the number of signals occurs from the approximately 10 million olfactory receptor cells to about 10 thousand signals from the mitral cells. In the olfactory system also signals to and from other parts of the brain are present, making the olfactory sensation associative with other external stimuli. A given odour produces a spatial and temporal signal pattern in the olfactory cortex. In contrast to the visual perception, which is based on a small number of different pigment molecule classes, there is no such simple rule for olfactory receptors. Although there are several different receptor classes, there are no receptors specific for one given molecule. The olfactory receptors rather respond with broad selectivity patterns towards several different odourant molecules, and it is this response pattern that determines the odour sensation. Also, several general properties of the molecules influence the smell, such as water- and fat solubility, shape, and also specific properties such as aromaticity and the position of functional groups. It was suggested long ago that there exist at least seven primary odours [8]: camphoraceous, musky, floral, pepperminty, ethereal, pungent, and putrid. The number of base odours has since then been increased, and the exact figure is not known. Molecules within a particular category have common molecular configurations. There are, however, many exceptions to this categorisation, i.e. that similar odours are not always given by molecules with similar structures. Some compounds are detected in extremely small concentrations, like molecules occurring in some natural odours (cork, butter, strawberry, pepperoni, grapefruit juice). These molecules have, however, no obvious structural similarities and the reason for this extreme sensitivity of the human olfactory system to such odours is not yet known.

12.1.1 Technology

This paper does not aim at a detailed description of chemical sensors, but at pointing out that there are a number of technologies available, where chemical species are used to create an electrically or optically measurable signal [9]. A few of the devices used in electronic noses are listed in Table 12.2, with a brief description. Such devices are then used in sensor arrays in the electronic nose. The gas mixture to be analysed is in general transported in the form of pulses across the sensor array and the response of the different sensors is recorded in this process (see chapter 8 in [2]). Several parameters from the signal can be used, such as the initial rate of change of the signal, its value after a given time, its time integral etc. Schemes with rapid heating and cooling of the sensors have been developed to increase the information obtained from the sensors.

Electronic noses now appear on the market, offered by an increasing number of companies [4].

Table12.2. Examples of gas sensor technologies

Type	**Sensitive material**	**Detection principle**
semiconducting metal oxides (M.O.S., Taguchi)	doped semiconducting metal oxides (SnO_2, GaO)	resistance change
quartz crystal microbalance, QMB surface acoustic wave, SAW	organic or inorganic layers (gas chromatography)	frequency change due to mass change
conducting polymers	modified conducting polymers	resistance change
catalytic field-effect sensors (MOSFET)	catalytic metals	workfunction change
pellistor	catalysts	temperature change due to chemical reactions
fluorescence sensors	organic dyes	light intensity changes
electrochemical cells	solid or liquid electrolytes	current or voltage change
infra red sensors	-	IR absorption

12.1.2 Samples of applications

The use of pattern recognition of different forms will be illustrated by two examples. The first example relates to the use of a sensor array with 10 different sensors to monitor the quality of five different packaging paper materials taken from different stages of the production process [10]. The sensor signals from each of the classes are shown in Fig.12.7. The first two principal components describe most of the observed variance in the data and as seen in Figure 12.8 the different classes of paper occurs in different areas of the two dimensional diagram made up by the two principal components.

The 10-dimensional data space has thus been reduced to a plane where the different samples cluster. Another example relates to the "exhaust" of a fermentor followed as a function of time with an electronic nose. One observation in such experiments is that if the points in a principal component analysis of the sensor responses versus time are plotted they cluster according to the different growth phases of the microorganisms, see Fig.12.9. [11]

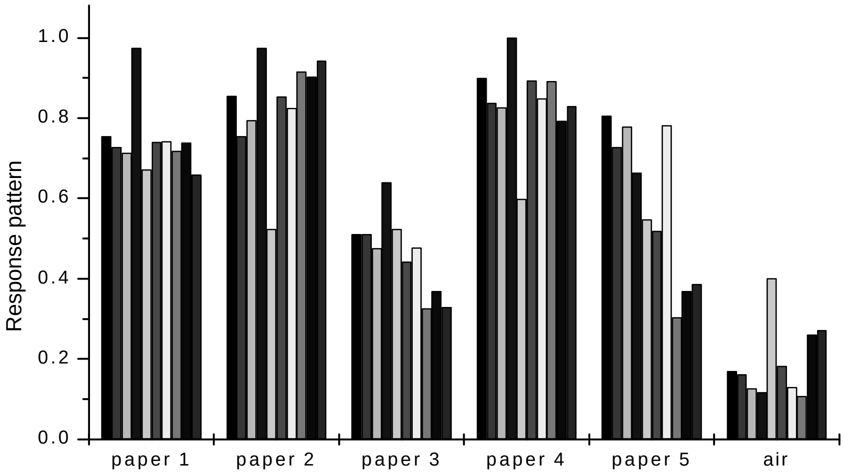

Figure 12.7 Sensor response patterns for five different paper types and air. Each of the patterns consists of measurements from ten different sensors.

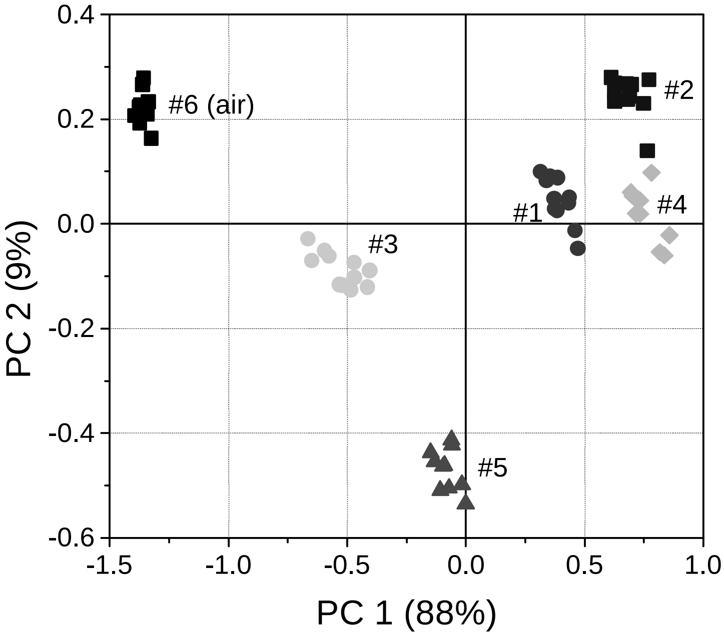

Figure 12.8 PCA of measurements on five different types of paper and air. Note that all measurements on paper 1 are clustered together, like all measurements on paper 2, etc. The spread in each cluster is due to noise and variations in the measurement system. [10]

Similar plots have been used to identify bacterial infections in fermentations with mammalian cells. [12] Furthermore, by using e.g. an ANN it is possible, from the gas phase, to estimate the concentrations of molecules (substrates, products) in the fermentor. Fig.12.10 shows a result obtained on a baker's yeast fermentation, producing ethanol and consuming glucose. [13]

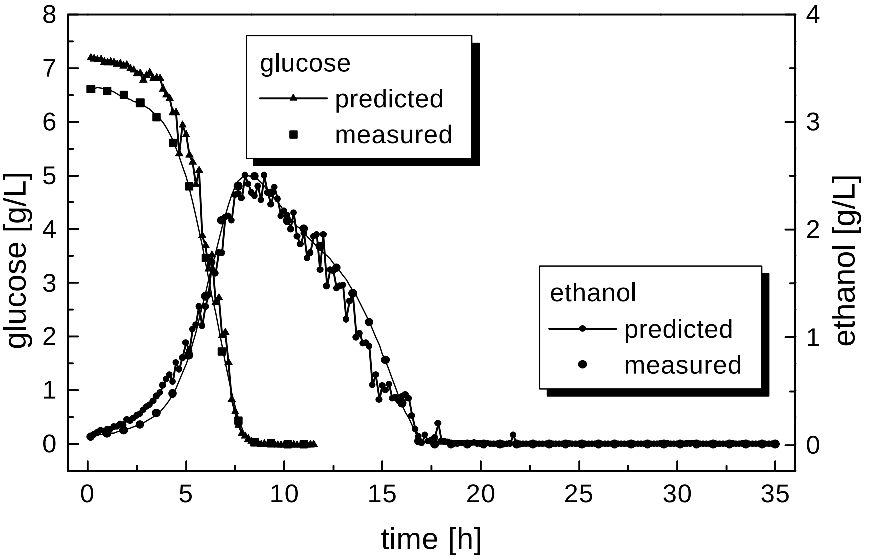

Figure 12.9 A PCA of measurements made on recombinant E. coli cultivation. Note how the system evolves over time, and how the different growth phases can be identified in the plot. [11]

Similar plots have been used to identify bacterial infections in fermentations with mammalian cells. [12] Furthermore, by using e.g. an ANN it is possible, from the gas phase, to estimate the concentrations of molecules (substrates, products) in the fermentor. Fig.12.10 shows a result obtained on a baker's yeast fermentation, producing ethanol and consuming glucose. [13]

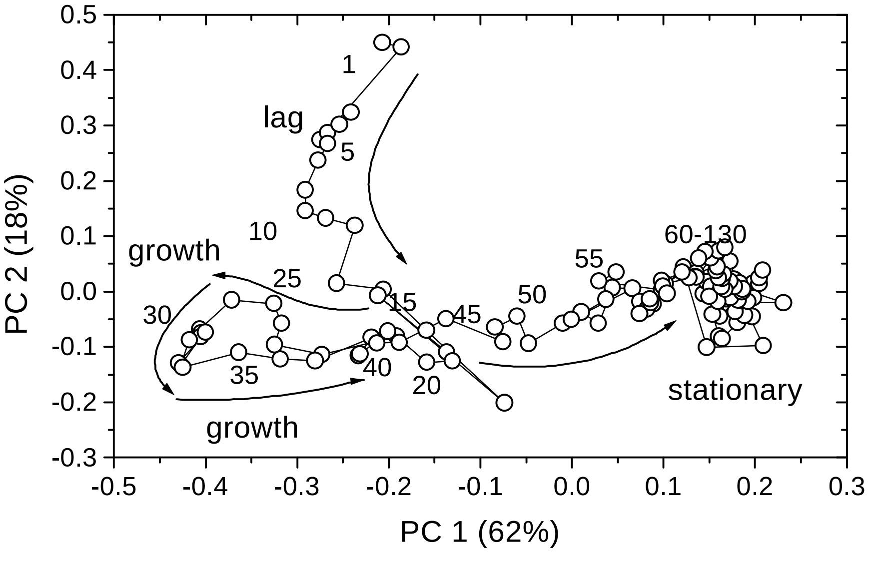

Figure 12.10 Prediction of the glucose and ethanol concentrations in a batch fermentation with baker's yeast (Saccharomyces cerevisiae). The inputs from eight chemical sensors were used in an ANN trained on six fermentations before the predictions were made on the seventh fermentation. [12]

The simple examples above indicate the usefulness of electronic noses for product and process control. Several applications areas have thus been suggested for the electronics noses, like:

- (online) product and process monitoring and control (food, biotechnology, paper and pulp, packages);

- replacement of sensory panels;
- medical diagnosis;
- environmental monitoring.

Most of the existing chemical sensor technologies suffer from long term drift problems, which makes re-calibration and/or drift compensation necessary in electronic noses. The rapid development in the chemical sensor area makes us believe that such problems will not hamper the commercialisation and use of electronic noses. Actually, several interesting developments can be foreseen including adaptive sensor arrays, hybrid systems, self-repairing sensors, and the use of (artificial) biological receptors. An adaptive electronic nose will e.g. choose the type of sensor array for a given application, automatically collect data at different physical conditions (temperature, light, gas flow rate,…) if necessary for the discrimination of the compounds in the analysed odour.

Present day chemical sensor technologies detect both general and specific properties of molecules, but not necessarily the same properties as detected by the human olfactory system. Sensors based on sensing layers having shape and functional group selection probably come closest to the olfactory system.

In order to really mimic the human olfactory sense, it is probably important to incorporate chemical sensors based on biological receptors or artificial constructs of the function of such receptors. Both the large sensitivity towards specific molecules of the olfactory system, and the large redundancy of that system have to be achieved for “true artificial olfaction”.

12.2 Virtual Olfaction and Teleolfaction

According to the vocabulary of the virtual environment community [14] some concepts should be introduced at this point. First, the operating definition of *odour*, meant as the property or quality of a thing that stimulates or is perceived by the sense of smell. Our analysis is centered around the sense of smell: odour is a sensation, and its characterisation should come more from the human response to it than from chemistry. The volatiles which come from an object and stimulate the smell are chemical substances called *odorants*. Thus *olfaction* is simply the act of smelling odorants. Virtual technology needs devices to produce odorants, related to target odours, in a controlled way: the *virtual olfactory display* (VOD) is the answer, a system made of hardware, software and chemicals, able to present olfactory information to the virtual environment user. In the science of transducers a VOD is simply seen as a transducer from the information domain (usually electric domain) to the chemical domain (in gas phase).

Virtual olfaction is defined as the act of smelling an odorant produced by a virtual olfactory display. This definition is again centred on the human sense of smell, but it makes a distinction about the source of the odorant. The last concept is *Teleolfaction*, defined as the act of smelling a mixture of odorants, whose composition is related to a mixture present in a remote place. Teleolfaction is a form of virtual olfaction, but it makes a distinction about the source of the olfactory information. Teleolfaction deals with making copies of reality, and involves the problem of fidelity.

Virtual environments need virtual olfaction for many reasons. The most obvious is that we live in a world full of smells, whose effect is strong, especially at the subliminal level. The importance of olfaction comes out clearly from the analysis of the competence domain of the human senses: smell and taste are the only onesable to perceive information from the chemical domain. Further, smell has the tremendous power of having long range, and it has been far more important for survival during the evolution than sight and hearing, as witnessed by the incredible amount of genes codifying olfactory receptors in humankind (nearly 1000 over 100.000 involved, an enormous percentage among the others gene families [15]). The actual usage of industry-made perfumes gives the measure of the present importance of the smell in our lives: 75% of the industry income in 1999 came from flavours for industrial food and objects; only 25% for perfumes to wear.

At present in communications and virtual environment, smell is either forgotten, or improperly stimulated (because of non controlled odorants, off odours, present in the physical space surrounding the user, that provide olfactory cues conflicting with the user's feeling of presence in the virtual environment or of being part of a communication session). Nonetheless a controlled presentation of olfactory information can give advantages in different application fields, as the following two examples prove:

- Training of users for complex skills in shared virtual reality environments: this implies displaying computer-generated objects that may or may not resemble the real world. It has been reported [16] that olfactory information, paired with virtual images, allows these synthetic objects to be learnt more accurately and recognised (say, smoke is associated with an engine, pollution with the street) even if their real counterpart is odourless (the odour may be related to an invisible but relevant characteristic of the object, such as temperature).
- Exploration of real environments in teleoperation, i.e. guiding a remote robot, for example inside a nuclear power plant, or in a craft at the bottom of the ocean or in a spacecraft in orbit round the earth. Virtual olfaction gives an invaluable help in broadening the sensory bandwidth of the pilot's brain. It has been proven that the smell modality may vehiculate further information related to the environment when the visual and auditory modalities are saturated: practical examples are the odorants added to the natural gas to allow people recognise leakage [17], or released in mines through the fan to raise the alarm.

Roughly, virtual olfaction may increase the sense of presence of people using virtual technologies, which is the main problem of the state-of-the-art applications. More formally, according to a powerful taxonomy for classifying types of synthetic experience, the Causality – Model Source [18], virtual olfaction technology (intended as the technology of virtual olfactory display) and teleolfaction technology (intended as the technology allowing for teleolfaction) may give contribution to the virtual technology applications according to the possibilities listed in Table 12.3. The set of reported dimensions allows for the classification of a given system or application, as shown for some samples: a remote piloted aircraft, a shared augmented reality environment

In a synthetic experience, including synthetic communications, the human user perceives a virtual world that is defined by a database of objects, properties and relationships, called *model*. The model defines how the virtual world looks like, sounds like, smells like, according to which display devices are available, and it can be derived in four ways: scanning the real world through a sensor (e.g. in communications and TV); by a human artist (e.g. cartoons); derived *on the fly* through the real time calculation of a computational model (e.g. simulation of fluid-dynamic phenomena); off-line derived by a mixture of the previous techniques, called editing (e.g. special effects in movies). When the synthetic experience refers to pieces of the real world, we have to handle the mapping between the place and time where and when scanning takes place and the place and time where and when the display happens. This mapping may be 1-to-1 but also distorted in many ways, as shown by the possibilities listed in Table 12.3. The last dimension is the superposition between the virtual stimuli and the real world, that exists in cases such as communications (e.g. the video-teleconference merges with the ambient light and sound) and it does not exist in the case of teleoperation, where the user is isolated in the virtual world. Virtual olfaction, providing essentially for an enrichment of the sensory modality range, is able to be fruitfully inserted in many of the possible systems, except when transmitted information is involved, as well as when the model source of the interaction is derived from scanning of real settings, or when time and space of scanning and display should be aligned. In these cases the teleolfaction technology, which is able to capture the olfactory information and reproduce it in a remote place, is used and it satisfies, in principle, the remaining possibilities. It is to be remarked that the current state of the technology imposes many limits to the performance of these systems, as it will be discussed in the next paragraph.

Table 12.3. Contribution of virtual olfaction interfacse to the synthetic experience in Causality – Model Source classification matrix. Two sample applications are reported to explain the taxonomy. The original matrix [18] reports nine dimensions, the remaining being: display type and sensor type, that are in our case obviously the virtual olfactory display and the electronic nose (when present); the action measurement type and actuator type that refer to actions made by the user on the environment, less relevant in the case of smell

Dimensions	Causality (possibilities: transmitted, simulated recorded)	Model source (possibilities: scanned, constructed, computed, edited)	Time scan-display alignment (possibilities: 1-to-1, accelerated, frozen, distorted)	Space scan-display alignment (possibilities: registered, remote, miniaturised, distorted)	Superposition (possibilities: merged isolated)
Impact of Virtual Olfaction	simulated recorded	constructed computed	indifferent for lack of scan ability	indifferent for lack of scan ability	merged isolated
Impact of Teleolfaction	transmitted recorded	scanned edited	1-to-1 accelerated frozen distorted	registered remote miniaturised distorted	merged isolated
Sample applications					
Remote piloted aircraft	transmitted	scanned	1-to-1	remote	isolated
Shared Virtual World	simulated	constructed	___	___	isolated

As a preliminary step to the analysis of the technology of virtual olfaction and teleolfaction, it is useful to sketch practical scenarios. Were users to share a virtual environment enriched with olfactory information, whose model source is not scanned as in the typical case of computer-generated virtual worlds (see example in Table 12.3), three components would have to be arranged: virtual olfactory displays at the user sites, a virtual world generator (i.e. a specialised computer with dedicated software), and a network mediating the information exchange, as shown Fig. 12.11, section *a*. Users make experience of olfactory stimuli provided by the environment model, changing in time as they interact with the environment and each other; the feeling of presence in the virtual world is thus strengthened. Should the scanning of real odours be added, applications need the basic Teleolfaction system: its components are an electronic nose as the sensor system, the virtual olfactory display which presents the olfactory information to the user in a remote site, and the network to link both. Fig.12.11, section *b*, shows the system in the teleoperation setting (say, a robot remotely operates in an environment full of olfactory stimuli; the user is virtually projected to the remote site). A further scenario shown in Fig.12.11, section *c*, is that of telecommunications enriched with olfactory information. This is a symmetric situation in which the teleolfaction system is doubled and the users are projected one to the other's site. The equipment per user is composed of an electronic nose and a virtual olfactory display.

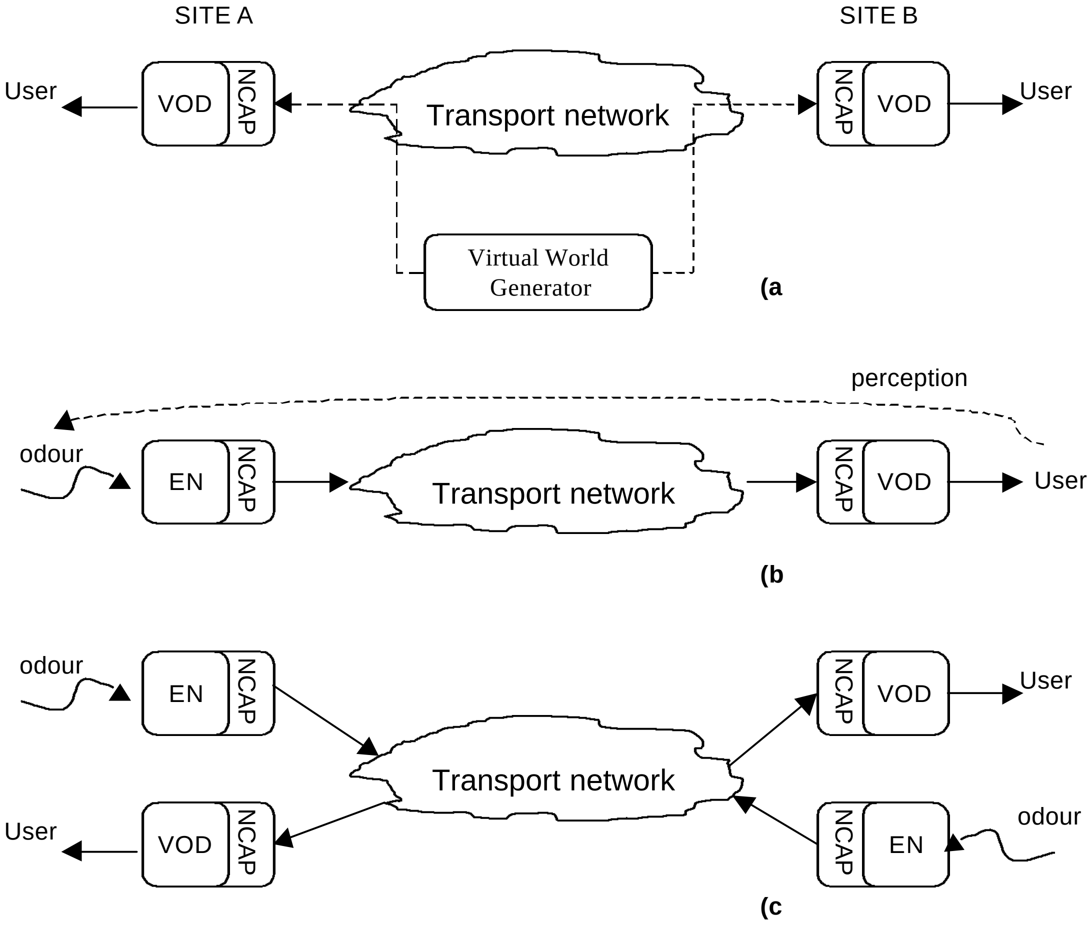

Figure 12.11. Three scenarios for including olfactory information in virtual technologies. a) Olfactory enabled virtual environment, users receive "constructed" olfactory information; expressivity of the provided information and its coherence with the generated virtual world are in the focus. The transport network is a multiplatform, heterogeneous infrastructure with standard access, without significant transport delay, transparent for the olfactory information. In all the scenarios NCAP means Network Capable Application Processor, a hardware and software component able to connect the olfactory interfaces to the network. b) Teleolfaction for telepresence, an asymmetric situation in which the user's perception is virtually directed to a remote site; fidelity of odour reproduction becomes a fundamental issue; c) Olfactory enabled communications, a symmetric situation in which emphasis is on transporting sensorial cues relevant to human communication; fidelity to real world is not in the focus.

In all the scenarios the virtual olfactory display should receive information about the type of smell, its concentration, its temporal dynamics and its spatial localisation. This information should be provided by the electronic nose, when present, otherwise by a computer simulator. This introduces the problem of smell coding. To codify information in order to transfer it has always been very important to man. One example is of course the written language, which is a codification of speech. In modern times, sound has also been transferred through electrical signals in the early telephones. The variations in pressure caused by the speaker were codified into variations in electric current, transferred over an electrical line, and then coded back into pressure variations in the receiver. These pressure variations have in recent years been digitalized, and subsequently compressed, to transfer this information over Internet. One of the most famous compressed formats for sound is the MP3, which is used to store and play music.

Another widely used technique to express information is the RGB colour code. Even if the degree of accuracy varies from case to case, each colour can be expressed as a function of three base-colours (red, green and blue). The colour information in the images transferred to e.g. a TV set is thus rather easy to code, transfer and de-code, and the viewer does not note a great difference compared with the real colours. For odour information, no such general scheme has yet been invented. As far as it is known, there is no simple mechanism such as pressure variations that can explain what we experience in a smell. Instead, different smells are formed by a complex pattern of many different chemical species. The way in which the brain interprets the signals from the receptor cells is not well-known, but it may be that future insights in the functionality of the brain in the future could give us clues on how to describe odours in a compact way.

Presently, humans in a sensory panel are often used to describe the smell of different samples, the so-called *sensory analysis*. The panellists are trained to recognise certain characteristics, such as burned aroma, mouldy, sweet, acidic, spicy, or whatever is necessary for the product under study. People that give very different descriptions from the rest of the panel due, for example, a cold, to stress, or other human factors, are then excluded from the data set. The average of the remaining panellists is then used to describe the product. As a concept, this, perhaps, might also work for odour codification in a general sense, but it is not known which, or how many, descriptors to use.

Many efforts have been made to find “base-odours” that are, at the same time, general enough to describe all odours, and as few as to be manageable. Research on this topic started in the 1960’s, but still no generally accepted way of representing odours has been found. As long as this is the case, we will have to settle for one of two options for odour codification and subsequent transfer:

1) Using crude descriptors such as “coffee”, “beer”, or “flower” and prototype odours. In this case, an electronic nose (or similar device) measures the odour, identifies it, and then transfers the information. On the receiving end, a generator could give off a prototype odour, which is of the same type as the original odour, but may vary in many of the minor components (e.g. different types of coffee). This would make it impossible to e.g. determine the quality of the coffee measured at a different location, but it would at least give the impression that the measurement is made on coffee rather than tea.
2) Using a limited number of “base-gases” to describe the odour. These base-gases may describe the odours very well in an application, even though there might be only a small difference between them. On the other hand, the chosen base-gases might not work at all for applications that have not been thought of by the person who chose the base-gases. It may thus be possible to distinguish between different brands of coffee with one set of

> base-gases, but impossible to distinguish between beer and vodka using the same set. In order to be able to describe all different smells in the world, a very large number of base-gases is probably necessary, unless the problems described above are solved.

Some remarks are due on synesthetic presentation of olfactory information. Art is the kingdom of synesthesia, where the artist program is specifically to arise "a concomitant sensation other than the one being stimulated" (according to the Merriam Webster's Collegiate Dictionary), that is, to break the boundaries of the native modality (sight for painting, sight and touch for sculpture, hearing for music and so on) and to cross activate different ones, better if conceptually distant. Think of panting, where sometimes you feel as though you are inside, loose the orientation (cross effect on spatial perception and proprioception), think of listening to a melody. The artist consciously gets the synesthetic effect because he knows well the psychological and physiological implications of his art. Unfortunately little has been done in art on cross involvement of olfaction, for the obvious lack of technology and tools. Also little research has been reported in the scientific literature. Some hints can come from food science which has worked out the relationship between smell and the colour of food or even the crunching emitted during eating. In order to suggest research directions, some examples of understandable and acceptable cross-modality mapping are the following: smoke emission from an object, instead of smell from the object; sound emission from an object, instead of smell from the object, with the advantage that melody may contain information on the smell type, concentration, in addition to source localisation; colour glittering of an object, instead of smell from the object; non spatial sound for unlocalized ambient smell; sparse fog for unlocalized ambient smell; etc.

Coming back to the scenarios of Fig.12.11.b and c, there are some applications that can avoid the intervention of a transducer from smell information to odorants release. In these cases the virtual olfactory display may simply be a software tool able to insert olfactory information into the available modalities, under the form of either qualities of existing virtual objects (e.g. brightness and sound qualities) or creation of new virtual objects (e.g. the fog).

12.3 Functions and technology of virtual olfactory displays

Some commercial companies already sell virtual olfactory displays, also called "odour generators", for personal computer use. Examples are AromaJet, DigiScents, and TriSenx. They all use a number of chemicals stored in a type of cartridge, and upon receiving a signal describing an odour, they release a mixture of these chemicals. This is done for example by using pumps similar to the ones used in ink printers. The resulting gas mixture is then blown towards the user with a small fan. So far, no standardised way of describing the odours has been created, so, one smell will be represented in different ways by different manufacturers. For the business to take off, it may be necessary to create a standard way of describing odours, like MP3 is used for music. This might happen in the near future, either by adopting one of the companies' solutions, or by creating a common platform. Since these products have only been on the market for a very short time, it is too early to say if the quality is high enough, and if there is a large enough demand for these products.

In order to have a closer look to the technology, let us start from the functional specifications that a general-purpose virtual olfactory display should match, paired with the relevant psycho-physiological issues. The first specification is: how many and which odours should be provided in a certain application domain. The answer cannot be given on the technical basis (that in principle places no constraint) but it should come from physiological studies, most of which agree that untrained subjects are able to make absolute identification of 15 to 32 common odours without training and noise, and of 60 (at the best), after training and still without noise [19]. Absolute performance (i.e. without a reference) of human smell is far below that of sight and hearing, that exhibit recognition in a noisy environment of hundreds of complex patterns (note that an odour is a complex olfactory pattern as a face is in the visual domain). The number of odours to be provided by a virtual olfactory display depends also on their distance in human perception: too much similarity may result in indistinguibility and inefficient usage of storage resources, whilst too much distance means a rough coverage of the olfactory stimulus space. Unfortunately the physical continuum in which to place the olfactory stimulus is unknown (differently from the light and sound spectra for vision and hearing), therefore the distance is to be empirically estimated through human panels or trained electronic noses, odour after odour. The number of odours is at present a little more than 10, bounded by cost of odour characterisation, nonetheless the micromachined technology allows for one more order of magnitude.

The second specification is about the concentration of odours provided, affecting both the scaling of the stimulus and the quality of the sensation. The starting point is the past research on dynamic olfactometry, that according to international standards [20,21] aims at measuring the concentration of a sample odour through sensory analysis made by human panels. The odour concentration is defined as the dilution ratio after which the odour is perceived at the detection threshold by half of the panel, and expressed in odorimetric units per cube meter (OU/m^3). This definition depends on the concentration of the odorant (in the sense of chemistry) and on its type: for example at a concentration of 1 ppm in air, ethyl mercaptan has an odour perceived of concentration 100 (because its detection threshold is 0.01 ppm) whilst in equal conditions a terpene (found in many essential oils of plants, such as conifers and oranges) gives an odour perceived of concentration ten times lower [22]. Moreover it must be taken into account that the spread between individuals in the perception of concentration for certain odours may be up to 1000 times. A related issue is the resolution of the concentration control provided by the virtual olfactory display. Some hints can be given again by studies in physiology that report human panels able to distinguish correctly, and without any reference, among 4 odours, on the average, differing only in concentration [23]. Finally, the technical specification for many applications is that odorants used in the virtual olfactory display have to be diluted according to a controlled ratio ranging between 10 and 10000. A database is also needed for relating the dilution ratio to the subjective olfactory sensation, considering the presence, on the one hand, of the phenomenon of *saturation*, i.e. the perceived concentration of a certain odorant becomes stable as its concentration overcomes a specific level, and, on the other hand, the phenomenon of *interference* between odorants simultaneously presented, i.e. odorants may shield each other at a certain degree, so that the perception thresholds change.

The third specification is referred to dynamics of odour presentation: how long does an odour last before fading a way and when should the display represent it? The common strategy is to avoid smell habituation, using repeatedly short or smoothly varying exposures. This follows from the consideration that the intermittent neural stimulation produced by sniffing enables convergent-divergent processing in the olfactory bulb [24]. Periodic stimulation helps also reducing the diffusion time of the odorants through the mucus covering the olfactory epithelium towards the cilia of the olfactory neurons, and therefore the delay of the sensory response [25]. It is to be expected that frequency and amplitude of odour stimulation are related to the perceived concentration but not linearly, so, again, the correct mapping should be provided in a data base after estimation through human panels: maximum value of frequency is in the order of the breath rate. Another clear advantage of short repeated exposures is that interference between cascaded odours might be decreased using the lapse time to withdraw the residuals of the past odour. Physiology and psychology help providing forgetting curves for odours that are qualitatively very similar to those of other modalities but have very different characteristic times [26]: a common result is that two odours in sequence should be divided by 20 to 60s in order to be clearly perceived, variability depending on the specific odours and the subject [27]. According to the requirements of the most common virtual applications, a virtual olfactory display should provide for frequency modulation in the order of 0.1-10 Hz, switching rate between odours in 1-10 second, and residuals removal (if needed) in the order of 1second.

The fourth specification involves the concept of space, in the sense of the geometrical 3-dimensional space, that is fundamental in virtual environments for users to navigate and feel inside. The consideration is that biological olfaction provides for localisation of the odour source. Dedicated studies demonstrated that humans can actually localise the odour source on the horizontal plane exploiting the differences perceived by the two nostrils for the same odour, mainly about relative delay and concentration gradient [28]. It is remarkable that spatial orientation is not substantially due to olfactory receptors but to the trigeminal nerve [29], an important neural structure of the cranium emerging in the nasal cavity, whose property is sensitivity to both odorants and chemical substances, such as carbon dioxide, that has no smell but an important meaning for the organism (say vectors of irritation or impairment). Birhinal olfaction results has the same importance as binaural hearing for spatializing the sensation (smell vs sound). Humans can derive the side of the source, with respect to the medial plane, from just a delay of 0.1 ms and an concentration gradient of 10%. Within the attention field of nearly 130° on the horizontal plane, called *smell field* for similarity with sound, a human can locate source with an error of 7-10°. Therefore a virtual olfactory display may be asked to position the odour in a sufficient smell field (order of 90-150°) with a sufficient angular resolution (in the order of 10-45°). This requires that the display handles two independent channels, a flow per nostril, and controls differences of amplitude and phase between them in a range of 10-80% and an error below 10%.

The structure of a virtual olfactory display is shown in Fig. 12.12. It is a layered structure made of three tiers. The lowest is the odorant formation and storage tier, with the task to provide in the vapour phase the specific odorant giving the required olfactory sensation, regardless of concentration, and other smell qualities. It contains chemical reactants and reactors, vaporisers, the carrier gas for dilution and a waste storage. If the odour codification for prototypes is adopted, this tier should store a specific odorant per prototype, resulting in a severe constraint on the number of prototype odours. An alternative strategy may be the introduction of odorant precursors that produce the odorants after a reaction; careful choice of precursors and reactions may broaden the range of outcomes from a limited set of stored precursors. The second tier is the delivery and control, with the task of presenting the olfactory information in vapour phase to the user. Components are of pneumatic type and cascaded, each one managing a gas flow and implementing a form of control on the smell qualities.

The process starts with the mixer, whose ability is, on the hand, to mix the odorants with the carrier gas after controlled dilution through mass-flow controllers and, on the other hand, to produce an air flow containing a certain concentration of a specific smell; furthermore the flow is dynamically modulated and optionally exchanged with others, preliminarily prepared;

the last stage of internasal regulation splits the flow into two streams, one per nostril, introducing a relative delay or attenuation between them in order to provide for information on the odour source localisation; finally the residuals of the odorants are collected and carried to the waste storage. It must be remarked that the proper gas mixture may be formed in two alternative ways either before vaporisation of the odorant, if in liquid phase, or during vaporisation.

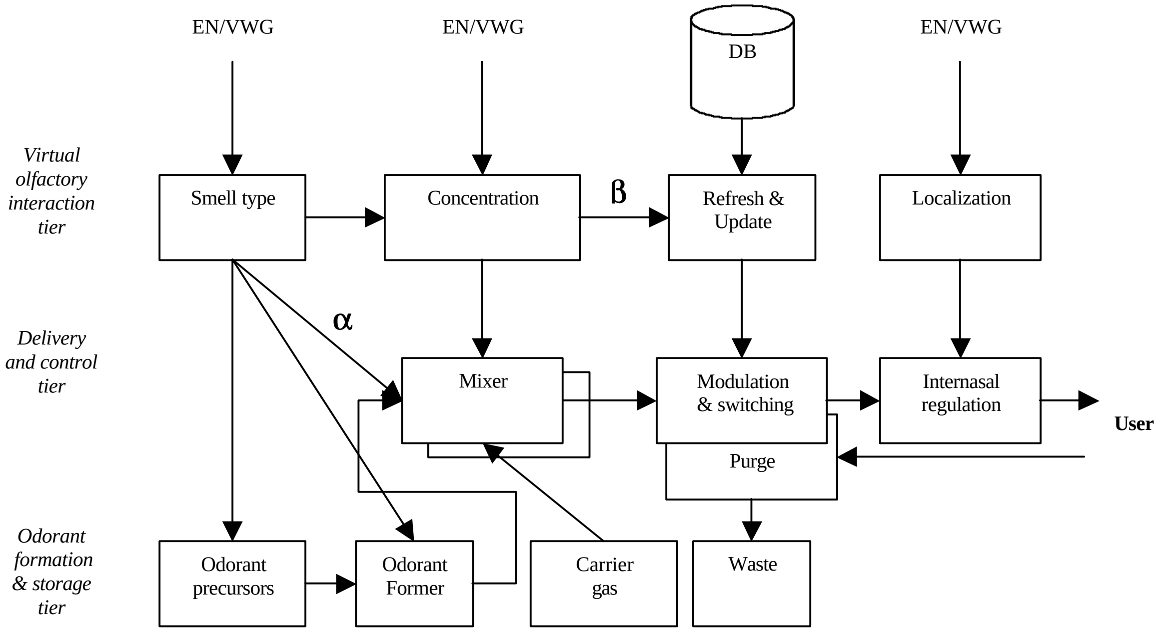

Figure 12.12 Schematic of a virtual olfactory display. The structure is layered, with three tiers identified. Remarks: EN/VWG means that input can come from an electronic nose or from a virtual world generator; arrow α is a control given only in case of prefetching of alternative smells; arrow β represents information about concentration and type of the actual smell, both needed for refreshing properly; the rightmost pile, Localization – Internasal Regulation is present only if a head mounted display is concerned.

The proposed mixing strategy after vaporisation, based on mass flow control, ensures the widest range of concentration and answer rate, it is the most precise and it relies on a well stated and developed technology being widely adopted in laboratory set up for testing of chemical sensors [30]. The further step is miniaturisation of the mass flow controller, where no technical obstacle is expected. The upper tier is the virtual olfactory interaction, with the task of issuing the control to the other tiers. The upper level derives information about type, concentration and localisation of the smell to be presented from remote electronic noses and from the computer that mediates the virtual interaction (Virtual World Generator). The module Refresh and Update needs information about smell type and concentration from the previous modules (this is the reason why it is cascaded) and about the dynamics of the odour sensation from a local source (i.e. stored in the database) because it heavily depends on the process of odour formation, odorant precursors choice and characteristic times. In case of tight real time constraints and fast dynamics, switching between two odours should be done with a prefetching strategy: the possible alternative smells, even if not actually presented to the user, should also be prepared in the mixer (this implies multiple mixers); the update will be implemented by a switch command to the Modulation and Switching module. Obviously the possible alternative smells should be communicated to the Smell Type module in advance.

12.4 Characteristics of the global virtual olfaction system

A fundamental issue is the characterisation of the performance of the end-to-end system including both electronic noses and virtual olfactory displays, as shown in Fig. 12.11.b and c. Table 12.4 reports quantitative indicators of the global system, as can be derived straightforwardly from the previous discussion of the virtual olfactory display specifications, fostered by physio-psychological results, and from the state of the art of electronic nose technology. For each characteristic of the system, Table 12.4 also shows the related issues of virtual odour displays and electronic noses, quantified for the best-case implementation in typical applications, both at present and in the perspective of a three years evolution. A general remark is that the end-to-end system characteristics are sometimes dominated, and constrained, by the electronic nose technology and sometimes by the virtual olfactory display technology.

For the characteristic *smells*, we are mainly interested to the widest possible portfolio of available smells, and to high end-to-end replicability, called also fidelity in the virtual reality applications. The actual performance in fidelity is bounded by the virtual odour display because of its lack of replicability (both for odorants and formation process stability), whilst electronic noses limit the number of odours for the cost of calibration, which becomes unsustainable if there are more than 20 odours. A strong implicit hypothesis has been inserted on the increase of the ratio between the number of stored odorants and the number of distinct displayable odours, that means the change of the odour production strategy towards an odorant creation in situ. The characteristic *concentration* is presently bounded by the practical limits of the odorants' storage and dilution in the virtual odour display. The odorants are stored and vaporised at the maximum possible concentration, so dilution can take place with an arrangement of two mass flow controllers, one controlling the odorant flow and the other the odourless airflow.

The mole fraction of the odorant y_o after dilution is:

$$y_o = \dot{V}_o \Big/ \left(\dot{V}_o + \dot{V}_{air}\right) \qquad (12.3)$$

expressed as a ratio of the standard volumetric flow rate of the odorant vapour over to the total flow. Present technology imposes a minimal flow in the range 0.1 to 1 standard cubic centimetres per minute (SCCM), the maximal flow is constrained by practical reasons, and therefore the dilution can be controlled up to a ratio of 1:100. Improving this figure means again to introduce the odorant creation in situ, so that the concentration may be tuned before the transformation in vapour phase. For electronic noses, there is no problem in measuring a wide range of concentrations, even if a non-negligible error on the concentration estimation should be taken into account with both the present and perspective technology, unavoidable due to the calibration cost. One characteristic of *smell dynamics* is the stability in time and rate of olfactory information transfer, that is, the behaviour of the system at the lowest and highest frequencies. Stability means that the same odour can be recognised repeatedly with regards to its type and concentration and reproduced with fidelity for a time enough long. This time is bounded by two effects: a) the sensor drift at the recognition stage, which after a characteristic time causes the sensors to change their response to the odour so that is no longer recognised as the same; b) the adsorption of the odorant onto the vaporiser and the vessels, at a degree depending on used materials, that makes the system increasingly sluggish and slows down the refresh cycles and the recovery at the odour change. The characteristic time of end-to-end information transfer, $t_{e\text{-}e}$, is given by the sum of the time to acquire the olfactory information t_a, the transmission time and the display time t_d: the transmission time being insignificant for our scenarios, we have $t_{e-e} \approx t_{ra} + t_d$. The electronic nose accounts for the acquisition time, depending on the response time of the used sensors, typically in the range 10-100 sec, and the pattern recognition time, which depends on the algorithm type and on the number of sensors and samples to be processed, and typically equal to half the sensor response time. If the electronic nose is forced to follow cycles of response and recovery, the revelation time is as long as the cycle. The virtual olfactory display accounts for three components of t_d: the delay due to the purging time for the previous odour, the odorant forming time, and the delivery time. The purge and delivery times depend proportionally on the smelling volume V_s, that is the volume to be either swapped out or filled of odour, in the order of the nasal airways if the display is head mounted, in the order of a room volume if a cave is considered. Delay and purge are in the order V_s / F_p considering the presentation flow rate F_p provided by the pumps in the display and limited by the fact that the air velocity has to be below 10 cm/s to avoid mechanical sensation on the skin (Table 12.4 reports typical values for the head mounted display). The odorant formation process has characteristic times strongly depending on the technologies, the possible ones being permeation, supercritical noozle, saturation, and vaporisation [30]. In the vaporisation technique, the odorant is in the liquid phase is injected into the vaporiser with a defined flow rate, and is simultaneously mixed with air. The volumetric flow rate in standard gaseous conditions is then simply proportional to the liquid volumetric flow rate. Dosing pumps usually work intermittently, and especially at the smallest output rates individual pulses are discernible. Smoothening may take place in the vaporiser if the mean residence time of the odourless air is many times longer than the conveying pulse. Further vaporisation efficiency is not instantaneously obtained. These effects are not negligible if two constraints are added: the total flow presented to the user always has to remain constant; the smell concentration should stabilise according to first-order asymptotic dynamics (monotonously increasing). In this situation, fluid dynamic design cannot provide for a delay time less than several seconds. This time can be decreased to half when odour prefetching is considered; in fact it turns out to be on the average:

$$E[t_{of}] = t_{of}(1-p) + t_s p \tag{12.4}$$

where t_s is the negligible switching time between the parallel air flows, and p is the probability of having prefetched the right odour, bounded by the number of additional odours and finally by the cost of the display. Finally, the high frequency behaviour of the system is bounded by both the detector and display technologies, future improvement is more difficult to gain. Regarding spatial localisation it is hard to assess the end-to-end characteristic if there is a poor evidence of localisation by means of two electronic noses posed in parallel with a sampling arrangement similar to the human nostrils. Nonetheless, the resulting smell field of the system is a function of the maximum concentration ratio between the two single-nostril channels.

Table 12.4 End-to-end characteristics of the global virtual olfactory system, and related characteristics of the electronic nose and virtual olfactory displays.

End-to-end characteristic	**Present and perspective performance of the end-to-end system**	**Present and perspective performance of head mounted Virtual Olfactory Display**	**Present and perspective performance of Electronic Noses**
Smells	Number of treated smells: Present 10 Perspective 30	Number of produced smells: Present 10 Perspective 100 Ratio between number of stored odorants and number of well distinct odours formed: Present 1:1 Perspective 1:10	Number of trained odours: Present 10 Perspective 30
	Fidelity [relative stand. dev.]: Present 30% Perspective 70%	Repeatability of smell formation [rel. stand. dev.]: Present 30% Perspective 70%	Recognition success rate: Present 80% Perspective 90%
Concentration	Range of concentration: [times the threshold limit of each odour] Present 1to 100 Perspective 1 to 10^3	Max dilution ratio Present 1:100 Perspective 1: 10^3 Mixing molar standard volumetric flow rate range [SCCM] Present 0.1 to 10 Perspective 0.01 to 10	Quantitative analysis range [compared to minimum threshold] Present 1 to 10^3 Perspective 1 to 10^4
	Precision/resolution on concentration: Present 10% Perspective 3%	Mass flow control error: Present 3% Perspective <1%	Quantitative analysis performance [relative Root Mean Square Error]: Present 10% Perspective 3%
Smell dynamics	Odour stability [length] Present 100 s Perspective 103 s	Poisoning time: Present 100 sec Perspective 103 sec Display rate: Present 0.03 Hz Perspective 0.3 Hz Smell volume V_s: 1 cc Presentation flow rate F_p: 6 CCM	Sensor drift [characteristic time] Present 10^3 to 10^4 s Perspective 10^4 to 10^5 s
	Max odour rate: Present 0.01 odour/s Perspective 0.05 odour/s	Purging and delivery time V_s/F_p Present 10 s Perspective 1 s Odour forming time: Present 5 to 10 s Perspective 0.5 to 1 s	Measuring cycle Present 100 s Perspective 10 s Response rate Present 0.1 Hz Perspective 1 Hz

Table 12.4 (part II) End-to-end characteristics of the global virtual olfactory system, and related characteristics of the electronic nose and virtual olfactory displays.

End-to-end characteristic	**Present and prospect performance of the end-to-end system**	**Present and perspective performance of head mounted Virtual Olfactory Display**	**Present and perspective performance of Electronic Noses**
Spatial localisation	Inter-nostril amplitude modulation Present 10% to 200% Perspective 3% to 200%	Max dilution ratio Present 1:100 Perspective 1: 103	Quantitative analysis range [compared to minimum threshold] Present 1 to 1000 Perspective 1 to 10000
		Mass flow control error: Present 3% Perspective <1%	Quantitative analysis performance [relative Root Mean Square Error]: Present 10% Perspective 3%
	Inter-nostril phase modulation Present - Perspective -	Mass flow control response time: Present 0.1 sec Perspective 0.01 sec	Response rate Present 0.1 Hz Perspective 1 Hz
Information rate	Information rate: Present 0.06 bit/s Perspective 0.98 bit/s	Display Information rate Present 0.34 bit/sec Perspective 5.42 bit/sec	Source information rate Present 0.06 bit/s Perspective 0.98 bit/s
		Information on odours Present 3.32 bit Perspective 6.64 bit	Information on odours Present 3.00 bit Perspective 4.75 bit
		Information on refresh Present 2 bit Perspective 3 bit	Information on concentration Present 3.00 bit Perspective 5.04 bit
		Information on concentration Present 5.04 bit Perspective 6.64 bit	

If the average concentration of the odour is considered as reference, this ratio can be as small as the resolution of the electronic nose measurement (the mass flow control is better resolved), and as large as 200%. The phase difference cannot be considered practically at the moment because the electronic noses suffer from response times that are too high compared to the biologically significant inter-nostril delay. The last characteristic that has more a theoretical than a practical interest is the information rate, mostly an addendum to system dynamics taking into consideration statistics and psycho-physiology of odour perception. The information rate is defined as the data rate required to remotely perform the replication of the odour sensation, and depends on the refresh rate, the update rate, the concentration level, and the number of possible smells. The starting point would be the knowledge of the channel capacity of the olfactory sense, meaning the amount of information that biological smells are able to carry. Following the discussion in the previous section, 60 odour classes, each in a four-degree scale of concentration, can be perceived in the best case: therefore not more than 8 bits are required. Further, odours in sequence cannot be presented in a time slot shorter than 20 seconds, since time dynamics is negligible in the slot. This leads to an upper boundary of the information rate for the smell channel equal to 0.4 bits/sec because no statistics of smells has been taken into account (in Shannon's theory of information the odour source can be modelled as a stochastic process, whose production of information is highest if the odours are equally probable). Table 12.4 shows that the bottleneck is the electronic nose, and that at present the end-to-end system can support a low information rate. Nonetheless, the requirement might be matched in three years. It must be remarked that the impressive increase of information rate on the display side is made at the expense of a poor fidelity in smell reproduction and of an excess of resolution in smell concentration control.

Unfortunately, considerations on the information rate do not take in due account the semantics of the information but merely its statistics. Let us shortly recall the four types of olfactory problems that are likely to be faced by the user in a virtual environment application: Detection, that means to detect whether the olfactory stimulus is present or if there is just background olfactory noise; Recognition, that is to classify a detected odour in a predefined category; Discrimination, that is to distinguish between two similar stimuli; Scaling, that is to determine how different two stimuli are. It is obvious that detection is primary for every task in an olfactory enabled virtual environment. Detection relies mostly upon the odour thresholds of both the electronic nose and the display database. Discrimination and scaling are typical tasks of relative character, because a reference odour is available. Current systems have sufficient ability to support relative tasks (e.g. to determine whether smoke flowing under a door is of chemical or electric origin), but unsatisfactory fidelity if the virtual experience tries to closely reproduce the real world.

12.5 Future prospects

Breakthroughs in the virtual olfactory interface field are expected both regarding odour modelling and system fidelity. Search for a (multidimensional) physical continuum in which to place the olfactory stimulus is ongoing. A first proposal is to include the molecular weight of odorants as a dimension of the representative space. Gas chromatography and sensory analysis have been used to develop this idea (this emerging technique is called *Gas Cromatography Olfactometry*). The odour is then assessed by sniffing the effluent of the gas chromatography column in parallel with mass spectroscopy (or other, e.g. flame ionisation detector). The first results are that key odorants are typically hydrophobic and polar molecules with molar masses around 300 Da. A second stream regards the application of allosteric models in order to model the complex functions of the olfactory receptors through the conformational changes of their proteins [31, 32]. Like for mainstream sight and hearing studies, diseases that cause a selective reduction of perception can also be used to understand the inner mechanisms of odour sensations. For instance, the selective loss of smell, called *anosmia*, occurs most frequently for odorants weighted in the range 235 to 260 Da (musk and amber families) [33]. Nearly 1% of the population in the western world is affected by anosmia, *hyposmia* (decreased ability to detect some odorants) and *dysosmia* (misclassification of smells or perception of ghost smells). This enables a joint research effort between physiologists and system engineers that is expected to fill the knowledge gap with the other sensory channels in a few years.

Coming back to the olfactory interfaces, there are enhanced schemes proposed by one of the authors [34] that may alleviate the problem of the poor fidelity of the global system, at least for relative tasks. The basic idea can be understood from Fig. 12.13.a: on a local basis, the virtual odour display produces an odour that is perceived by the electronic nose, then the class of the recognised odour is fed into the virtual odour display. If the process is controlled by a local controller, we expect that in an ideal case the numerical labels at time 1, $x(1)$ and $y(1)$ coincide: in this case the virtual olfactory interface is said to be *aligned,* or also that there is a *local alignment.* If there is no alignment, a process of self-alignment may be started, that will change the look-up tables, T_{en} and T_{vod}, implementing the odour formation and/or the class recognition, in order to get the alignment. This may require many iterations: at the i-th iteration the difference $y(i)- x(i)$ and its past values can be used to compute a variation for T_{en} and T_{vod} according to some control strategy, able to ensure convergence to the alignment after significant samples of the available odours have been tested. One of the simplest control strategies is the following:

$$T_{vod}(i+1, y(i)) = T_{vod}(i, y(i)) + k_{vod}(y(i) - x(i)) \tag{12.5}$$

$$T_{en}(i+1, z(i)) = T_{en}(i, z(i)) + k_{en}(y(i) - x(i)) \tag{12.6}$$

where k_{en} and k_{vod} are two constants with the meaning of update gain. It is worth to note that x and y are digital signals whilst z is a variable in the odour domain. Practically speaking, this means that T_{en} is an implicit look-up table, more difficult to change than T_{vod}. Anyway, they have to be changed together in an appropriate way. If changes are made only on T_{en} (k_{vod}=0), the electronic nose would be retrained to recognise correctly the odours produced at present by the virtual odour display. Nonetheless, this is not a guarantee of fidelity because if the odour formation process has undergone a shift due to ageing, there is a reduced correspondence between the actually produced odours and the intended ones. On the other hand, changes done only to T_{vod} (k_{en}=0) are cumbersome, since the physical continuum representing the odour space is largely unknown, and it is unlikely that a random search of odours guesses the pre-chosen electronic nose answer. Many efforts are presently planned to get a balanced update of both the look-up tables for the sake of an improved fidelity with a reference odour set (such as the scratch and sniff patches used in the University of Pennsylvania Smell Identification Test [35]). It is fundamental to note that a relative fidelity extended end-to-end, in the sense that two communicating users can experience similar olfactory stimuli even if their fidelity to real world is not sufficient, can further improve the performance of the olfactory interfaces. In this respect the non-local scheme proposed in Fig. 12.13.b turns out to be useful: we have two remote sites A and B with two complete olfactory interfaces with different history of use. If the hypothesis of both interfaces being locally aligned holds, it is easy to understand that there is no way to say if the virtual odour displays produce the same odours when asked: the hypotheses are that at time 1 we have $y_A(1)=x_A(1)$, $y_B(1)=x_B(1)$, $x_A(1)=y_B(1)$, $y_A(1)=x_B(1)$, therefore $x_A(1)=x_B(1)$ and $y_A(1)=y_B(1)$. At this level, there is no possibility to check if $z_A(1)=z_B(1)$: everything goes as if two people agree to call two different things by the same name, one per site (it must also be considered that it makes no sense to compare the look-up tables, since the histories of the two interfaces are different by hypothesis). If the local alignment does not hold, it can be shown that the difference between $z_A(1)$ and $z_B(1)$ comes into play. The technique shown in Fig.12.13.c starts noting that if $z_A(1)$ and $z_B(1)$ are not too different, a long range alignment may be attempted between EN_A and VOD_B by means of controller A following a process as in equations 12.4, 12.5, and considering controller B as transparent (i.e. $x_B=y_A$). Further, this approach has to be repeated for EN_B and VOD_A with controller A switched off. Finally, a check of local alignment has to be done in case the procedure should be repeated. Using the same metaphor as before, we can say that if at the check $y_A=x_A$ and $x_B=y_B$, it is highly unlikely that the same name may refer to different things. This strategy has been called by one of the authors *eight shape*: because it exploits two interleaved feedback loops. Preliminary results make us expect a smaller difference between z_A and z_B at the end of the procedure, hence a better inter-site reproducibility of the odour stimuli and minimum usage of reference odours [36]. In some sense the eight shape strategy uses more efficiently the information contained in the digital domain in order to understand the (chemical) smell domain.

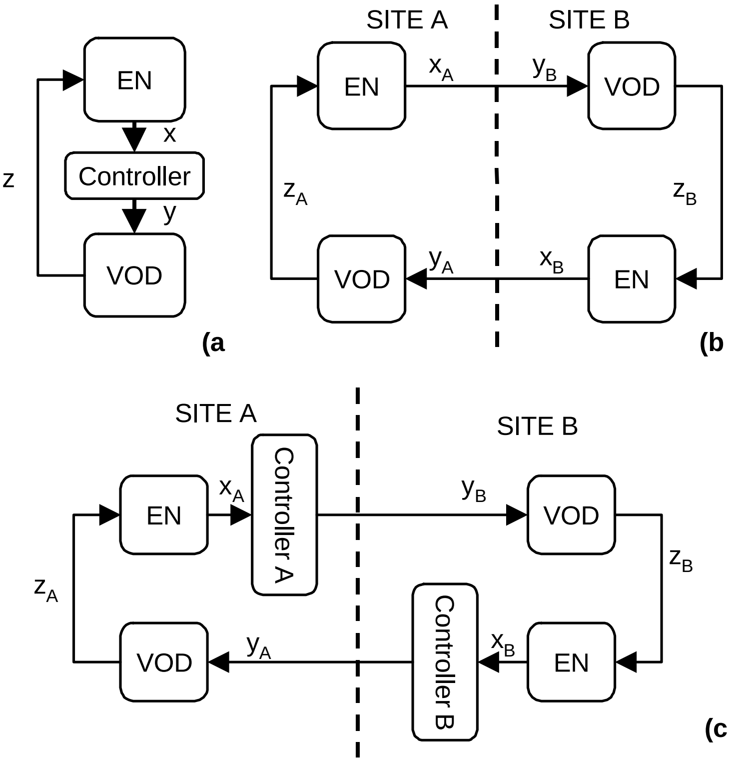

Figure 12.13. Enhanced schemes for self-tuning of olfactory interfaces: a) local alignment scheme: the arrangement prescribes that the virtual odour display produces an odour z to be perceived by the EN, instead of a user. The recognition label *x* is given to a controller that changes it into *y*, according to a control law; then *y* is issued to the VOD as a display command and the cycle is repeated. b) general symmetric operating scenario: the arrangement is that on site A the virtual odour display produces an odour that is perceived by the electronic nose, then communicated as a reproduction command to the remote display, and so on. With no form of control in the loop the dynamics is usually unstable. c) global alignment scheme: the arrangement is as before but two controllers are added; the alignment procedure works first by tuning the components on the upper level (EN_A and VOD_B) and considering the lower level frozen; afterwards, the reverse is done; everything works as if each subset of distant components is moved to the same site and locally aligned.

12.6 Acknowledgements

The authors would gratefully thank Prof. Thomas Furness III for giving F. Davide the chance to stay at his centre, the Human Interface Technologies Laboratory, University of Washington (WA) in 1998. This gave the author the opportunity to learn of the importance of virtual olfactory interfaces and the pioneering work of W. Barfield and E. Danas (ref. 14) and many others.

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