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Discrimination of Wine Using Taste and Smell Sensors

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The taste-smell sensory fusion was conducted by combining a taste sensor array using lipid/polymer membranes and a smell sensor array using conducting polymer elements. Responses to different brands of wine were investigated and a clear discrimination among different samples was obtained by processing the data from either type of sensors. The effect of the aging process on the quality of wine was also studied. It was found that the system can discriminate among differently aged samples of the same red wine. The information provided by one type of array is independent of that provided by the other and their combination enhances the overall information available concerning the sample being measured. This suggests that the sensory fusion can be a powerful way to improve the performance of sensor technologies currently available.

1. Introduction

Wine has both taste and smell qualities due to different aromatic molecules in the liquid and vapor phases. An average wine contains about 80–85% water and over 500 different substances, some of which are very important for the wine's flavor in spite of their low concentrations.(1) Acids, alcohols, esters, sugars and tannins are the main groups to which the compounds of wine belong. The difference in the color of wine is mainly due to tannins

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(which are also responsible for the flavor). The tannins are present in the solid part of the grapes which are fermented together with the liquid part when a red wine is made (in the case of white wines only the liquid part of grapes is used). It is known that tannins are responsible for the astringency of a solution whereas some acids are responsible for "freshness" and others for peculiar smell nuances.[2]

Among this large number of molecules, those which can easily pass in a vapor phase represent potential stimulus for the human olfaction when they reach the bulb in the nasal cavity and interact with the smell receptors.[3] On the other hand, the molecules in the liquid phase are responsible for the perceived taste when they interact with the taste buds on the tongue. As for the sense of smell, there are 5 to 10 thousand compounds which can produce different perceptions in one's brain, whereas for the sense of taste,[4] the five kinds of basic tastes are known to be the main factors responsible for perception: sourness produced by HCl and acetic acid; sweetness produced by sucrose, glucose and aspartame; bitterness produced by quinine, caffeine and $MgCl_2$; saltiness produced mainly by NaCl; *umami*,[5] which is a Japanese term for "deliciousness," produced by monosodium glutamate (MSG) contained in seaweeds, disodium inosinate (IMP) contained in meat and fish and disodium guanylate (GMP) contained in mushrooms. The overall perception of a substance as far as its chemical properties are concerned is due to the combination of smell and taste senses and also due to the so called trigeminal sense (responsive to irritant chemical species). This kind of perception is hereafter referred to as flavor. Wine, therefore, is a suitable candidate for testing the performance of the sensory fusion of taste and smell sensors.

2. Materials and Methods

The sensing system proposed by us is composed of two different arrays, each in turn, composed of several similar sensing elements.

2.1 *Smell sensor*

The smell-sensor array is composed of four different novel conducting polymers which have been recently developed.[6] The monomer (25 mg) is dissolved in trichloroethylene (2 ml) and the oxidizing salt previously dissolved in acetonitrile is added dropwise to it, following which polymerization occurs. The resulting solution is sprayed onto an alumina substrate where four interdigitated electrodes were previously evaporated. After evaporating the solvent, the conducting polymer is connected with the four electrodes, as shown in Fig. 1. Four different sensing elements were obtained by combining two different monomers and two oxidizing salts (see Table 1).

The electric resistance between the inner electrodes of these sensing elements ranges from 1 kΩ to 100 kΩ. The resistance measured at the inner electrodes varies when volatile molecules are adsorbed at the surface of the polymer film. The average sensitivity expressed as the ratio of the resistance change to the base resistance value was almost always less than 2% in the case of the elements used in this work for wine sensing. These sensors show broad and overlapped sensitivities to many compounds such as alcohols,

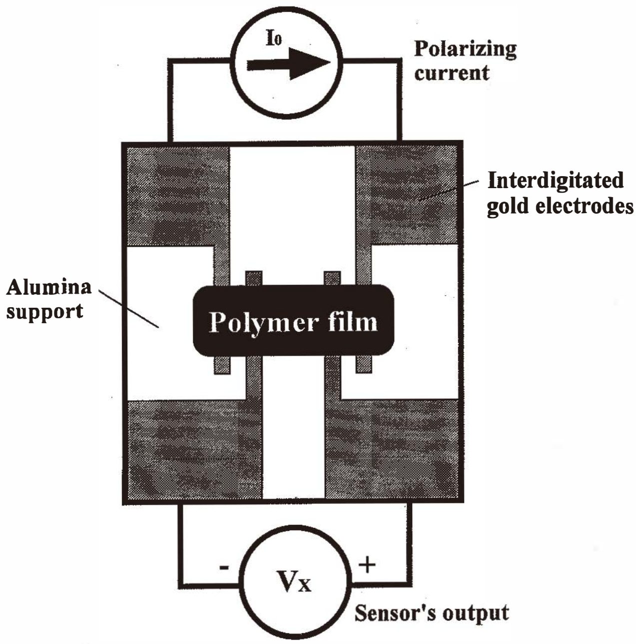

Fig. 1. Layout of a single smell sensing element on Alumina substrate.

Table 1
Materials used for the conducting polymer forming process.
(3DPO2BT = 3,3'-Dipentoxy-2,2'-bitiophene; 3,3'-DPTTT = 3,3'-Dipentoxy-2,2': 5',2''-tertiophene)

Channel	Monomer	Oxidizer
1	3DPO2BT	$Fe(ClO_4)_3$
2	3,3'-DPTTT	$Fe(ClO_4)_3$
3	3,3'-DPTTT	$Cu(ClO_4)$
4	3DPO2BT	$Cu(ClO_4)$

amines, hydrocarbons and phenols. They also show a cross sensitivity to water vapor (relative humidity; RH) so that the monitoring of RH was necessary during the experiments.

2.2 *Taste sensor*

The taste sensor has been applied to many kinds of foodstuffs such as beer, coffee, sake, miso (soybean paste), rice, green tea and milk;[7–11] it is shown that the taste can be measured quantitatively. The taste-sensor array is composed of eight kinds of polymer/lipid membranes (see Table 2), each fitted at the bottom of a plastic tube such that the inner part of the cylinder is isolated from the outside, in the same manner as described in the earlier works.[7–11] The other end of the cylinder is sealed with a stopper that holds an Ag/AgCl wire electrode. The tube is then filled with 3 M KCl solution. Each membrane was prepared by mixing a lipid or a blend of lipids with polyvinyl chloride (PVC) and a plasticizer (dioctyl phenylphosphonate) previously dissolved in tetrahydrofuran. The mixture was then cured on a glass plate, placed on a thermally controlled plate at a temperature around 30°C. The membrane resulting from this technique is a 200-μm-thick transparent, colorless soft film.

After preparation, the electrodes were immersed in a Japanese red wine solution for 4 weeks (the wine used as a standard solution) before they were used for the experiments. This preconditioning process adjusts the sensitivities of the membranes toward a particular set of substances (wines in this case). The preconditioning process reduces the amplitude of the response to the sample concerned. On the other hand, this process increases the stability of the responses and enhances the discrimination ability when the analyzed substances are similar to each other.

2.3 *Sample preparation*

The four different wines used for the experiments are listed in Table 3. As mentioned above, two sets of measurements were taken. The first set was to discriminate among the four wines and no special sample preparation was necessary. The second set was to analyze the effects of aging on a single kind of wine (wine 2). For this purpose five differently aged samples were prepared two weeks prior to taking the measurements. Each sample was obtained from a new bottle of wine 2 as per the following schedule: 2 weeks, 1 week, 3 days, 1 day and a few hours before the measurements were taken. All the samples were stored at room temperature during the aging period. At the time of the actual measurements other bottles of wine 2 were opened, the contents were mixed together and were used as the standard solution for the taste sensor. Mixing the contents of the bottles served to minimize small differences among different bottles of wine 2.

Table 2
Lipid materials used for the membrane forming process.

Channel	Lipid
1	Decyl alcohol
2	Oleic acid
3	Dioctyl phosphonate (DOP)
4	DOP : TOMA = 9 : 1 (used only in the first set of measurements)
5	DOP : TOMA = 5 : 5
6	DOP : TOMA = 3 : 7
7	Trioctyl methyl ammonium chloride (TOMA)
8	Oleyl amine

Table 3
Wines used for the experiments.

Wine	Brand name
Wine 1 (White)	Est! Est! Est! di Montefiascone 1995. Italia
Wine 2 (Red) (Standard solution)	Bon Marche' Mercian. Japan
Wine 4 (White)	Chablis 1994. France
Wine 5 (Red)	Rosso di Montalcino, Fattoria dei Barbi. 1994. Italia

2.4 *Experimental apparatus*

2.4.1 *Smell sensor setup*

The array of smell transducers is housed in an exposition chamber where the sensing elements adsorb the volatile molecules present in the vapors flowing through the pipeline system. The vapor is obtained by letting the air in the closed loop pipeline flow through the flask containing the wine sample and after the vapor has reached the exposition chamber it reverts to the flask. After exposing the sensors to the vapors for 90 s the flask containing the wine is cut off by two valves and new air is forced into the chamber to wash the sensing elements. The electrical connections to the sensing elements are attached to the exposition chamber. Each sensing element has four connections; the outer ones are used to inject a constant current for polarizing the sensing element and the inner ones to measure the voltage drop across the polymer film. Four operational amplifier current generators polarize the sensing elements and four high-CMRR (Common Mode Rejection Ratio) switched-capacitors differential amplifiers read the voltage drop across the elements and feed them into a digital voltmeter interfaced with a personal computer via a GPIB (General Purpose Interface Bus) interface-board. A computer-controlled scanner multiplexes the four outputs from the differential amplifiers into the voltmeter. The computer program for data acquisition, data preprocessing, real-time data presentation and data storage was developed using the C programming language under DOS V operating system.

2.4.2 *Taste sensor setup*

Eight electrodes and a reference electrode are fitted in an electrode holder and connected to a scanner and to a digital voltmeter. The controlling software records the electrode potential while they are immersed in the standard solution (wine 2 in our case). The recordings of these potentials are then used as the reference values for the further readings taken for different wines (note that the wine 2 is used as a standard solution and as a testing solution). Each single measurement lasted for 90 s after which the electrodes were washed two times in two different beakers containing, again, the standard solution. In the first set of measurements eight electrodes were used and all the necessary steps were manually performed whereas in the second set of measurements the commercial version of the taste-sensing system was used (SA401, Anritsu Corp.).

2.5 *Normalization of raw data*

The raw data were normalized according to the following method. Let $\overline{S}_{cs}$ be the set of measurements taken with the smell sensor array:

$$\overline{S}_{cs} = \begin{bmatrix} S_{11} & S_{21} & S_{31} & S_{41} \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ S_{1N} & \cdots & \cdots & S_{4N} \end{bmatrix}, \tag{1}$$

where N is the number of measurements, c is the channel number and s is the s-th measurement. Each element of the matrix represents the response of a single element of the smell sensor array expressed as the ratio of the maximum resistance change, upon exposure to the vapors, to the base resistance measured in presence of clean air flowing through the exposition chamber. Let $\overline{T}_{cs}$ be the set of measurements taken with the taste sensor array:

$$\overline{T}_{cs} = \begin{bmatrix} T_{11} & \cdots & \cdots & T_{81} \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ T_{1N} & \cdots & \cdots & T_{8N} \end{bmatrix}, \tag{2}$$

where N is the number of measurements, c is the channel number and s is the s-th measurement. Each element of the matrix represents the response of a single electrode of the taste sensor array expressed as the difference between the electric potential in the testing solution and the electric potential in the standard solution.

The mean values of the responses for each channel are:

$$\overline{S}_{c.} = \frac{1}{N}\sum_{s=1}^{N} \overline{S}_{cs} \tag{3}$$

for the smell sensor array, and

$$\overline{T}_{c.} = \frac{1}{N}\sum_{s=1}^{N} \overline{T}_{cs} \tag{4}$$

for the taste sensor array.

Computing the average of the square errors of the responses, first among the samples and then among the channels, we obtain:

$$\sigma_{ss}^2 = \frac{1}{4N} \sum_{c=1}^{4} \sum_{s=1}^{N} (\overline{S}_{cs} - \overline{S}_{c.})^2 \tag{5}$$

for the smell sensor array. And:

$$\sigma_{ts}^2 = \frac{1}{8N} \sum_{c=1}^{8} \sum_{s=1}^{N} (\overline{T}_{cs} - \overline{T}_{c.})^2 \tag{6}$$

for the taste sensor array.

Now the original sets of data can be normalized as follows:

$$\overline{S}_{cs}^N = \frac{\overline{S}_{cs} - \overline{S}_{c.}}{\sigma_{ss}} \tag{7}$$

for the smell sensor array, and

$$\overline{T}_{cs}^N = \frac{\overline{T}_{cs} - \overline{T}_{c.}}{\sigma_{ts}} \tag{8}$$

for the test sensor array.

Combining the normalized sets of data we obtain the data set:

$$\overline{F}_{cs} = [\overline{S}_{cs}^N \;\; \overline{T}_{cs}^N], \tag{9}$$

that is, a $12 \times N$ dimensional data array.

Although it seems that the analysis is biased to the taste end of spectrum because of 4 smell sensors and 8 (or 7) taste sensors, it will be seen that different information from these two types of sensors appears in the combined result. Therefore, the present method is effective for the study of wine flavor.

3. Results

3.1 *Discrimination of different brands of wine*

3.1.1 *Result of taste sensor*

The raw data obtained from the taste sensor indicate the differences between the electric potentials in the testing solution and potential in the standard solution. From each measurement an eight-dimensional vector representing eight membrane potentials was extracted. One cycle of measurements consisted of four different acquisitions made by rotating the testing samples in the following order: wine 1, wine 2, wine 4 and wine 5 (note here that wine 2 was also used as the standard solution).

Principal component analysis (PCA) was conducted after normalizing. The distribution of data in the principal component space is shown in Fig. 2.

We can observe that the data are clustered in four well-separated groups representing the four different wines used. The first principal component accounts for the differences between red and white wines, whereas the second principal component accounts for the differences between wines of the same color. As mentioned above, the color of wine is mainly due to its tannin content. The sensitivity of the taste sensor to tannins was investigated in a previous work[12] to show that the array's element, DOP : TOMA = 3 : 7, was most sensitive for tannic acid. This is in accordance with the present results because the element DOP : TOMA = 3 : 7 is the larger contributor to the first principal component, which, in turn, accounts for the discrimination between red and white wines.

Figure 3 shows the averaged taste patterns of the four wines. The taste pattern can be considered the finger print of a wine in the eight-dimensional space represented by the taste sensor. Each wine is characterized by its own taste pattern.

3.1.2 *Result of smell sensor*

From each measurement, a four-dimensional data vector representing the peak values of the electric resistance changes was extracted. The value of each component is relative to the base resistance of each sensing element measured in the presence of air flowing prior to the exposure to the wine vapors. PCA was conducted after normalizing the data in the same way as for the taste sensor. The plot in Fig. 4 shows the distribution of clusters in the

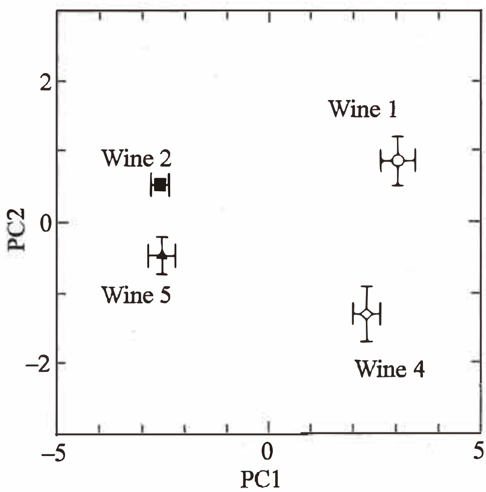

Fig. 2. Results of the PCA applied to the data set from ten measurements of each wine using the taste sensor. Wines 1 and 4 are white; wines 2 and 5 are red.

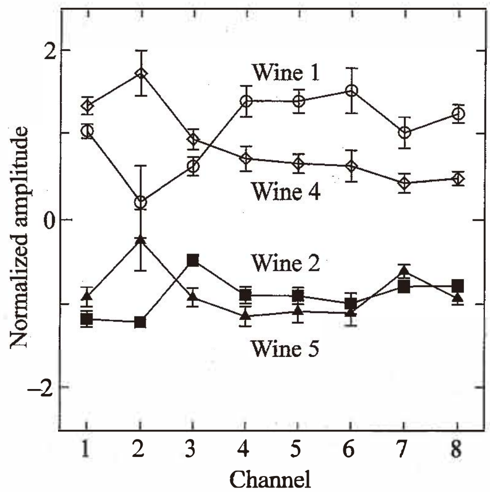

Fig. 3. Eight-dimensional taste patterns of the testing wines. Wines 1 and 4 are white; wines 2 and 5 are red.

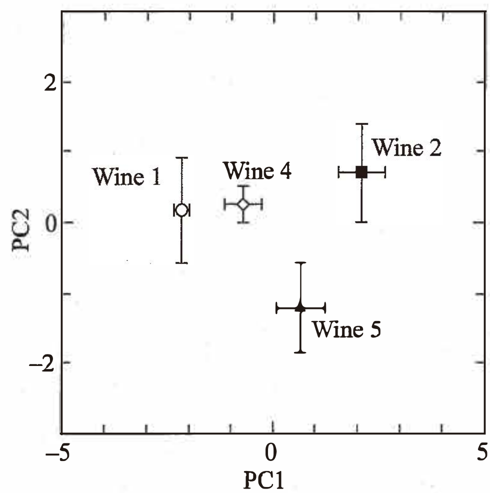

Fig. 4. Results of the PCA applied to the data set from seven measurements of each wine using the smell sensor. Wines 1 and 4 are white; wines 2 and 5 are red.

principal component space. Again, discrimination among different wines was achieved. At this stage no data were available concerning the sensitivity of smell sensors to the main components of wines and therefore no quantitative consideration can be put forward to account for these results. Nevertheless, in this case the mutual distribution of clusters differs from that in the previous case and this can be considered as an evidence that the information concerning the samples provided by the smell sensors accounts for different characteristics of the wines themselves. In this case the PC1 is still responsible for the discrimination between red and white wines and also for the differences between the two white wines and the two red wines. PC2 gives information about further differences between the two red wines. Note here, in the PCA plot, how the overall information about the set of samples is topologically distributed in a different way with respect to the taste sensor.

Figure 5 shows the averaged smell patterns for the four wines tested. Again, the smell patterns are the representation of the wines in the four-dimensional space of the smell sensing elements. Each sample has its own smell pattern which differs slightly among samples belonging to the same kind of wine because the responses of the smell sensor and the fluid-dynamic conditions[13] are not highly reproducible, as in the case of the taste sensor.

3.1.3 *Result of the taste-smell combination*

After either set of data was normalized, according to the method mentioned earlier, a twelve-dimensional data array was obtained for each measurement. The twelve-dimensional data array is composed of the four-dimensional data array of the smell sensors and of

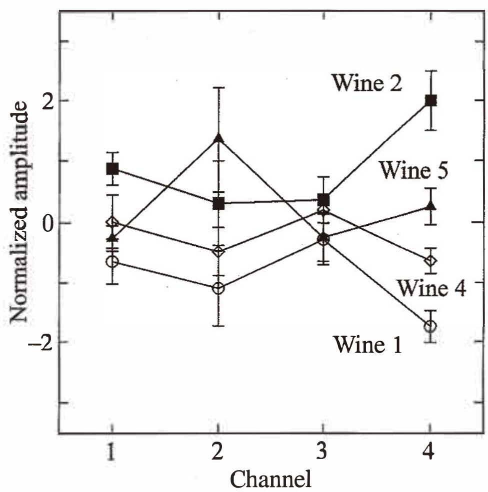

Fig. 5. Four-dimensional smell patterns of the testing wines. Wines 1 and 4 are white; wines 2 and 5 are red.

the eight-dimensional data array of the taste sensors. Another PCA was performed on this new set of data and the results are shown in Fig. 6.

We can observe that the relative positioning of the clusters in the principal component plane is similar to the case of the smell sensor and the relatively high distance between clusters of the red (2 & 5) and white (1 & 4) wines were successfully achieved by the contribution of the taste sensor, as in Fig. 2. The combination of the two sets of data has led to a new rcpresentation of the samples in the twelve-dimensional space which we refer to as flavor pattern. A flavor pattern simultaneously contains information from smell and taste sensors concerning the sample measured.

3.2 *Detection of aging effects*

As previously mentioned, for this set of measurements a sample preparation was necessary. When the measurements started we had five differently aged samples of Japanese red wine, wine 2. The five samples were opened 2 weeks, 1 week, 3 days, 1 day and just before the measurements were taken. In this context aging means the time elapsed after the bottle was opened.

3.2.1 *Result of taste sensor*

These measurements were taken with the automated taste sensing device the SA401. The computer-controlled robot arm handles all the samples and the washing solutions and performs all the steps necessary for the execution of the measurements.[7,8] The robot head housed seven electrodes out of the eight previously used. Again, the raw data were

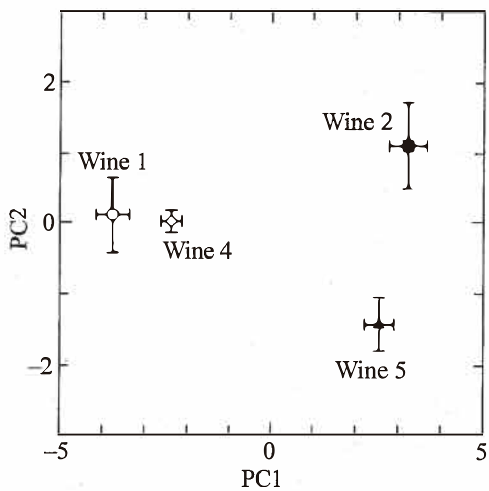

Fig. 6. Results of the PCA applied to the combination of the data set from the smell sensor with the data set from the taste sensor. Wines 1 and 4 are white; wines 2 and 5 are red.

normalized and a PCA was performed; the PCA plot is shown in Fig. 7. From the PCA plot we can easily observe that all five clusters are lined up in the direction of increasing PC1 in the order from the new wine to the old one of two weeks. Furthermore, the PC1 is nearly a linear function of the aging period. This result means that the PC1 can be used for assessing the age of the wine at least within the period of two weeks. The cluster scattering for which PC2 accounts, might be due to other unknown chemical processes occurring in the samples during the aging period. Figure 8 shows the seven-dimensional taste patterns for the five aged samples.

3.2.2 *Result of the smell sensor*

Figure 9 shows the PCA plot after normalizing the raw data from the smell sensor. Here, the PC1 is responsible to some extent for placing the clusters according to their aging period, but this time the cluster corresponding to the new wine represents an exception among these aged wines. The cluster for the new wine is apart from the other clusters and is nearer to the cluster composed of wines aged two weeks than to the cluster of the one-day-old wine, as expected. Channel 4 is responsible for this effect because its contribution to the PC1 is much greater than those of the other channels. If we take a closer look to the smell patterns in Fig. 10 we can see that channel 1 accounts for the aging effect in a manner similar to the taste sensor. The responses of channel 1 are correlated to the respective aging periods of the samples, starting from the new wine down to the 2-week-old wine. Since the amplitudes of the responses of channel 1 are much smaller than those of channel 4, this conceals the information carried along by the sensor and results in the PCA distribution, as observed in Fig. 9. This anomalous behavior might be due to a sudden change in the

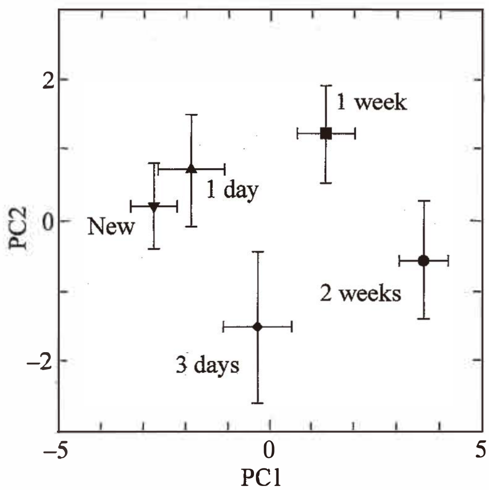

Fig. 7. Results of the PCA applied to the data set from three measurements of each wine using the taste sensor for the detection of aging effects on wine 2.

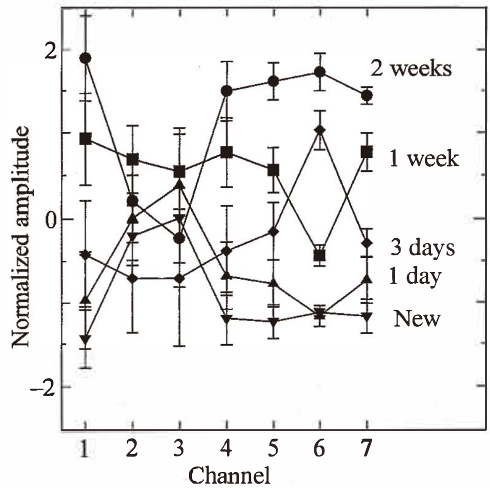

Fig. 8. Seven-dimensional taste pattern of the five aged samples of wine 2.

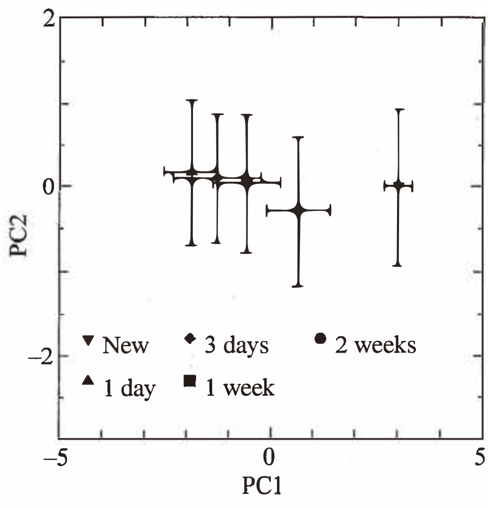

Fig. 9. Results of the PCA applied to the data set from three measurements of each wine using the smell sensor for the detection of aging effects on wine 2.

concentration of some substances which occurred only on the first day of aging. Then, the concentration must have changed gradually in accordance with the aging period. The response may reflect two factors of different changes with time in the concentrations of some different substances, which occurred at opening of the bottle and gradually from the first day of aging.

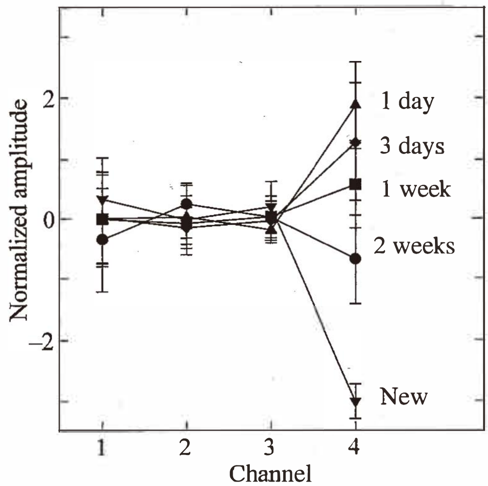

Fig. 10. Four-dimensional smell pattern of the five aged samples of wine 2.

3.2.3 *Result of the taste-smell combination*

Putting together the four-dimensional data array of the smell sensor and seven-dimensional data array of the taste sensor for each measurement taken, we obtain an eleven-dimensional data array which we refer to as the flavor pattern. As is observed in the PCA plot in Fig. 11, the contribution from the two different sensor arrays is evident and the overall information is shared by the first two principal components. The first principal component accounts for the aging period as it did in the taste sensor, and the five clusters corresponding to the five aging periods are well-spaced and distinguishable along the component. The placement of clusters in the case of the smell sensor is somehow reproduced by the second principal component in which we find the same ordering as far as the aging period is concerned; the cluster of the new wine is closer to the cluster of the two-week-old wine rather than to the clusters of other aged wines. Looking at the two dimensions together we notice that the information concerning the aging period is still present and the cluster of the new wine is well apart from the others, as observed in the case of the smell sensor.

4. Discussion

The feasibility of a sensory fusion between taste and smell sensors has been investigated with the aim of discriminating among substances with subtle differences such as the wines used. Discrimination among the testing samples was obtained in the case of the four different wines and in the case of the five aged samples of the same wine. Discrimination of wines, having the same denomination but coming from different vineyards, was

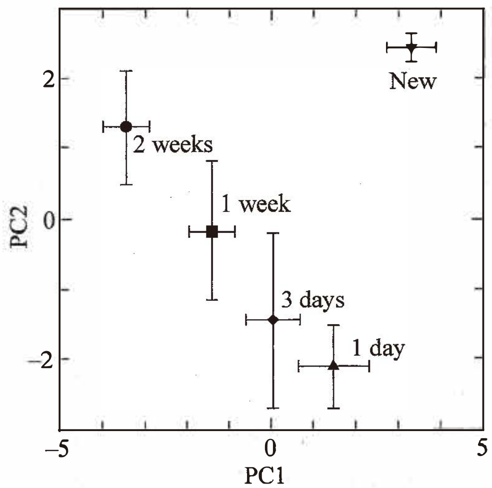

Fig. 11. Results of the PCA applied to combination of the data set from the smell sensor with the data set from the taste sensor for the detection of aging effects on wine 2.

successfully made using an array of metal-oxide semiconductor gas sensors.(13) The sensor fusion is very effective because the information provided by the different arrays are to some extent independent from each other; they account for different characteristics of the wines themselves since the relative positioning of clusters in the principal component space differs from one case to the next. Conventional multiple-sensor arrays have several sensing elements belonging to the same kind of technology;(14–17) *e.g.*, conducting polymer sensor array, metal-oxide sensor array and lipid membrane sensor array. These arrays show broad sensitivities to certain groups of substances, but on the other hand, they are not sensitive to other compounds. If different kinds of sensor technologies are simultaneously applied, provided that the information from the different sources are independent, it is worthwhile to combine them to obtain a broader viewpoint of the samples measured.

In the measurement of aged wines using the smell sensor, a peculiar behavior was obtained. The response magnitude of channel 4 was the lowest for the new wine, whereas it was the highest for the 1-day-old wine and then was reduced as the aging period prolonged (Fig. 10). This response is directly reflected by PC1 in Fig. 11. Effect of roasting time of coffee on the response of an array of tin oxide sensors was such that almost all the responses increased with the roasting time.(15) A straightforward comparison with the present result is difficult because of the large differences in the object (wine and coffee), the treatment (aging and roasting) and the used sensor material (conducting polymers and tin oxides). However, it may be noticeable that channel 1 shows a simple response from new to 2-week-old wines, as found in Fig. 10. It implies a possibility that the smell sensor utilizing conducting polymers has two different informations of wine aging. To pursue this point we may need chemical analysis during the aging process.

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References

1 G. H. Burns and B. H. Gump: Technological Advances in the Analysis of Wines (American Chemical Society, 1993) p. 3.
2 J. N. Boidron, A. Lefebvre, J. M. Riboulet and P. Ribereau-Gayon: Sci. Aliments. **4** (1984) 609.
3 G. M. Sheperd: Olfaction (1991) Chap. 1.
4 C. Pfaffmann: The Sense of Taste: Handbook of Physiology, Sec. 1 Neurophysiology ed. J. Field (American Physiological Society, Washington D.C., 1959) p. 507.
5 Y. Kawamura and M. R. Kare (eds.): Umami, A Basic Taste (Marcel Dekker, Inc., New York, 1987).
6 E. Stussi, S. Cella, G. Serra and D. De Rossi: Materials Sci. Eng. C **4** (1996) 27.
7 K. Toko: Reviews on Heteroatom Chemistry, Vol. 14, ed. S. Oae (MYU, Tokyo, 1996) p. 245.
8 K. Toko, T. Iyota, Y. Mizota, T. Matsuno, T. Yoshioka, T. Dai, S. Iiyama, T. Kato, K. Yamafujii and R. Watanabe: Jpn. J. Appl. Phys. **34** (1995) 6287.
9 T. Imamura, K. Toko, S. Yanagisawa and K. Kume: Sensors and Actuators B **37** (1996) 179.
10 K. Toko and T. Fukusaka: Sens. Materials **9** (1997) 171.
11 K. Toko: Materials Sci. Eng. C **4** (1996) 69.
12 S. Iiyama, K. Toko, T. Matsuno and K. Yamafuji: Chem. Senses **19** (1994) 87.
13 C. Di Natale, F. A. M. Davide, A. D' Amico, P. Nelli, S. Groppelli and G. Sberveglieri: Sensors and Actuators B **33** (1996) 83.
14 T. Nakamoto, A. Fukuda and T. Moriizumi: Sensors and Actuators B **3** (1991) 221.
15 J. W. Gardner, H. V. Shurmer and T. T. Tan: Sensors and Actuators B **6** (1992) 71.
16 H. Nanto, S. Tsubakino, M. Ikeda and F. Endo: Sensors and Actuators B **24 – 25** (1995) 794.
17 Y. Kanai, M. Shimizu, H. Uchida, H. Nakahara, C. G. Zhou, H. Maekawa and T. Katsube: Sensors and Actuators B **20** (1994) 175.