Multivariate statistical analysis and odour-taste network to reveal odour-taste associations

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ABSTRACT (100-150 mots)

Odour taste association has been successfully applied to enhance taste perception in foods with low sugar or low salt content. Using gas chromatography/olfactometry-associated taste (GC/O-AT), 68 odorant zones have been described with 41 odour descriptors and 4 taste associated descriptors (sweet, salty, bitter, sour). The relationships between odour and taste descriptors were analysed using multivariate analyses. A partial least square analysis allowed to visualise the odours associated with a specific taste, for example fruity, sweet, strawberry, candy, floral and orange with sweetness. A network representation using Cytoscape allowed visualising the links between odour and taste descriptors for example the positive association of butter with both saltiness and sweetness. Multidimensional scalling projection allowed allocating the odorant zones to their odour and taste descriptors. Our approach provided a visualisation tool of the links between odour and taste description and could be used to select odour-active molecules with a potential taste enhancement effect.

KEYWORDS : odour-taste association, multivariate analysis, sweetness, odorant compound

INTRODUCTION

Considering the rising rate of pathologies such as diabete, obesity, which are related to unbalanced diets with an excess of consumption of sugar, salt and fat, there is an urgent need to decrease the content of these ingredients in food while maintaining their sensory acceptability by consumers. In the present paper, we will focus on sugar reduction. Concerning sugar, a high consumption of foods rich in free sugar increases the risk of tooth decay. High intake of sugar-sweetened beverages is highly linked with an unhealthy diet, weight gain and increased risk of noncommunicable diseases. The food industry has to integrate these nutritional criteria in the formulation of food products. Different strategies have been used for sugar reduction in foods as reviewed (*1, 2*). Simple sugars, such as fructose or sucrose, could be replaced by new molecules, which confer a sweet taste to the product without the added calories, such as intensive sweeteners (i.e.: acesulfame k, aspartame, neotame, cyclamate, saccharin, sucralose, thaumatin, steviol, monogroside, brazzein and monatin). However, such molecules with an intense sweetness are used in very small amount resulting in losses of volume and modification of the final texture. Alternatively, a part of simple sugars can be replaced by soluble fibres or carbohydrates, such as polyols (i.e.: sorbitol, mannitol, isomalt maltitol, lactitol, xylitol, and erythritol) or fructo-oligosaccharides (i.e.: nystose, kestose and fructosylkestose), in order to use as bulking agent and restore the texture. These two strategies are often combined because excessive consumption of polyols and fructo-oligosaccharides may cause gastrointestinal symptoms, such as gas or laxative effects, then maximum levels are regularized and also to achieve a more pleasant taste. Other strategies are based on modifications of food texture and structure, which impact on the dynamic of sugar release in the mouth and as a consequence on taste perception (*3*), but the effect on sweetness perception was dependant on both the nature of the texturing agent and of the taste compound (*4*). By varying the gel hardness using a mixture of agar and gelatin, it was observed that the fracture properties of the gels affected the surface area of the fragments formed during chewing and thus the rate of sugar release (*5*), soft gels were perceived sweeter than medium gels, due to the formation of a large number of fragments during chewing, which facilitated the release of sweet molecules and the stimulation of the taste receptors. Moreover, in 20% sugar-reduced gelled products, a heterogeneous distribution a sugar was able to enhance sweetness intensity and thus maintain consumer acceptability (*6*). By combining these two strategies, it was observed that hard gels were perceived sweeter when sugar distribution was heterogeneous due to a long-lasting in-mouth sucrose concentration, the hard matrix being able to maintain the taste contrast due to different sucrose concentrations, for a longer time in the mouth during chewing (*7*). The authors concluded that the fracture properties of food can be modulated to enhance sweetness perception, in association with heterogeneous distribution (*5*). Another innovative strategy is the use of aroma-taste interactions and multimodal integration, based on the fact that an odour may evoke a taste (*8, 9*) but are not able to activate taste receptors and the metabolisms that entails. This strategy has been used with success to develop low-salt food while maintaining saltiness and consumer acceptability (*10*), to enhance fat perception in real foods varying in structure-texture properties (*11*) and to enhance sweet perception in sugar-reduced fruit juices (*12*). Using such an approach needs an adequate selection of odours. As food odours can evoke a specific taste through mental imagery, it has been possible to select promising odours for saltiness enhancement based on the expectation taste profiles of food products being evoked by their names (*13*). In different volatile compounds databases, such as Flavor-Base (*14*) or Volatile Compounds in Foods (*15*), the word "sweet" is often used as odorant descriptor. Considering this observation that some odours are described with a "smelled taste", Stevenson et al (*16*) calculated the correlation between odour sweetness and taste sweetness for 10 odorant molecules and found that the degree to which an odour smelled sweet was a good predictor for taste tasting. This association was also used to select odorants able to enhance sweetness in fruit juices, using gas chromatography/olfactometry-associated taste (GC/O-AT) (*12*), showing that odorants described with a "smelled sweet taste" were able to enhance the perceived sweetness odour of a fruit juice. Moreover, other odorants not described with a "smelled sweet taste" were also found to be good candidates for sweetness enhancement. In the aim to look for volatile compounds able to enhance some specific taste, we tried to find links between taste descriptors and odour descriptors, starting from the whole set of data previously obtained using gas chromatography/olfactometry-associated taste (GC/O-AT) (*12*). The aim of the present work was to perform different multivariate analyses to search for the links between odorant descriptors and taste associated descriptors, starting from a total of 68 odorant zones (identified and non-identified), which have been described first with odorant descriptors and second with taste associated descriptors (sweetness, sourness, saltiness, bitterness). These links could then be used for a first selection of molecules susceptible to enhance taste perception.

MATERIALS AND METHODS

Sample preparation

We used the raw data previously obtained after the extraction of volatile compounds from a commercial multi-fruit juice provided by Eckes Granini (France), following the vacuum distillation procedure and dichloromethane extraction described by Barba et al. (*17*). The extract was then concentrated with a Kuderna-Danish apparatus to a final volume of approximately 200 µL and 1 µL (splitless mode for 0.5 min) submitted to gas-chromatography/mass-spectrometry (GC/MS) for compounds identification and to GC/O-AT for odour description (*12*) using the same column (30m x 0.32 mm i.d. fused silica capillary column coated with a 0.5 µm layer of polyethylene glycol, DB-Wax, Agilent, Agilent Technologies, Santa Clara, CA). GC/O-AT was done with 12 panellists used to GC/O experiments. In a first run (first injection of the extract), panellists were asked to indicate the detection of an odour using a buzzer and to give an odorant descriptor. In a second run (second injection of the same extract), panellists were asked to attribute for each odour, one of the four associated taste descriptors: sweet, salty, sour or bitter. Detection times, odour descriptors and taste associated descriptors were recorded using AcquiSniff software (Saint Genès Champanelle, France). The detection frequency (DF) was calculated for both odour descriptors and taste associated descriptors (*18*). Only the odorant zones with a DF higher than 30% were selected, to limit the false detection risk. For each selected odorant zone, we took into account all the odour descriptors given by the 12 panellists. For taste associated descriptors, we also calculated the DF for each specific taste: sweetness (%), sourness (%), saltiness (%), bitterness (%).

Data preparations

From the whole set of data, we selected 68 odorant zones, with the name of the corresponding identified compound if known or mention that this compound is unknown (uki). We identified 70 odorant descriptor, of which 7 are present only in the description of one odorant zone and are not retained for the analyse. We validated a list of 63 odorant descriptors and 4 taste associated descriptors. In a second step, odour descriptors only present in 1 or 2 odorant zones were deleted. The multivariate analyses were done with 45 variables, the 41 remaining odorant descriptors and the 4 associated taste descriptors. A co-occurrence matrix was built with, for the 68 odorant zones, the number of occurrences of the 41 odorant descriptors and the DF for the 4 associated tastes. Additionally, we also use a binary version of this matrix: 1 when the odour descriptor or the taste associated descriptors appears in the odour description, 0 otherwise.

Computational analysis and statistical methods

Multivariate statistical analyses were performed using XLStat (Addinsoft). A Partial Least Square (PLS) analysis was done, on the 68 odorant zones, to explain the taste association descriptors (Y variables: DF for each associated taste) by the odorant descriptors (X block: number of occurrence of the 63 odorant descriptors).

The multidimensional scaling (MDS) approach allows the visualisation of the similarity between elements of a dataset by disposing them in an N-dimensional space. MDS is one of the methods that allow dimensionality reduction and producing meaningful representations of high-dimensional data into a lower-dimensional space (usually two or three dimensions space).

In the present study, we used the Euclidian distance to obtain a similarity matrix between 68 odorant zones on the basis of the frequency of 63 odorant descriptors. Then the MDS was achieved on the matrix to derive Euclidian coordinates and distances. We used the coordinates of the first three dimensions to display the odorant zones in a three-dimensional scatterplot. The 3D graphical visualisation was obtained using Miner3D (version 7).

Network visualisation

We aimed to explore the associations between odour descriptors and taste descriptors using a network of odorant and taste descriptors. For that purpose, we first calculated the co-occurrence matrix of the odorant and taste descriptors using the binary matrix of 68 odorant zones and 67 descriptors (63 odorant and 4 associated tastes). The co-occurrence matrix is a square 67x67 matrix in which the off-diagonal terms are the number of the odorant-taste pairs in the description of an odorant zone, while the diagonal terms are the number of all occurrences of each odorant and taste descriptors.

The calculations of MDS and co-occurrence matrix were conducted using R version 3.0.1 (*19*). The odorant and taste descriptors were considered to be variables in the context of odorant zones.

Cytoscape (*20*) was used to build a network of the links between odour descriptors and taste associated descriptors. This required the square matrix to be transformed into a twoway data table, which was performed via Statistica (TIBCO Software Inc. 2017).

RESULTS AND DISCUSSION

The 68 selected odorant zones with DF odour values higher than 30% are listed in Table 1 with the name of the corresponding volatile compounds, if identified, or the number of the unknown compound. For each odorant zone, all the odour descriptors given by the 12 panellists are listed with the number of occurrence when higher than the unity. We have deleted from the list the descriptor “unknown”, which was given by panellist who was not able to describe the odour. This list of descriptor was used to build the Euclidian matrix. For each odorant zone, 2 values are given for DF, the detection frequency for the odour (DF odour %) which is the percentage of panellists having smelled the odour during the first run of GO/O and the detection frequency for the associated taste descriptor (DF taste %) during the second GC/O-AT run. We then calculated the DF for each of the four taste attributes, sweetness (%), sourness (%), saltiness (%), bitterness (%), these values are used for the statistical analyses. The value is in bold for the main associated taste. A total number of 33 odorant zones are more associated with sweetness (13 with a value higher than 40%), 16 odorant zones are more associated with sourness (5 with a value higher than 40%), 10 odorant zones are more associated with saltiness (3 with a value higher than 40%) and 21 odorant zones are more associated with bitterness (3 with a value higher than 40%).

Explanation of taste association by odour descriptors using PLS.

The PLS was done on the 68 odorant zones, using the occurrences of each of the 41 odour descriptors as X variables and the DF for each associated taste as Y variables. We verified that the representation of the remaining 41 variables is the same as on the PLS realised with the 63 odour descriptors (supplementary files). Figure 1 shows the projection of the variables on the two main components. The 4 associated tastes are well discriminated in the first plan, the sweetness on the positive part of component 1, bitterness on the negative part of component 1, sourness on the positive part of component 2 and saltiness on the negative part of component 2. The odour descriptors fruity, sweet, strawberry, candy, floral, orange are positively correlated with component 1 and thus contribute to sweetness perception. The odour descriptors sour, unpleasant, cheese, acid are positively correlated with component 2 and thus contribute to sourness. The odour descriptors hot plastic, plastic, spicy are negatively correlated with component 1 and thus contribute to bitterness. The odour descriptors toasted, potatoe, mushroom, sulphur are negatively correlated with component 2 and thus contribute to saltiness. A model has been built to predict the taste association by a linear combination of the odour descriptors. Table 2 presents the coefficients affected to each odour descriptor to explain one taste descriptor. The odour descriptors are ranked according to the decreasing number of their total occurrences. The odours with the highest impact on sweetness are strawberry, red fruits, sweet, citrus, leather, butter, orange, foot, chemical, candy, fruity, floral and those with the highest negative impact are sour, sulphur, hot plastic, land, plastic, wood, metallic, toasted, potatoe, smoky. The odours with the highest impact on sourness are sour, sweaty, hot plastic, metallic, lemon, land, solvent and those with the highest negative impact are peanut, strawberry, toasted, leather, foot, chemical, butter. The odours with the highest impact on saltiness are sulphur, potatoe, toasted, smoky, land, butter, mushroom and those with the highest negative impact are citrus, animal, peanut, strawberry, dust, metallic, grass, vegetal, unpleasant, plastic, red fruits, foot, sweet, chemical. The odours with the highest impact on bitterness are animal, metallic, peanut, plastic, wood, grass, hot plastic, vegetal, dust and those with the highest negative impact are butter, strawberry, orange, cake, acid, red fruits, leather, lemon.

It can be noticed that most of the odours positively associated with sweetness are negatively associated with saltiness, except butter, spicy and leather which are positively associated to both sweetness and saltiness.

Looking at the odorant zones (Figure 2), the compounds with a high positive correlation with component 1 are the most associated with sweetness, ethyl2-methylbutanoate (E2MB) is described with fruity, apple, strawberry, candy and sweet odour descriptors (Table 1), methyl-2-methylbutanoate (M2MB) is described with fruity and sweet notes, linalool is described with floral, fruity, sweet and candy notes, (E)-β-ocimene (β-Oci) is described with fruity, floral, strawberry notes, phenylmethanol (PhM) is described with floral, fruity, sweet, candy notes, β-damascenone (β-Dam) is described with fruity, floral and sweet notes, γ-decalactone (γ-Dec) is described with floral, fruity and sweet notes, ethyl butanoate (EB) is described with fruity, floral and sweet notes. The compounds the most associated with sourness (positive correlation with component 2) are pentanoic acid (PA), described as acid, sharp, cheese, unpleasant, allo-ocimene (allo-O), described as green, metallic, sour, hexanal (HEXA) described as green, herb, floral. The compounds the most associated with bitterness (negative correlation with component 1) are tricosane, described as plastic, petrol, isobutylalcohol (IBA), described as plastic, hot plastic, spicy, wood. The compounds the most associated with saltiness (negative correlation with component 2) are furfural, described as potatoe, toasted, sulphur, 2-hexen-1-ol (2Hexe), described as mushroom, toasted, sulphur, 1-octen-3-one (1o3o), described as mushroom and n-butanol (Buta), described as toasted, peanut.

Visualisation of the links between odour descriptors and associated tastes

In order to better understand the associations between odour descriptors and tastes, we build a network characterized in terms of nodes and edges or links, following the approach used for odour notes (*21*). In our case, the nodes are odour and taste descriptors and the edges are the odorant zones. We used a total of 45 descriptors (41 odorant descriptors and 4 taste descriptors). We obtained a list of 2025 pairs of descriptors by stacking the 45x45 co-occurrence matrix. After excluding the diagonal elements and the pairs zero values link, it remained 1098 pairs. We considered only the pairs between odour and taste descriptors, and after removing the entries below the main diagonal (for any X and Y odor notes, the pairs XY and YX are equivalent), the network displayed 143 odour-taste pairs.

Figure 3 represents the links between the odour and the tastes descriptors. This representation allows a rapid visualisation of the odour taste associations.

Many odour descriptors are linked to all tastes, but some are only linked to one, two or three tastes, as can be seen in Figure 3 by the lines between odour descriptors and tastes. Plain lines are used for more than 4 occurrences, different types of discrete lines are used for 1, 2, 3 or 4 occurrences as indicated in the legend. The size of each odour descriptor depends on the number of odorant zones in which they are present. The fill colour of each odour descriptor is that of the main associated taste and the border colour is that of the second associated taste. In case the odour is equally associated with every taste, the colour is grey.

One odour descriptor in only linked to one taste, strawberry, which is only linked to sweetness. This explains its high positive value in the regression to sweetness perception.

Three odour descriptors are only linked to two tastes, they are orange, candy and red fruits linked mainly to sweetness and then to sourness.

The descriptors linked to three tastes can be discriminated by the taste to which they are not linked to. Caramel is not linked to bitterness. Butter, mushroom and peanut are not linked to sourness. Hot plastic, potatoe and sour are not linked to sweetness. Grass, citrus, lemon, metallic and dust are not linked to saltiness.

The other odour descriptors are linked to all the tastes. Fruity and floral are the most cited descriptors with respectively 79 and 70 total number of occurrence and present in respectively 35 and 37 odorant zones. They are mainly linked to sweetness, then to the three other tastes without any distinction. Cake and rose are mainly associated to sweetness but with only few occurrences. Among the other odour descriptors mainly associated to sweetness, the second associated taste is sourness for sweet and solvent, bitterness for vegetal, chemical and foot and saltiness for leather. Only sweaty is first associated to sourness. Green, plastic, herb, wood and animal are first associated to bitterness, the second associated taste is saltiness for wood, sourness for animal and both sourness and sweetness for green and herb. Toasted, cheese, sulphur, smoky and land are first associated to saltiness and toasted, sulphur and land are also associated to bitterness. Unpleasant, sharp, spicy and acid do not present any specificity towards a specific taste.

Allocation of odorant zones according to their odour descriptors and associated taste

A MDS realised on the dissimilarity matrix obtained using the Euclidian distance allowed to determine the level of similarity of odorant zones based on their odour descriptors. The distances and coordinates calculation was performed using the frequency of odour descriptors; nevertheless, the data used for graph depictions involves also ~~the taste descriptors and~~ the DF for each of the four taste descriptors.

Figure 4 and 5 present the projection of the MDS 3D space of odorant zones. We decided to focus only on the links between the different taste attributes and two odorant descriptors, fruity and floral which have the greater total number of occurrences. The shape of the plots depends on the associated taste, sphere for sweetness (4A, 4B), cone for sourness (4C, 4D), diamond for saltiness (5A, 5B) and star for bitterness (5C, 5D), their size depends on the percentage of taste DF. The fruity odours are represented by a colour gradient depending on their occurrence in the odorant zone (4A, 4C, 5A, 5D). They are more perceived in the odorant zones present on the negative part of axis 1. The floral odours are represented by a colour gradient depending on their occurrence in the odorant zone (4B, 4D, 5B, 5D), they are more perceived in the odorant zones present on the positive part of axis 3 and negative part of axis 2. The odorant zones with a high DF for sweetness (4A, 4B) are mainly located on negative part of V1, due to a greater number of occurrence for fruity and some on the positive part of axis 2, due to the presence of floral odours, but some are in the middle of the space due to links between sweetness and other odour descriptors as was highlighted by Cytoscape Network. The odorant zones with a high DF for sourness (4C, 4D) are located on the negative part of axis 3 and positive part of axis 1. They have low occurrences for both fruity and floral. However, some odorant zones perceived as fruity or floral are also associated to sourness. On Figure 5, it can be noticed that the odorant zones with a high DF for saltiness and bitterness have low occurrence of fruity and floral odours.

DISCUSSION AND CONCLUSION

The different tools involved in this study allowed finding links between odour descriptors and taste descriptors. As the data used in this study are from an extraction of volatile compounds from a fruit juice, the odour descriptors cover a specific domain. However, we were able to find links with not only sweetness and sourness, which are the main taste descriptors in fruit juices, but also with saltiness and bitterness.

A lot of the literature on odour-taste interactions relies on sweetness perception. A review by Valentin et al (*22*) presents the different studies reporting an effect of odour on sweet perception. The most studied aroma is strawberry which has been reported to enhance sweetness perception for example in model systems (*23, 24*), in whip cream (*25*) and in fruit juice (*12*). Our results show that the strawberry descriptor is only associated with sweetness and has a high positive value in the regression to sweetness perception. This can be explained by associative learning (*16*), due to simultaneous exposition of strawberry odour and sweet taste in a great variety of food products such as jams, jellies, marmalades, yogurts, ice creams or candies. Other odour descriptors are mainly associated with sweetness, such as caramel, which was already found to increase sweetness perception in model solutions (*16*) or ciders (*26*). Fruit odours, such as orange, redfruits and lemon are potential candidates for sweetness enhancement. They have a high positive value in the regression to sweetness perception and a negative value for saltiness and bitterness. A sweetness enhancement has been observed for orange and raspberry (*27*). The odour descriptor sweet is, as expected, associated with sweetness but also with sourness, which can be explained by the fact that fruit products are often perceived sweet and sour.

Concerning lemon odour, Schifferstein and Verlegh (*24*) observed that the sweetness enhancing effect was lower than with strawberry odour. Our results show that lemon odour was mainly associated with sweetness but also with sourness. In water solution, a significant enhancement of both sweetness and sourness was observed by addition of lemon flavour (*28*), whereas in acidic solutions, other authors did not found any effect of the addition of lemon odour on sourness perception (*29*). These different results are in agreement with other observations, that the effect of odour on sweetness/saltiness enhancement is higher at low to medium intensities of the tastes (*26, 30, 31*). It can be noticed that even if lemon and citrus are both associated with sweetness, with a positive contribution in the regression, lemon is secondly associated with sourness with a higher contribution to sourness and a negative contribution to bitterness in the regression, whereas citrus is secondly associated with bitterness, with a positive contribution to bitterness in the regression. These results can be explained by the fact that lemon extract are perceived as sour and sweet (*32*) and that some citrus fruit drinks such as grapefruit are perceived sweet and bitter (*33*).

Only few odours have been mainly associated with sourness. As expected, the odour descriptor sour is mainly associated with sourness, but not with sweetness. Metallic is also associated with bitterness and sweaty also associated with sweetness. There is no information in the literature on the effect of addition of such odours on sourness perception.

Even if the odorant zones were isolated from a fruit extract, which cannot be associated with saltiness itself, some odorant zones were described with odour descriptors mainly associated with saltiness, such as toasted, smoky, sulphur, cheese, potatoe, butter, leather and mushroom. This association was already mentioned for similar odours such as bacon, cheese or peanuts and were able to enhance saltiness intensity in water solution by orthonasal and retronasal perception (*13*). Another study on odour induced saltiness enhancement showed that at least 15% salt reduction can be compensated by addition of either beef or chicken bouillon aroma and that the odour descriptors mainly contributing to this enhancement were brothy, meaty and roasted (*34*). Soysauce odour was also able to induce salty taste in water solution with a very amount of sodium chloride, below the detection threshold (*35*). These observation confirm that the odour descriptors found in this study associated with saltiness could have an impact on saltiness enhancement.

The positive association for butter with both sweetness and saltiness can be explained by the consumption of both fat-sweet and fat-salty foods and for spicy by the consumption of both spicy-sweet and spicy-salty foods. In fact, the addition of butter aroma was found to enhance fat perception in model cheeses with an additional small effect on saltiness enhancement (*31*).

The links we observed between some odours (green, grass, vegetal) and bitterness have already been used to increase bitterness perception in a model olive oil by addition of cis-3-hexenol, a cut grass odorant compound (*36*). Considering our results, other odour descriptors could be good candidates for bitterness enhancement, such as plastic, wood, herb and animal. In the case of bitterness reduction in food products, such odours have to be discarded from the product. However the impact of odours on bitterness has not been the subject of many studies. In the aim to reduce bitterness in foods, our network representation can allow to select odours which have no link or only few links with bitterness and then test the effect of the corresponding odorant compounds.

A focus was done on the present paper on two odour descriptors with the greatest number of occurrence in our odorant zones, due to the nature of the extract, from a multifruit juice. These two odours are mainly associated with sweetness on the network representation and then to the three other tastes. However the MDS projection allowed to differentiate the links between these two odours and the taste descriptors. Sweetness perception can be linked either with fruity or with floral. Both odours are negatively correlated with saltiness and bitterness, which means that an addition of molecules perceived fruity and/or floral could decrease saltiness and/or bitterness.

Our results also point out other negative associations. Orange, candy and red fruits are not linked with saltiness and bitterness, which explains their negative value in the regression for saltiness and bitterness. Some descriptors are not linked with one specific taste. Caramel is not linked to bitterness, which explains its negative impact on bitterness. Butter, mushroom and peanut are not linked to sourness and have all a negative impact on sourness. Hot plastic, potatoe and sour are not linked to sweetness and have all a high significant negative impact on sweetness. Grass, citrus, lemon, metallic and dust are not linked to saltiness and have all a high significant negative impact on saltiness, except lemon, which has a moderate negative impact on saltiness. These odours could be then tested for an eventual masking effect of undesirable tastes such as an excess of bitterness or sourness.

In the present manuscript the descriptors have been generated from a multifruit juice extract, a generalisation of the approach to other extracts could increase the number of odour descriptors and their links with taste descriptors. The proposed approach is simple to handle and could be a good way for the selection of odorant molecules with an impact on taste perception. The links formalised between odour and taste descriptors could then be used to predict a potential odour-induced taste enhancement in model system or real foods or even an eventual masking effect.

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Table 1: Odorant zones detected by GC/O and GC/O-AT, with the list of odour descriptors, the detection frequency for odorants and for each associated taste. ^{a}: mode of identification, MS: comparison with mass spectra database and retention index, St: mass spectra and retention index verified with standard injected in the same condition, refer to Barba et al., (12, 17), n.d. means not detected.

Table 2: PLS regression to explain the taste descriptors by odour descriptors: for each odour descriptor the number of total occurrences and the number of odorants zones in which it has been described are given with the regression coefficients for each associated taste.

Figure 1: PLS regression with 45 variables and 68 individuals, projection of the 4 taste descriptors (Y variables) and the 41 odour descriptors (X variables) on components 1 and 2.

Figure 2: PLS regression with 45 variables and 68 individuals, projection of the 68 odorant zones (individuals) on components 1-2.

Figure 3: Network representation of the links between odour descriptors (circle) and taste associated descriptors (octagon). The nature of the line varies as a function of the number of occurrences. The size of each odour descriptor depends on the number of odorant zones in which it is present. The file colour of the odour descriptors varies as a function of the number of occurrences with each taste: blue if the odour is mainly associated with sweetness, green for saltiness, violet for sourness, light brown for bitterness. The border colour is that of the second associated taste, it is grey if the odour is equally associated to the three other tastes and dark blue if the second associated taste is equally sourness and sweetness.

Figure 4: Allocation of odorant zones according to their odour descriptors and associated taste: MDS representation in a 3D space. The colour represents the occurrence of fruity (A, C) floral (B, D), the shape of the plots represents the associated taste (sphere for sweetness, cone for sourness and the size depends on the percentage of taste detection frequency in the odorant zone.

Figure 5: Allocation of odorant zones according to their odour descriptors and associated taste: MDS representation in a 3D space. The colour represents the occurrence of fruity (A, C) floral (B, D), the shape of the plots represents the associated taste (diamond for saltiness, star for bitterness and the size depends on the percentage of taste detection frequency in the odorant zone.

Supplementary Figure 1: PLS regression with 67 variables and 68 individuals, projection of the 4 taste descriptors (Y variables) and the 63 odour descriptors (X variables) on components 1 and 2.

Supplementary Figure 2: PLS regression with 67 variables and 68 individuals, projection of the 68 odorant zones (individuals) on components 1-2.