# Data-driven methods for the study of food perception, preparation, consumption, a...

Health & Medicine

# Introduction

From an anthropological and social perspective, few aspects of everyday life are as fundamental as the consumption of food. Culinary culture is an important cornerstone of human society, and its diversity matches that of any other cultural form of expression across the globe. On the level of the individual, the perception of food is an incredibly complex process involving the chemical properties of aroma compounds, the biochemistry of receptor proteins, the physiology of the mouth, nose, and other organs, the neuroscience of the olfactory bulb and brain, and the psychology of multi-sensory associations and memories. Similar to many other research disciplines, the highly interdisciplinary study of food perception, consumption, and culture is being transformed by the ubiquity of data sets—on flavor chemistry and biochemistry, but also on food consumption, eating habits, and culinary diversity—and new data analysis methods, including network analysis and machine learning. In this article, we lay out three areas in which this transformation is leading to far-reaching changes in our understanding of food perception and our culinary practice.

# Digital Deliciousness: Understanding Taste from Sensory Perception Data

The study of flavor and sensory perception of food has in recent years increasingly been influenced by approaches based on concepts, experimental methods, and theories from the physical sciences, not least fueled by the acquisition of quantitative data and use of physics-inspired thinking and extensive modeling. New scientific disciplines such as neurogastronomy ( Shepherd, 2012 ) and gastrophysics ( Mouritsen and

Risbo, 2013 ; Mouritsen, 2015 ; Mouritsen and Styrbaek, 2017 ) are emerging and offering themselves as the possible scientific underpinnings of gastronomy.

Gastrophysics takes its empirical starting point in an observation of the phenomenological world of gastronomy, posing first a research question and a hypothesis, then applying physical sciences to investigate the hypothesis, and finally returning back to gastronomy, possibly with a deeper understanding and a result (e. g., a recipe) that may improve a dish, a preparation technique, or a commercial product.

Below we give several examples that illustrate this process and highlight the importance of solid data, which is the key to this approach.

The fifth basic taste, umami, is elicited by certain components in the food, in particular free glutamate from proteins and free 5′-ribonucleotides, such as inosinate, guanylate, and adenylate, from nucleic acids. It has been known for a long time that glutamate and the nucleotides, when together, synergistically enhance the taste of each other, a fact that is used in most cuisines across the world by pairing specific kinds of foods, e. g., eggs and bacon, ham and cheese, meat and vegetables, and *konbu* -seaweed and *katsuobushi* in Japanese *dashi* .

The umami compounds are detected by a certain G-protein-coupled receptor T1R1/T1R3 harbored by the taste cell membranes in the taste buds. The synergy between glutamate and nucleotides can be investigated using large-scale molecular dynamics simulations. These reveal that the mechanism of the synergy ( Mouritsen and Khandelia, 2012 ) is based on an allosteric principle, where co-binding of glutamate and a nucleotide in the so-called venus fly-trap motif of the receptor makes the receptor snap up tightly compared to binding of one type of compound alone.

Extensions of simulations of this type could lead to data that might help us explore how the umami sensation is influenced by other basic tastes, such as salty and sweet, possibly leading to formulations of foods with lower levels of salt and sugar without compromising palatability. It may also stimulate further work using flavor network analysis ( Ahn et al., 2011 ) to explore glutamate–nucleotide flavor pairing in recipes from different cuisines across the world. Flavor pairing has turned out to be a particularly elusive problem whose phenomenological validity can be probed by applying network analysis to massive amounts of metadata, generated by mining an extensive compilation of 56, 000 recipes ( Ahn et al., 2011 ), which is combined with a large data set of 1, 021 aroma compounds in 381 foods that appear in these recipes. Such data sets on aroma compounds are now widely available, for example in form of the Volatile Compounds in Foods database, 1 and the odor threshold database compiled by van Gemert. 2 Somewhat surprisingly it was found in the study by Ahn et al. that the hypothesis of common chemical compounds in different ingredients being the main reason for good pairing seemed to hold for Western cuisines, but not for Southern European and East Asian cuisines. Incidentally, these latter two cuisines rely heavily on the use of umami-rich ingredients. In the case of the basic taste umami there is, however, a scientifically based hypothesis for a flavor-paring principle, being the synergetic action of free glutamate and free nucleotides on the umami receptor ( Zhang et al., 2008 ). Whereas there is currently a fair amount of data available on the free amino acid contents of a variety of foods, there is still a lack of data for free nucleotides. Upon establishing more extensive databases for these chemical constituents it should be possible by performing a large-scale network analysis along the lines of Ahn et al. (2011) to investigate the hypothesis that umami is a desired taste in all food cultures as one would expect based on evolutionary principles, and whether umami might be the shared property that binds together recipes in umami-rich cuisines. Among the challenges of such large-scale analyses of chemical data, however, is the fact that such data have typically been accumulated over decades by thousands of individual researchers in separate experiments. The conditions and quality of the data in such collections may therefore vary widely.

Traditional food chemistry often characterizes foods through chemical and physico-chemical analyses, e. g., correlating the contents of capsaicin with the pungencies of chillies ( Duelund and Mouritsen, 2017 ), whereas sensory sciences most often employ tasting panels and psycho-physical methods to explore the flavor of food samples, e. g., the flavor of insects ( Evans et al., 2016 ). It is possible to combine the two approaches in a more powerful setting.

An example of such a combination is a recent study of the flavor of fermented sauce-derived from fish, insects, game, and pulses ( Mouritsen et al., 2017 ). The deliciousness and umami taste of these fermented products is largely due to compounds such as free amino acids, formed during fermentation. The study involved chemical analysis of 21 experimental and commercial fermented sauces along with a quantitative sensory evaluation based on taste descriptors. The sensory analysis enables a reasonably good prediction of sensory properties from the chemical characterization of the sauces, using multivariate data analysis. However, the relationship between glutamate concentration and intensity of umami taste is not simple. It demonstrates that in the complex solutions that constitute these sauces, there may be other perceptions that interfere with the main umami taste compounds.

The research group behind this study ( Mouritsen et al., 2017 ) is now embarking on a related study of *dashi* -like extracts of 37 different species of brown seaweeds and plan to determine concentrations of free amino acids, sodium- and potassium salts, as well as iodine. These data will be correlated with sensory analysis not only of taste but also of odor and aroma in order to reveal the relationships between concentrations of compounds such as glutamate, salts, and iodine, and the sensory perception of umami, saltiness, and seawater flavor.

## Food Online: Studying Culinary Culture through Online Recipes and Social Media

We are living in the age of the social web. Social media have become a major mode of communication, and we are leaving digital traces of all kinds of activities online. As food is central in our life, a significant fraction of online content is about food. We find and share recipes, talk about foods, and share pictures of foods online. In other words, a huge amount of information about our culinary habits is now being recorded digitally and available for our enquiries.

The web has revolutionized how we cook. In addition to recipes that are handed down or passed between friends, and those found in cookbooks, we can now also browse or search websites with thousands of recipes. In fact, the most popular Japanese website, called " http://cookpad. com ," lists more than two million of them! Like other content services such as YouTube, recipe websites are eager to allow users to share their own recipes and discuss recipes with others. Furthermore, for many recipes, one can find detailed demonstrations by famous chefs, including some of the best cooks in the world, on YouTube.

Recipe websites can be a treasure trove for scholars. First, online recipe data is digital, which makes it easy to obtain and process large amounts of recipes. Instead of typing recipes from a pile of cookbooks, researchers can now download recipe webpages or establish partnerships with recipe publishing companies to obtain tens of thousands of recipes. Second, online recipes often have rich metadata about the recipes. In addition to the list of ingredients and instructions, recipes often contain useful information such as cuisine categories, tags (e. g., seasons or holidays), cooking time, or macronutrient composition. Such metadata can be used to study questions about food, culture, and health. One example is the work by Ahn et al. (2011) described above, which used online recipes to analyze food pairing patterns in terms of flavor compounds across different global regions. Another study examined the regional recipes in China, again using the cuisine metadata, to demonstrate that distance between regions, rather than climate similarity, is more closely related to the similarity in the recipes ( Zhu et al., 2013 ). Moreover, many recipe websites provide " social" features such as ratings and comments, and such social feedbacks can be useful. For instance, a study showed that one can build a good recipe recommendation model based on user ratings and comments ( Teng et al., 2012 ).

In summary, online recipe websites not only make it easier to accumulate recipe data but also allow researchers to answer questions that were unimaginable before the advent of the World Wide Web. It is now possible to computationally analyze a huge number of recipes and identify statistical patterns, in order to understand our eating habits and preferences.

Every day, many people spend hours on social media such as Facebook or Twitter. Moreover, these social media services are predominantly accessed through mobile devices that people carry around with them all the time. Social media data can therefore act as a giant social sensor that gives an insight into everyday life around the globe. For instance, it has been shown that clear, universal rhythmic patterns regarding work, sleep, and eating can be observed through Twitter ( Golder and Macy, 2011 ). Similar temporal and spatial patterns can be found by analyzing online recipe websites ( Wagner et al., 2014 ; Kusmierczyk et al., 2015 ). Food is a common subject on social media, which makes it possible to study the relationship between geography and health in new ways. It has been shown, for example, that tweets about food are informative about the regional prevalence of obesity and diabetes ( Abbar et al., 2015 ).

In addition to textual data, images on social media provide even greater opportunities and challenges. With the advent of Facebook, Instagram, and other visually oriented social media services, it is a common practice to share food photos. These photos contain rich, detailed information about what people eat, how much, when, where, and even with whom. Combined with the so-called “ quantified self” movement, it is increasingly common to record photos of meals. Recent studies have used large collections of food photographs posted on social media to investigate food perception, eating behaviors, common associations and emotion connected to particular foods, and the relationship between fast food and obesity ( Mejova et al., 2015 ; Ofli et al., 2017 ). These data sets are enormous—Mejova et al. analyze images that were taken in 164, 753 restaurants and posted by over three million users on Instagram, and Ofli et al. analyze 1. 9 million images, also on Instagram. Like with large textual data sets on Twitter the size and scope of these data collections enables entirely new ways of mapping food perception, food consumption, and nutritional health across time and space.

As briefly summarized above, an ever-increasing amount of food-related data is being digitally recorded in text, image, and video formats. It presents researchers with an unprecedented opportunity to study culinary culture, eating habits, and health. Of course, these opportunities come with significant challenges, such as the sheer size of the available data, the difficulty of understanding natural language in recipes, computer vision, and many other machine learning challenges. However, the recent breakthroughs in machine learning, particularly in deep learning, herald a bright future for social and food data analysis. Deep neural network techniques are now outperforming other approaches in many relevant tasks such as visual object recognition ( LeCun et al., 2015 ) and leading companies such as Google are already investing in food-related machine learning tasks. It is reasonable to assume that detailed records of individual food consumption will soon be available for millions of people, which will then revolutionize our understanding of food choice and culinary culture, and their impact on health and well-being. Even traditional machine learning methods have been shown to be useful in studying food and flavor. For instance, a recent study combined machine learning with crowd-sourced data about olfactory perception to create a model to predict olfactory perception (e. g., " garlic" or " fish") just using chemical features of molecules ( Keller et al., 2017 ). The combination of crowd-sourced or crowed-contributed data and advanced computational techniques will continue to have strong impact on food science and gastronomy.

## The Chef as Flavor Scientist: Applications of Flavor Chemistry in Gastronomy

Flavorists have spent many years identifying which aroma and taste compounds are key to driving the flavors of different foods. This information has been invaluable to the food industry in explaining how flavor perception is influenced by the addition and removal of key components of commercially available food products, such as sugar, fats, and starches. The recent expansion of the web means that this knowledge, along with information about the chemical structure and properties of these flavor molecules which had previously been restricted to scientific textbooks and journals, is now readily available online through websites such as www.

chemspider. com . As a result of this, the more scientifically minded chef who is interested in this technical information can now find it fairly easily in these online resources, and they can use it to help direct and guide their experimentation as they start to work with new equipment and techniques.

In recent years, research and development chefs have sometimes found themselves faced with unfamiliar scientific equipment to experiment with in their test kitchens, and this apparatus often demands a more detailed understanding of scientific data in order to maximize the potential impact and benefits of its usage. For example, take the rotary evaporator. Most commonly used in laboratories by chemists to separate mixtures of liquids, chefs sometimes use these machines to create flavored distillates from both edible and inedible ingredients. Depending on their boiling points, flavor molecules will either end up in the collecting flask or remain in the evaporating flask, therefore producing two products from the initial ingredient, each with a completely different flavor profile. Citric acid, with its very high boiling point, is extremely unlikely to end up in the collecting flask, which means that any citrus fruit distillate recovered from the evaporating flask will lack the characteristic acidity—although this highly soluble acid can subsequently be added to the flavor distillate at a later stage, to bring back its refreshing notes. Acetic acid, however, which has a boiling point much closer to water, will almost always end up in the collecting flask, meaning that any ingredient containing this acid will result in easily identifiable vinegary flavor notes in the distillate. Therefore, by knowing which aroma and taste compounds are key to constituting certain flavors and what their respective boiling points are, one can predict more reliably which aspects of the flavor might end up in the collecting flask, and which will end up in the evaporating flask, before running the machine. This knowledge will also help indicate which ingredients are most likely to produce good flavored distillates. Furthermore, knowing which specific flavor compounds may be lacking from the final distillate, due to their elevated boiling points, can be useful when working out what needs to be added back in to the final product to recreate or enhance certain aspects of the original flavor.

Similarly, an understanding of the specific molecular structure of key flavor compounds within ingredients can be useful when working out the best way to extract a flavor from its source using other methods and pieces of scientific equipment. Ingredients in which the key flavor compounds are hydrophobic rather than hydrophilic will be more efficiently extracted in a fat-based medium compared to an aqueous one. For example, a chef wanting to extract the pungency from ginger will benefit from knowing that the key trigeminal stimulant within ginger is gingerole, which is primarily hydrophobic, and therefore best extracted in fat or alcohol. When using modern equipment such as a centrifuge to separate fatty components from the aqueous ones in foods, or to extract the flavor from different ingredients, understanding the relative hydrophilicity and hydrophobicity of key flavor compounds can be helpful in predicting and explaining which aspects of flavor will be extracted into which phase, and whether flavors will be best extracted in fat, water or alcohol. Therefore, being able to access information on the chemical properties of flavor compounds can inform innovative chefs not only how to produce flavorful distillates but also how to effectively extract flavors from ingredients. Also, the use of the web as a forum for people to share their culinary experiments online can also be hugely helpful in guiding research and development in this area. Keen enthusiasts can benefit from results of tests and trials that other people, both chefs and scientists, have done using these different pieces of equipment, which can help them explore new and alternative avenues when working with these techniques, even before they have started doing any testing.

Furthermore, social media and other forms of online communication can now open up more frequent communication streams between chefs and scientists and encourage them to share knowledge and ideas about science and cooking. Not only do chefs with an interest in science share their findings, through websites such as www. cookingissues. com and www. chefsteps. com , scientists with an interest in food (e. g., www. blog. khymos. org ) are also happy to share their knowledge with the public, encouraging and facilitating more advanced experimentation, which can help further push the boundaries of flavor creation, combination, and delivery in modern gastronomy.

## Conclusions

In conclusion, the advent of information technology has transformed the way we prepare, perceive, consume, and discuss food. There are many forms of food-related data that are being collected on an enormous scale, ranging from a variety of chemical and nutritional data to recipe collections and social media postings. Large-scale computational data analysis can not only provide a way to examine these data sets individually, but most importantly, it can also connect them to each other, for example, to analyze the relationship between chemical data and recipes ( Ahn et al., 2011 ) or social media images and obesity ( Abbar et al., 2015 ; Mejova et al., 2015 ). It is these connections between different types of data that can provide us with a new perspective on the study of our culinary culture.

# Author Contributions

All the authors contributed to the text of this perspective article.

# Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Footnotes

1. ^ www. vcf-online. nl .
2. ^ www. thresholdcompilation. com .

# References

Abbar, S., Mejova, Y., and Weber, I. (2015). " You tweet what you eat: studying food consumption through twitter," in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (ACM), 3197–3206.

Google Scholar

Ahn, Y.-Y., Ahnert, S. E., Bagrow, J. P., and Barabási, A.-L. (2011). Flavor network and the principles of food pairing. *Scientific Rep.* 1, 196. doi: 10. 1038/srep00196

CrossRef Full Text | Google Scholar

Duelund, L., and Mouritsen, O. G. (2017). Contents of capsaicinoids in chillies grown in Denmark. *Food Chem.* 221, 913–918. doi: 10. 1016/j. foodchem. 2016. 11. 074

PubMed Abstract | CrossRef Full Text | Google Scholar

Evans, J., Müller, A., Jensen, A. B., Dahle, B., Flore, R., Eilenberg, J., et al. (2016). A descriptive sensory analysis of honeybee drone brood from Denmark and Norway. *J. Insect. Food Feed* 2, 277–283. doi: 10. 3920/JIFF2016. 0014

CrossRef Full Text | Google Scholar

Golder, S. A., and Macy, M. W. (2011). Diurnal and seasonal mood vary with work, sleep, and daylength across diverse cultures. *Science* 333, 1878–1881. doi: 10. 1126/science. 1202775

PubMed Abstract | CrossRef Full Text | Google Scholar

Keller, A., Gerkin, R. C., Guan, Y., Dhurandhar, A., Turu, G., Szalai, B., et al. (2017). Predicting human olfactory perception from chemical features of odor molecules. *Science* 355, 820–826. doi: 10. 1126/science. aal2014

PubMed Abstract | CrossRef Full Text | Google Scholar

Kusmierczyk, T., Trattner, C., and Nørvåg, K. (2015). " Temporality in online food recipe consumption and production," in *Proceedings of the 24th International Conference on World Wide Web* (ACM), 55–56.

Google Scholar

LeCun, Y., Bengio, Y., and Hinton, G. (2015). Deep learning. *Nature* 521, 436–444. doi: 10. 1038/nature14539

PubMed Abstract | CrossRef Full Text | Google Scholar

Mejova, Y., Haddadi, H., Noulas, A., and Weber, I. (2015). "#FoodPorn: obesity patterns in culinary interactions," in *Proceedings of the 5th International Conference on Digital Health 2015* (ACM), 51–58.

Google Scholar

Mouritsen, O. G. (2015). The science of taste. *Flavour* 4, 18. doi: 10. 1186/s13411-014-0028-3

CrossRef Full Text | Google Scholar

Mouritsen, O. G., Duelund, L., Calleja, G., and Frøst, M. B. (2017). Flavour of fermented fish, insect, game, and pea sauces: garum revisited. *Int. J. Gastro. Food Sci.* doi: 10. 1016/j. ijgfs. 2017. 05. 002

PubMed Abstract | CrossRef Full Text | Google Scholar

Mouritsen, O. G., and Khandelia, H. (2012). Molecular mechanism of the allosteric enhancement of the umami taste sensation. *FEBS J.* 279, 3112–3120. doi: 10. 1111/j. 1742-4658. 2012. 08690. x

PubMed Abstract | CrossRef Full Text | Google Scholar

Mouritsen, O. G., and Risbo, J. (2013). The emerging science of gastrophysics. *Flavour* 2. Available at: http://www. flavourjournal. com/series/gastrophysics2012

Google Scholar

Mouritsen, O. G., and Styrbaek, K. (2017). *Mouthfeel: How Texture Makes Taste* . New York: Columbia University Press.

Google Scholar

Ofli, F., Aytar, Y., Weber, I., al Hammouri, R., and Torralba, A. (2017). " Is Saki# delicious? The food perception gap on Instagram and its relation to health," in *Proceedings of the 26th International Conference on World Wide Web* (International World Wide Web Conferences Steering Committee), 509–518.

Google Scholar

Shepherd, G. (2012). *Neurogastronomy: How the Brain Creates Flavor and Why It Matters* . New York: Columbia University Press.

Google Scholar

Teng, C. Y., Lin, Y. R., and Adamic, L. A. (2012). " Recipe recommendation using ingredient networks," in *Proceedings of the 4th Annual ACM Web Science Conference* (ACM), 298–307.

Google Scholar

Wagner, C., Singer, P., and Strohmaier, M. (2014). The nature and evolution of online food preferences. *EPJ Data Sci.* 3, 38. doi: 10. 1140/epjds/s13688-014-0036-7

CrossRef Full Text | Google Scholar

Zhang, F., Klebansky, B., Fine, R. M., Xu, H., Pronin, A., Liu, H. T., et al. (2008). Molecular mechanism for the umami taste synergism. *Proc. Natl. Acad. Sci. U. S. A.* 105, 20930–20934. doi: 10. 1073/pnas. 0810174106

PubMed Abstract | CrossRef Full Text | Google Scholar

Zhu, Y. X., Huang, J., Zhang, Z. K., Zhang, Q. M., Zhou, T., and Ahn, Y. Y. (2013). Geography and similarity of regional cuisines in China. *PLoS ONE* 8: e79161. doi: 10. 1371/journal. pone. 0079161

PubMed Abstract | CrossRef Full Text | Google Scholar