RUNNING HEAD: ON THE MEANING(S) OF COMPLEXITY IN THE CHEMICAL SENSES

On the meaning(s) of perceived complexity in the chemical senses

Charles Spence & Qian (Janice) Wang

Crossmodal Research Laboratory, Oxford University

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CORRESPONDENCE TO: Prof. Charles Spence, Department of Experimental Psychology, New Radcliffe House, University of Oxford, Oxford, OX2 6BW, UK. E-mail: charles.spence@psy.ox.ac.uk

ABSTRACT

Complexity is a term that is often invoked by those writing appreciatively about the taste, aroma/bouquet, and/or flavour of food and drink. Typically, the term is used as though everyone knows what is being talked about. Rarely is any explanation given, and the discussion soon moves on to other topics. However, oftentimes it is not at all clear what, exactly, is being referred to. A number of possibilities are outlined here, including physical complexity at the level of individual molecules, at the level of combinations of molecules giving rise to a specific flavour profile (e.g., as in a glass of quality wine or a cup of specialty coffee), at the level of combinations of distinct ingredients/elements (e.g., as when composing a particularly intricate dish in a high-end restaurant, say, or when pairing food with wine), and/or the number of stimuli/steps involved in the process of creation. Of course, people might also be referring to some aspect of their perceptual experience, and one of the intriguing questions in this space concerns the nature of the relationship(s) between these different ways of conceptualizing complexity in the chemical senses. However, given that physical/chemical and perceived complexity so often diverge, we argue that it is the latter notion, or rather inferred complexity, that is the most relevant when it comes to the chemical senses. Finally, we look at the role of expertise and review the evidence suggesting that inferred complexity can emerge either from a unitary taste experience that is judged to be complex, or from a tasting experience having multiple individuable elements.

KEYWORDS: COMPLEXITY; FLAVOUR; TASTE; AROMA; EXPERTISE.

1. Introduction

Talk of complexity in the chemical senses is common. But that does not necessarily mean that it is entirely clear what, exactly, is being discussed. (Just take the *Forbes* writer who suggests that a Zind Humbrecht Riesling, made by arguably the best biodynamic winemaker in Alsace, has *'multiple layers of fathomless complexity'*; Passmore, 2015). Getting to the bottom of what people who talk of complexity are referring to, as far as the chemical senses are concerned, is not just of theoretical interest, but is also of applied relevance too: Wendy Parr (2015), for instance, has described how some New Zealand wine producers have, in recent years, been explicitly trying to develop a 'more complex' product offering, believing that it is something that the consumer is willing to pay for. Going back more than half a century, one finds Singleton and Ough (1962, p. 189) suggesting that: *"Complexity has long been considered a desirable factor in the quality of most flavorsome or odorous products."* (see also Smith, 2014).

At the outset, one might imagine that what people are referring to, when talking about complexity in the chemical senses, is perceived complexity (e.g., Laing, Cain, McBride, & Ache, 1989; Parr, 2015; Smith, 2014; cf. Strother & Kubovy, 2003), and this will indeed be our focus in this review. Alternatively, however, one could be forgiven for thinking that it is the chemical complexity of the food or beverage that is being addressed instead (Gill, 2008; Thorngate, 1997). Chemical complexity, in this case, being roughly equal to the number of distinct volatile and, importantly, smellable (i.e., detectable, or volatile aromatic; note that not all volatile molecules are detectable by the human nose), compounds that are to be found within the particular foodstuff or beverage under discussion.

"Is the complexity to be found in the chemosensory stimulus or in the mind of the taster?" In a sense, this question is analogous to the on-going debate about whether flavours themselves reside in the food (i.e., out there in the world) versus in the mind of the person(s) doing the tasting (see Prescott, 1999; Shepherd, 2012; Small, 2012). Note, here, that some philosophers have stressed the importance of distinguishing between flavours and flavour perception (Smith, 2017). The following quote from Duccio Cavalieri, a professor of microbiology at the University of Florence in Italy, would seem to hint that he, for one, believes that complexity can be found both in the wine and in the brain: *"One of the most beautiful things of wine is the fact that basically it's complex; it's made of several parts and it communicates to several parts of your brain"* (quoted in Shogren, 2012; see also Thorngate, 1997, for a similar position). The link between complexity in the chemical senses and cerebral activity is also hinted at by Wendy Parr (2015, p. 5) when she states that: *"If the ability of a wine to evoke cerebral (cognitive) and sensorial responses is not a given, what makes a particular wine encourage thought? A reasonable assumption is that a wine we consider "complex" has a higher probability of doing so than a wine we consider "simple"."*

If it turns out that it is perceived complexity that is, or should be, being talked about, then one of the natural follow-up questions concerns the role of (domain-specific) expertise (e.g., Parr, Mouret, Blackmore, Pelquest-Hunt, & Urdapilleta, 2011; Schlich, Maraboli, Urbano, & Parr, 2015) and cultural factors in accessing complexity. That said, if perceived complexity is the

thing, then one may also wish to distinguish, as some other researchers have, between informational complexity (e.g., Friedes, 1974; Rudel & Teuber, 1975) and hedonic complexity (Grabenhorst, Rolls, & Margot, 2011; Smith, 2014; cf. Crolic & Janiszewski, 2016). These terms presumably equating with the sensory-discriminative (*"What is it?"*) and hedonic (*"How much do I like it?"*) evaluations that one can make concerning food and drink.

2. Physical/chemical complexity & its relation to perceived complexity

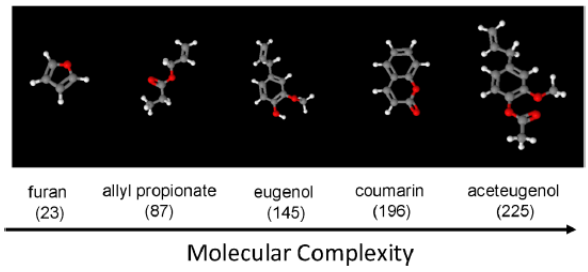
2.1. Simple vs. complex molecules

Some volatile aromatic molecules are undoubtedly more complex than others. However, this is certainly not the right way to conceptualize the complexity of a drink, like coffee or tea, given that most food and beverage products are composed of multiple different volatile aromatic compounds. One of the formulae used to calculate molecular complexity takes into account both the elements composing the molecule and structural features such as symmetry (see Hendrickson, Huang, & Toczko, 1987). So, for example, those molecules that are smaller and/or highly symmetrical, and those compounds having fewer distinct types of atoms (or elements), are judged to have an objectively lower complexity. But what exactly is the link, if any, between this physical property and the complexity (or nature) of the ensuing perceptual experience? An intriguing study in this regard was reported by Kermen, Chakirian, Sezille, Joussain Le Goff, Ziessel, et al. (2011). These researchers assessed the number of distinct olfactory notes that experts and non-experts ascribed to a range of 411 monomolecular odorants. On average, the two groups of participants perceived a greater number of olfactory notes in response to the presentation of more structurally-complex monomolecular odorants (see **Figure 1**). Furthermore, functional magnetic resonance imaging (fMRI) research by Sezille, Ferdenzi, Chakirian, Fournel, Thevene, Gerber, et al., 2014) has revealed that not only do simple and complex molecular odorants evoke differing numbers of olfactory quality descriptors, they also have different activation patterns in the brain. Specifically, more structurally complex odorant molecules gave rise to a higher number of descriptions, and evoked greater activity in the dorsal anterior cingulate gyrus (a brain area responsible for odour-related verbal and lexical processing, and for the resolving of cognitive conflict – perhaps associated with competing descriptors), than did simpler odorants.

Elsewhere, Khan et al. (2007) have reported that the pleasantness of an odour tracks (or at least weakly correlates with) the size of the molecule (see also Zarzo, 2011). Khan et al. used a range of novel volatile aromatic compounds that participants would have been unlikely to have come across previously (so that familiarity effects could, in this case, be ruled out). Thus, on average, it would appear that more complex monomolecular odorants do indeed give rise to perceptual experiences that are both more pleasant and give rise to a larger number of describable olfactory elements (or notes). However, given that any natural product, like wine, say, is made up of many hundreds of volatile compounds, this level of

complexity/explanation does not necessarily seem to be the appropriate one at which to talk about the relative complexity of the two drinks we started with – namely coffee and tea.

A)



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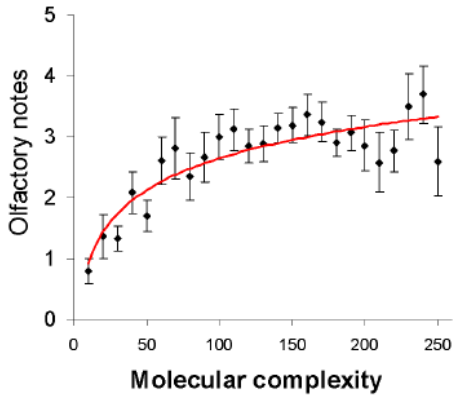

Figure 1. A) Examples of odorants displaying various degrees of molecular complexity (increasing from left to right); B) Graph highlighting the logarithmic relationship between the molecular complexity of monomolecular odorants and the average number of olfactory notes that are perceived/reported. Note that such relationship was shown for trigeminal notes. [Figures reproduced from Kermen et al. (2011).]

2.2. Simple vs. complex combinations of molecules

Rather than discussing the complexity of a specific odorant molecule, one might think that what people are really talking about, or at least what they should be talking about, is the number of different volatile aromatic compounds that are to be found within a particular food (or aroma; Gill, 2008; Kew, Goodall, Clarke, & Uhrín, 2017; Thorngate, 1997). But what exactly is the relation between perceived and physical/chemical complexity at this level of analysis? A naïve view might posit that there is little to distinguish the two, since the former obviously tracks (or correlates with) the latter. It is, however, important to stress that such a relationship is not always found. Perhaps the more relevant question here is whether it is generally true. It can, though, be argued that this relationship between perceived and physical

complexity is generally not observed. For instance, what might smell "just like a rose" is actually extremely complex and difficult to model, even if it might not be perceived as a "complex" smell. The difference here is that our odour descriptions tend to be based on real-world objects, and those odour objects (like a rose) tend to be very complex, chemically-speaking (see also Yeshurun & Sobel, 2010). By contrast, a single molecule (as sometimes used in modern perfumery) might be described as complex simply because it evokes many real-world objects (flowers, fruits, etc.). Perhaps humans have a different basis function when it comes to aromas, one that is not based on molecular structure but rather on learned associations with complex smell objects. It is certainly the case that many of the foods that we, in the West, often describe as complex – think here only of the bouquet of a quality wine or the aroma of a speciality coffee (Croijmans & Majid, 2016; Parr, 2015; Singleton & Ough, 1962), do indeed contain many hundreds of different detectable (by machine at least) volatile organic compounds.

Exact figures are hard to come by, and will obviously vary as a function of the particular product under consideration, but one finds ballpark estimates of something like 1,200 volatiles in coffee (Clarke, 2013), as compared to 600-1,000 in wine (e.g., Rapp, 1990; Tao & Li, 2009). This would seem to back up the commonly-heard claim that a specialty coffee contains more volatile molecules than a quality wine. Apple juice, by contrast, has been estimated to contain something like 137 natural volatile chemicals (Maarse, 1983). That said, if one is going by the perceived complexity of these substances, then it is only the subset of those volatile molecules that are detectable by the (average) human nose (and/or that exert an influence over that which we detect) that matters. The latter constraint typically drops the relevant figures down to the range of 30-40 volatile aromatic molecules that are detectable by the human nose and which contribute in some meaningful way to perception (see Benzi, 2008). In other words, perceived complexity is something very different from the physical complexity that, say, one finds in the read-out from gas chromatography.

2.2.1. Does physical/chemical complexity predict perceived complexity?

One of the problems for anyone wishing to equate perceived complexity with physical complexity is that synthetic flavour chemistry and perfumery has, in a number of cases, managed to come up with unique aromatic molecules (or small numbers of such molecules) that are perceptually indistinguishable from the much more chemically complex nature-equivalent versions that they have been designed to imitate (see Anon., n.d.). The company, *Escentric Molecule* (https://www.escentric.com/), has developed a series of successful boutique perfumes consisting of only a single aroma-molecule. Were such perfumes to be presented together with other more chemically-complex high-street perfumes, it is by no means clear that people would be able to distinguish the chemically simple (i.e., monomolecular perfumes) from the chemically more complex alternatives. As such, there are certainly (many) situations in which the chemical complexity of a substance is not going to be ascertainable perceptually, even by a trained nose. Of course, should such synthetic 'hits',

or metamers (see Deroy, Spence, & Noppeney, 2016), turn out to be rare, they might end-up being the exceptions that prove the rule.

2.2.2. Assessing the complexity of single malts/grape varieties vs. blends

Here, one might also ask about the experience of single malt vs. blended whisky, or of the differences between single varietal wines and blends. The self-proclaimed connoisseurs, of course, would have us all believe that the difference between the two would be perceptually obvious. The blend must surely be more chemically complex than any one of its constituent parts (assuming that the latter, or something like it, is used as one component making up the former; see also Gill, 2008; Kew et al., 2017)? However, it is important to note that simply increasing the chemical complexity of a drink does not mean that the additional complexity will necessarily also be experienced perceptually. Just take the medical men of Scotland who put their beliefs in this regard to the test more than 30 years ago (see Chadwick & Dudley, 1983). The results of this admittedly rather informal study (appearing in the Xmas 'festive' issue of the BMJ) revealed that the 6 medics concerned failed abysmally in their attempts to discriminate the single malts from the blends! Subsequent research has come to much the same conclusion (see Campbell, Campbell, & Roberts, 1994; Smith, Sester, Ballester, & Deroy, 2017) – much to the relief of the Johnnie Walker brand it should be said. While whiskies do taste distinctively different, one from the next, those differences are not those in terms of perceptual complexity that track changes in physical/chemical complexity.

Indeed, the notion that the art of blending involves the obscuring of some of the individual elements links to what is often said about a good Indian curry. While the latter may well contain 20-30 or more herbs and spices, and so is likely more chemically complex than many other dishes, it is commonly held that the chef has failed if the taster can detect the individual elements (i.e., spices) within their tasting experience (see also Adapon, 2008; Jain, Rakhi, & Baglerb, 2015; Singleton & Ough, 1962). Nevertheless, this bringing together and combining of multiple separate elements in a dish would seem to be one of the ways in which people commonly use the term 'complexity'. Indeed, as Singleton and Ough (1962, p. 196) noted more than half a century ago, when describing the increased ratings of quality seen when they blended single varietal wines: *"A further implication is that a flavour that may be undesirable when recognizably strong, may be a contributor to complexity and therefore not undesirable if below the recognition threshold in the blend."*

One can, of course, ask much the same question of wines – namely, can the experts discriminate single-varietal wines from blends of different grapes? Anecdotal evidence suggests that they sometimes can, though we are not aware of any published research on this specific issue. Perhaps the research that comes closest to answering this kind of question is from a classic study by Singleton and Ough (1962). These researchers selected 34 pairs of similar commercially available single varietal Californian wines from the 1960 vintage that presented somewhat different flavour profiles. They also prepared a 50-50 mix of each pair of wines. Participants were presented with the individual wines and also with the blend, though

they were blind as to the condition (i.e., individual wine or blend) with the order of presentation randomized. The wines were rated on a 20-point quality scale by the 10 highly-experienced sensory panellists. Intriguingly, the quality scores given to the blends were significantly higher than the mean score of the two wines when evaluated separately. Furthermore, in 7 out of the 34 cases, the blend was actually rated as tasting better than the best of the two individual wines. Overall, the scores given to the blends did not differ significantly from the best of the individual wines. Although uncertain as to why blending should, on average, have lifted the quality ratings for the wines thus produced, Singleton and Ough did suggest that, in at least some cases, an increase in complexity may have been a major factor. It would certainly be interesting to repeat this type of experiment while at the same time having the tasters rate the complexity of the wines that they have been asked to evaluate in order to obtain some empirical data on this intriguing question.

2.3. Complex combinations of elements/ingredients

A third level at which the term complexity emerges when people talk about food and drink occurs when they describe the combination of separate elements/flavours that are deliberately brought together in a dish in a high-end restaurant, say (see Spence, Wang, & Youssef, 2017). A similar usage of the term also appears when people discuss the challenges associated with pairing food with wine say (see Chartier, 2012; Harrington & Hammond, 2005; Passamore, 2015; Paulsen, Rognsa, & Hersleth, 2015). In both cases, complexity comes about due to the relationship between the perceptibly-different elements rather than because of the components that can be found within a singular unitary flavour experience.

One example of a tasting experience that one might wish to describe as pleasantly complex is shown in **Figure 2**. This dish has been intentionally designed with several distinct elements in order to deliver a series of impressions that evolve (or emerge) over time, as the flavour/texture of each element hits the taster's palate (see Spence et al., 2017). This dish, served on a spoon, is to be consumed in a single mouthful, and delivers a distinctive series of flavour experiences (with the order carefully crafted by the chef). In other words, this is a designed tasting experience, and that is where the complexity comes in. Here, complexity depends on the relationship between the elements, rather than merely on the number of components in the composition. One might wish to contrast this with the 100-ingredient Mugaritz leaf salad (see **Figure 3**). The latter dish is intentionally arranged as a random composition. That is, there is no obvious relation between the elements. One can certainly ask whether this is a complex dish? One might also wonder whether it delivers a complex tasting experience, or does it rather give rise to a kind of gustatory 'white noise' instead (cf. Weiss, Snitz, Yablonka, Khan, Gafsou, Schneidman, & Sobel, 2012)?

Figure 2. The *Thon au chocolat blanc et piment Thaï* dish served at Denis Martin's namesake restaurant in Vevey, Switzerland (http://www.denismartin.ch/; Martin, 2007). [Picture from http://www.cavesa.ch/blog/wp-content/uploads/archives/b/bl/blog.cavesa.ch/aoctobre/thonlivre10_small.JPG. Author: Denis Martin]

Figure 3. Mugaritz Leaf and flower salad – no two plates are ever quite the same. What level of complexity should we ascribe to this dish? Is this an example of the 'unity in complexity', or the 'complexity in unity' (see Mroczko-Wąsowicz, 2016)? [Figure from Aduriz (2014).]

2.4. Interim summary

Thus far, a number of situations have been highlighted in which perceived complexity does not coincide with physical complexity at the level of flavours constituted of multiple volatile organic compounds (i.e., the sort of thing that one finds in natural substances / processed foodstuffs such as wine, coffee, and tea; Gill, 2008; Thorngate, 1997). Problematic observations for anyone wanting to equate the two include the fact that single molecules may give rise to complex percepts; And something that we describe as 'smelling just like a rose' might, in fact, be made up of tens if not hundreds of different molecules (cf. Yeshurun &

Sobel, 2010). Additionally, mixtures of detectable volatile molecules are sometimes indistinguishable from unimolecular synthetics. As yet, we are not aware of any attempt to look for a correlation between perceived and physical complexity in a large sample of odorous stimuli. That is, researchers have not conducted anything analogous to Kermen et al.'s (2007) study of monomolecular complexity (but using mixtures of unfamiliar odorants instead).

Currently, therefore, there is no good reason to believe that physical/chemical complexity (in terms of the number of component volatile aromatic stimuli) is what people mean when they talk about complexity in the chemical senses. So, one can ask instead, what *might* people have in mind when referring to *perceived* complexity (no matter what its relation to physical complexity turns out to be)? Is it the number of elements that can be perceived/individuated and the relation between them that matters? Wendy Parr and her colleagues have conducted a number of intriguing studies that are relevant to answering these questions. They argue for a very different notion of complexity, as least in the minds of western wine experts (see Parr, 2015; see also Smith, 2014). We return to a fuller discussion of these studies below.

3. What might 'perceived complexity' refer to in the chemical senses?

There would seem to be several possibilities here as to what is meant when talking about 'perceived complexity' as far as the chemical senses are concerned:

3.1. Perceived complexity in number of senses involved

A simple sense in which researchers discuss flavour complexity is in terms of the multiple senses that are constitutively involved in giving rise to flavour percepts, not to mention the other product-intrinsic sensory cues, such as colour, that can modulate the ensuing flavour experience (e.g., Mroczko-Wąsowicz, 2016; Smith, 2012; Spence, Smith, & Auvray, 2015). However, while this interpretation of complexity in flavour is entirely sensible, it is not one that we wish to spend any time discussing here. It is, after all, clearly the case that more senses must be stimulated in order to deliver an experience of flavour (incorporating gustation and retronasal olfaction at a bare minimum, and possibly also oral-somatosensory/trigeminal inputs too; see Spence et al., 2015) than the single sense directly targeted by a painting, say, or a piece of music. More importantly, though, people do not seem to have much awareness of the complexity of the various multisensory contributions giving rise to their flavour experiences (see Spence, 2015), and so this cannot work as a satisfactory explanation of perceived complexity.

Instead, below we outline a number of plausible alternatives to what people might have in mind when talking about perceived flavour/food complexity. The focus here will be on the olfactory component, since this makes up the majority of what we experience as the taste (i.e., flavour) of food (Spence, 2015). (Indeed, those working in the flavour industry often

refer to food aromas as flavours for just this reason; see Shankar, Simons, Shiv, Levitan, McClure, & Spence, 2010). Importantly, the various alternatives outlined below should not necessarily be considered as mutually exclusive and, in fact, all might (confusingly) account for some part of what people are referring to when they claim, for example, that tea, say, is more complex than coffee.

3.2. Complexity (in the chemical senses) in the moment

One could perhaps imagine people taking a 'sensory snapshot' of that which they are tasting at a particular moment in time. To the extent that they can pull apart, or attend to, multiple elements in that flavour experience, then they will be more tempted to describe that which they are tasting as 'complex'. Things to consider here, though, when considering this putative account, include the fact that it takes time to shift the focus of one's attention from one element of an olfactory experience to another (cf. Ashkenazi & Marks, 2004; García-Ogueta, 1993; Spence, Kettenmann, Kobal, & McGlone, 2001). That said, it is presumably possible to use the olfactory memory trace, or olfactory mental imagery, to help prolong the sensory component of the snapshot as it were (e.g., Stevenson & Case, 2005).

Additionally, there is also the lingering sense that complexity, as far as the chemical senses are concerned, is something that happens/evolves over time rather than occurring in a moment (see Parr, 2015, on this point). In fact, perhaps this temporal evolution of flavour sensations is important given the limited attentional span 'in the moment'. This is also sometimes referred to as 'the bandwidth problem': Namely, far less neural resources appear to be given over to the processing of the chemical senses than to the higher senses (see also Gallace, Ngo, Sulaitis, & Spence, 2012; though see McGann, 2017). Though note that this limitation does not hinge specifically on one assuming a sensory snapshot view of perceived complexity. In fact, the limited bandwidth of the chemical senses might help to explain people's limited ability to identify anything more than two to three individual components in multi-odour mixtures (Jinks & Laing, 1999, 2001; Laing, Link, Jinks, & Hutchinson, 2002). Importantly, these robust limits in the number of distinct elements that can be individuated have been documented even when a person can identify each element when it is presented in isolation (e.g., Marshall, Laing, Jinks, & Hutchinson, 2006; see also Ferreira, 2012a, b).

3.3. The temporal evolution of chemosensory perception

Another possibility here is that, as far as the chemical senses are concerned, perceived complexity refers to those taste/flavour/aroma experiences, like those associated with coffee and wine, that evolve/change over time (though over what timeframe is a relevant question), possibly as a result of selective adaptation (Frank, Fletcher, & Hettinger, 2017). A couple of empirical approaches to tracking the rise and fall of particular elements within one's tasting experience have emerged from the field of sensory science research. The first, known as

Time-Intensity (TI) analysis, enables the researcher to examine any changes in the intensity of a specific taste/flavour that occur over a specified time period. This technique is often used to analyse flavours in wine (e.g., Goodstein, Bohlscheid, Evans, & Ross, 2014). By contrast, 'the temporal dominance of sensations' approach (or TDS for short) is used by sensory scientists studying the chemical senses in order to track the relative salience of different aspects of the tasting experience as they evolve over time (e.g., see Galmarini, Loiseau, Visalli, & Schlich, 2016; Pineau Schlich, Cordelle, Mathonnière, Issanchou, Imbert, Rogeaux, Etiévant, & Köster, 2003; Reinbach, Toft, & Moller, 2009; Sokolowsky & Fischer, 2012). Normally the time-frame that researchers have their participants evaluate is restricted to a single extended mouthful (see **Figure 4**). Notice also how TDS allows for the serial inspection of multiple distinct elements within the flavour experience by means of attention (see Rabin & Cain, 1989; Smith, 2014).

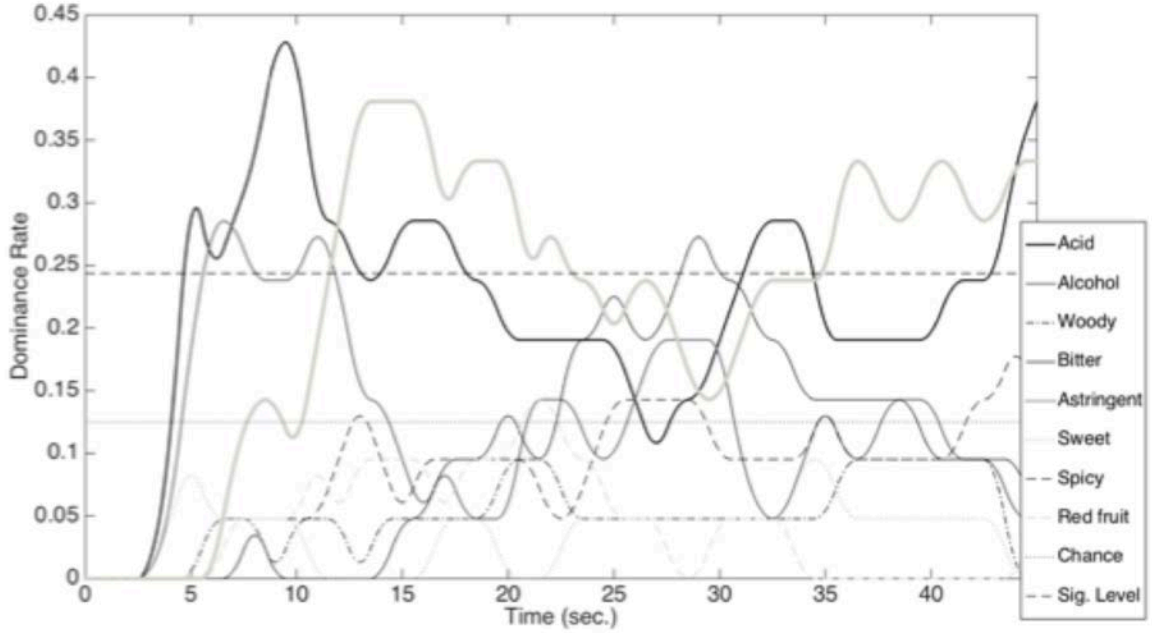

Figure 4. A typical TDS plot showing the temporal evolution of the various flavours in a mouthful of Manos Negras Pinot Noir 2014 held in the mouth for a period of 45 seconds. This plot comes from a study by Wang, Mesz, and Spence (2017) in which the effect of different pieces of music on the various elements in a wine-tasting experience was assessed. [Figure reprinted from Wang et al. (2017).]

The notion of serial exploration of the elements within a stimulus seems to be one that is common to discussions of complexity in the so-called 'higher' senses (e.g., vision, see Berlyne, Ogilve, & Parham, 1968; Blackmore, Brelstaff, Nelson, & Trocsciano, 1995; Wohlwill, 1975; Yarbus, 1967). Here, one might also think of Jakesch and Leder's (2015)

work on complexity in vision, where the idea that ambiguity (of meaning) is an important component of complexity perception is discussed. Is there, one might wonder, an equivalent to this notion in the chemical senses? While the idea of trying to understand complexity in the chemical senses with reference to studies of complexity in the other senses is undoubtedly an appealing notion, it is perhaps worth noting that research by Kreitler, Zigler, and Kreitler (1974) suggests that the notion of complexity may be just as difficult to pin down in vision as it is in the chemical senses! And, regardless of the merits of any such comparative approach to complexity, a fuller discussion of this issue will need to await a fuller treatment of the topic elsewhere. The same lack of space unfortunately also prevents us from considering the relevance of definitions of complexity that are used more broadly by biologists, computer scientists, psychologists, social scientists, etc.

3.4. Interim summary

Given what we have just seen, it would seem plausible that a more complex tasting experience may not only be more complex at any single moment in time (the sensory snapshot idea), but also more complex as the various individual attributes of the experience wax-and-wane over the time period of assessment (whatever that might be). At the same time, however, it is worth stressing that this approach to assessing complexity in the chemical senses requires there to be individuable (thus, measurable) elements within the tasting experience. But is that necessarily always the case? Is it even the way that people do, in fact, talk about the complexity of their own flavour experiences? There are also a number of relevant constraints (both explicit and implicit) concerning the temporal account that are worth mentioning here, and which may question/nuance this particular notion of perceived complexity.

3.5. Over what timeframe are we talking?

One relevant question concerning the temporal evolution account (of perceived flavour complexity) is to specify over what timescale it operates. Are we talking over the duration of a (prolonged) mouthful, over the various sensory snapshots of a trained wine (or tea) taster's experience, say, or over the evolution/lifetime of the product itself? The following quote is interesting in this regard: "*The single greatest standard used in assessing the quality of a wine is complexity. The more times you can return to a glass of wine and find something different in it—in the bouquet, in the taste—the more complex the wine. The very greatest wines are not so much overpowering as they are seemingly limitless.*" (Matt Kramer, *Wine Spectator*, as cited in Crolic & Janiszewski, 2016). Notice here how this notion of perceived complexity emerges as a result of multiple separate independent tasting episodes. The expert taster learns to train their palate and to engage in a sequence of steps when interrogating a quality wine, e.g., first assessing appearance (colour, legs, etc.), then aroma/bouquet, taste, aftertaste, length, etc. (e.g., Fielden, 2009; Smith, 2014). Certain hot beverages also have

their own ceremonies, of course, think only of coffee cupping (Seo, Lee, & Hwang, 2009) and the Chinese/Japanese tea ceremonies (e.g., Anderson, 1991; Okakura, 1989). Note that the Chinese tea ceremony often involves the taster taking a series of different sensory impressions of the tea (e.g., after the first brew, the second, and so on).

However, we can go further and think about the evolution of the product itself over longer periods of time. So, for example, quality wines are often said to benefit from "breathing" – coming into contact with air. They certainly mature/age in the barrel as well as in the bottle (Ribéreau-Gayon, Glories, Maujean, & Dubourdieu, 2006), and they supposedly evolve in the decanter, too (Boulton, Singleton, Bisson, & Kunkee, 1999). And, as if that wasn't enough, they also evolve in the glass (though that change may not be perceptible to the majority of drinkers; see Spence, 2011, for a review). Wine, of course, is not the only product that has these temporally-changing properties. There are a few other foods/chemical sensory stimuli out there that display the same temporally extended development (think, for instance, of what happens when a hot drink cools down, see Cardello & Maller, 1982; Steen, Waehrens, Petersen, Münchow, & Bredie, 2017). The notion of perceived complexity here concerns the evolution of the product over its lifetime. In this sense, then, one could imagine arguing that a quality wine is simply more complex than a cup of quality coffee, since the latter has a much shorter lifetime over which it evolves than does wine.

At this point, though, it may be important to stress that the temporal evolution of the product has in some sense to have been designed. All organic matter will, of course, decay sooner or later. And this natural process will, over time, presumably bring out all manner of 'interesting' flavours. Importantly, however, these transformations are not part of the designed tasting experience. The evolution that takes place in a bottle of fine wine or, say, a wheel of ripening cheese, feels different in this regard in that it has been more-or-less intentionally designed, or controlled (see also Hincks, 2017, on deliberately aged meats). Miller and Harrison (1991, p. 77) similarly note that drying chillies have a much more distinctive taste that their fresh counterparts: *"with flavours that are deep and often quite complex."* Hence, it can perhaps be argued that judgments of the perceived complexity of food/beverage products (such as wine) as they develop/age is relevant only insofar as the changes in the product have been intentionally designed/managed. Such musings, then, can perhaps be taken to hint that part of the complexity in the chemical senses (e.g., in a quality wine) is in the art/science of creation/management of the vines etc. That is, in the case of wine the oenology and viticulture. This is certainly the conclusion that emerges from Wendy Parr's intriguing work with wine experts (see Parr, 2015, for a summary).

4. What role do individual differences play in discerning the complexity in the chemical senses?

Thus far, individual differences in background knowledge/experience have not been considered as far as they impact ratings of complexity. However, it is important to bear in mind that there are various kinds of individual difference that are relevant to any

consideration of perceived complexity in the chemical senses. Cultural differences are clearly going to be relevant here, but we will have to save discussion of this intriguing topic for another day. Now, to the extent that it is the perceived complexity that is important when it comes to talking about the chemical senses, one can ask the question of the role of expertise, either domain-specific (e.g., asking the wine expert about wines) or general (e.g., asking the wine expert about coffee or vice versa) in judgments of complexity. Croijmans and Majid (2016) assessed linguistic description of coffees, wines, and everyday odours by wine experts, coffee experts, and normal observers. Their results provided some limited evidence for a domain-specific benefit in the consistency of descriptions given by the wine experts. It should be noted, however, the wine experts were no better at identifying everyday smells and tastes than were the coffee experts or normal observers.

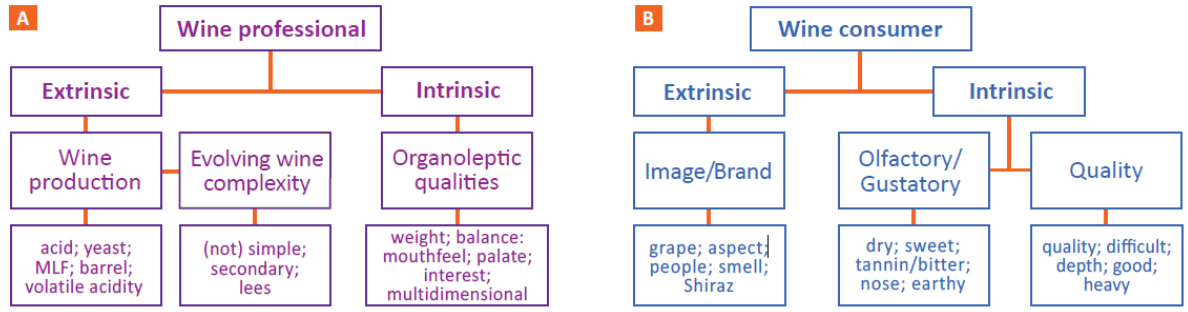

Figure 5. Dimensions of inferred or perceived complexity in wine as a function of wine expertise. MLF = malolactic fermentation. [Figure reprinted from Parr (2015, p. 5) with permission.]

Meanwhile, Wendy Parr and her colleagues interviewed groups of Antipodean wine professionals and consumers regarding their representations of wine complexity in general, and with regard to perceived aging ability in particular (Parr, Mouret, Blackmore, Pelquest-Hunt, & Urdapilleta, 2011). The results revealed that wine novices focused largely on intrinsic factors in their description of complexity. The wine experts, on the other hand, talked of complexity in terms of extrinsic factors such as wine production or terroir (see **Figure 5**). Additionally, the wine experts were able to articulate differences in attributes of complexity between age-worthy white and red wines whereas the wine consumers did not link aging ability with complexity. Interestingly, both groups of individuals equated complexity with wine quality to a certain extent (as hinted at by the quotes in the opening paragraph of this article). Recently, Wang and Spence (2018) assessed the meaning of complexity in wine for a group of 18 social drinkers. Eight wines, chosen to display different aspects of complexity, were presented in flights of three (white), three (red), and two (dessert) wines, respectively. The results showed that complexity is positively correlated with both liking and quality (same as Parr et al., 2011), but not with wine price or the number of perceived flavours. Furthermore, flavours associated with the process of winemaking and ageing (such as smoke and vanilla) were more often used to describe more complex wines. Intriguingly, natural language processing on participants' choice of flavour descriptors

suggested that participants used more consistent vocabulary to describe more complex wines as well as more preferred wines.

Moving on from verbal data to the actual tasting experience, Schlich, Maraboli, Urbano, and Parr (2015) addressed the role of domain-specific expertise in ratings of the perceived complexity of Sauvignon Blanc wines. 13 New Zealand Sauvignon Blanc wines were evaluated by experts (oenologists in this case), connoisseurs (non-professionals with a great deal of experience in wine tasting), and consumers via a free sorting task and a complexity questionnaire. Notably, experts associated complexity with the number of flavours, with harmony, with balance, with the length of finish (duration of aftertaste remaining in the mouth) as well as with familiarity, whereas connoisseurs and consumers correlated complexity with intensity. The evidence collected by Schlich et al. additionally suggested that experts had closer agreement amongst themselves in their evaluation of complexity as compared to either the connoisseurs or the regular wine consumers. However, there was no evidence that perceptual separability enhanced the perception of complexity.

Schlich et al.'s (2015) study should, however, be taken with a grain of salt, given that the French participants who took part did not find any of the New Zealand Sauvignon Blanc wines (which are, after all, known for their simple and approachable styles) to be particularly complex to begin with! To address the potential issue that the wines were simply not complex enough, further research is needed using recognisably complex wines, such as those from classified growths in Burgundy or Bordeaux, in order to establish the robustness of their results. Nevertheless, the key finding to emerge from Parr and colleagues' studies of wine expertise and the perceived complexity of wines is that expertise is an important factor that needs to be considered, since experts appear to have somewhat different notions of complexity than do regular consumers. Even more interestingly, the 'experts' also came to somewhat different conclusions concerning the wines that they would wish to group as being high or low in complexity than the 'connoisseurs', implying that wine expertise is somehow different from wine-tasting experience.

One other way in which individual differences are relevant to the study of complexity in the chemical senses comes from intriguing work by Snitz, Arzi, Jacobson, Secundo, Weissler, and Yablonka (2016). These researchers have proposed a performance-based method of assessing the intricacy of sensory stimuli, one that they claim works for both olfactory and visual stimuli. Specifically, their suggestion is that the degree of variance in people's response to questions about a sensory stimulus provides a measure of intricacy. The notion goes that a less intricate sensory stimulus will engender more consistent ratings across subjects than one that is more intricate. To the extent that sensory intricacy is synonymous with complexity, Snitz et al.'s proposal certainly provides an exciting new way of thinking about the notion of complexity in the chemical senses. That said, it is also worth bearing in mind that the authors themselves conclude that "*the data does not support the hypothesis that there is a connection between measured intricacy and rated complexity*" (Snitz et al., 2016, p. 11). It will be interesting, therefore, to see whether Snitz and colleagues bold suggestion

captures the imagination, and, more importantly, empirical support from other researchers who are interested in the notion of complexity/sensory intricacy.

This discussion of Snitz et al.'s (2016) work also raises another distinction that should perhaps have been made earlier between 'perceptual complexity' and 'perceived complexity'. The former refers to the complexity of the perception which could mean the amount of mental resources utilized to perceive it or the number of biological systems which respond to it etc. (cf. Parr, 2015; Sezille et al., 2016). One might draw an analogy with Snitz et al.'s measure of sensory intricacy. The latter term, 'perceived complexity', might simply be defined by an assessment by tasters of the property of 'complexity', in the same way as they would assess how lemony, smoky, or pleasant the odour is.

5. Conclusions

The topic of complexity as far as the chemical senses is concerned is, as this review has hopefully made clear, itself undoubtedly rather complex (see also Kreitler et al., 1974, on this theme). And, unfortunately, despite the fact that talk of complexity in the literature on the chemical senses is common, it is often unclear what, exactly, is being referred to. This confusion exists despite the fact that many commentators believe complexity to be a desirable characteristic (e.g., in wines) for consumers (Parr, 2015; Singleton & Ough, 1962). As highlighted here, some of those who talk of complexity in relation to the chemical senses would seem to mean little more than that multiple distinct sensory systems contribute to the flavour experience. Indeed, for that very reason, the multisensory perception of flavour can be said to be one of the more complex of the experiences that we have (e.g., Mroczko-Wąsowicz, 2016; Smith, 2012; Spence, 2015; Spence et al., 2015). However, such accounts do not seem to be all that relevant when it comes to thinking about perceived (or inferred) complexity.

Some commentators who talk of complexity in relation to food/drink appear to be referring to the range of components and perhaps their temporal change/evolution. Meanwhile, others use the term when referring to either individual molecules that can be classified as either simple or more complex (Kermen et al., 2011; see also Zarzo, 2011) or to the number of different molecules that are in a foodstuff (some restricting this to the number of volatiles that are either directly perceptible, or else which affect what is detected; Benzi, 2008; Parr, 2015; see also Campbell et al., 1994; Chadwick & Dudley, 1983; Smith et al., 2017). Finally, some authors use the term 'complexity' when describing food/drink that is made up of a large number of components/ingredients (e.g., Adapon, 2008). In this review, we have provided a number of examples to highlight the frequent disconnect between these physical/chemical assessments of complexity and perceived complexity. We stress, therefore, the need to focus on perceived complexity, which is often taken to refer to the number of different individuable elements (or features) in the tasting experience, and/or over the designed lifetime of the product (e.g., in the case of a wine that is designed to age, say).

However, before closing this review, it is important to note that this elemental view of perceived complexity is certainly not the only way in which people discuss the term. Indeed, as noted by Wendy Parr (2015, p. 5), there is also a fundamentally different notion of complexity: *"For example, are wines with many perceivable components the most likely to be considered complex and to challenge us intellectually and sensorially? Or, perhaps the converse, namely that well-integrated and seamless wines appear more complex?"* Parr (2015, p. 6) continues: *"Complex may be a single perception while being a multi-dimensional term."* In fact, some researchers have suggested that complexity in flavour perception, when it links to a single unitary experience (of complexity), relates to the notion of configural processing (Jinks & Laing, 2001; Parr, 2015; Smith, 2014). Returning to the theme of aging Singleton and Ough (1962, p. 189) noted more than half a century ago that aging often leads to the emergence of complexity: *"In wines, flavour complexity is considered very important to high quality and is believed to be one of the primary effects produced by proper aging."* Here, though, the complexity may be perceived in a moment in a well-aged wine, rather than necessarily resulting from an extended assessment of the wine across the lifetime of the product. Configural processing refers to the emergent whole, or property, resulting from the simultaneous processing of a number of distinct features that somehow belong together (e.g., see Maurer, Le Grand, & Mondloch, 2002; Piepers & Robbins, 2012). Proponents of the configural view (of perceived flavour complexity) would have us believe that complexity can be ascribed to a unitary flavour percept (one that is not necessarily decomposable into its component parts). According to the latter account, individual elements in the tasting experience are grouped together into a singular configural impression as a result of gestalt grouping. There is a great deal of evidence supporting the view that complex patterns can be turned into simple ones through the proper organization into chunks (Kreitler, 1965, cited in Kreitler et al., 1974; Miller, 1956).

However, to our way of thinking, there is an important difference here between a unitary percept in the chemical senses that one wishes to describe as 'complex' and the prototypical notion of configural processing, e.g., as discussed in the literature on face/object perception. In the latter cases, the observer does indeed identify the configuration of features as a specific individual, say, in the case of face perception. At the same time, however, they are also able to attend to the individual features (e.g., the colour of the eyes, the size of the nose etc.; see Piepers & Robbins, 2012). Given that while people, especially the experts, might identify the configuration of multisensory features presented by a particular wine as a specific vintage etc., they do not necessarily have the ability to perceptually identify all that many of the individual elements in the bouquet (though, that doesn't mean they can't infer/imagine their presence given what else they know about a wine; see Smith, 2008). As such, it does not seem to us so clear that the configural account really works as an explanation. Thus, while we are happy to acknowledge the intuitive appeal of the configural account of flavour complexity, and while we also accept the suggestion that judgments of complexity may emerge from a single unitary flavour experience, we believe that another account is needed to explain what, exactly, is going on, and how, and why, one unitary flavour experience may be judged as more complex than another (cf. Snitz et al., 2016). Perhaps it is more appropriate to talk of inferred complexity rather than necessarily perceived complexity, given the differing

perceptual attributes (not to mention inferential processing) that would seem to underlie such judgments.

Finally, one can ask the question of whether it is ever possible to answer the question of whether there is more flavour complexity in one drink versus another, say, coffee vs. wine? Can we make any meaningful relative judgments on this score? Given what we have just seen, if what is meant is that elemental complexity is higher for one drink that the other, then this could potentially be assessed meaningfully using TI or TDS type techniques (Wang et al., 2017). However, if the complexity of the drink is experienced rather as a unitary flavour experience (one that may not be individuable into its component elements) then perhaps we must defer to subjective report. That is, if someone says that it feels like the unitary flavour experience associated with coffee is just more complex than the unitary flavour experience associated with tea then we may have to accept that judgment at face value – it may not, in other words, be amenable to scientific assessment. The situation, of course, will become even more challenging to resolve if one drink is experienced in terms of elemental complexity whereas the other gives rise to a unitary perception of complexity (the latter situation is presumably a bit like comparing apples and oranges). Or perhaps, in the future, researchers may find a way of assessing Parr's (2015, p. 5) suggestion that it is the ability of a flavour experience derived from our exposure to the chemical senses to evoke "cerebral (cognitive) and sensorial responses" that is what leads us to consider it as 'complex' rather than 'simple' (cf. Sezille et al., 2014, on the differing patterns of brain activity seen in response to simple vs. complex volatile aromatic molecules). In the meantime, however, it would be interesting to see what answer Snitz et al.'s (2016) performance-based measure of sensory intricacy, would give, and whether they would agree with the judgment of either regular consumers or experts.

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REFERENCES

Adapon, J. (2008). *Culinary art and anthropology*. Oxford, UK: Berg.

Aduriz, A. L. (2014). *Mugaritz: A natural science of cooking*. New York, NY: Phaidon.

Anderson, J. (1991). *An introduction to Japanese tea ritual*. Albany, NY: State University of New York Press.

Anon. (n.d.). Citrus, rose and lavender – nature-identical fragrances from the chemical laboratory: Small difference, big effect: How BASF's raw material citral becomes an enchanting bouquet of fragrances. https://www.basf.com/us/en/company/news-and-media/science-around-us/citrus--rose-and-lavender--nature-identical-fragrances-from-the-nature.html.

Ashkenazi, A., & Marks, L. E. (2004). Effect of endogenous attention on detection of weak gustatory and olfactory flavors. *Perception & Psychophysics*, **66**, 596-608.

Benzi, F. (2008). The flavourist. In H. Blumenthal, *The big Fat Duck cookbook* (pp. 476-478). London, UK: Bloomsbury.

Berlyne, D. E., Ogilve, J. C., & Parham, L. C. C. (1968). The dimensionality of visual complexity, interestingness, and pleasingness. *Canadian Journal of Psychology*, **22**, 376-387.

Blackmore, S. J., Brelstaff, G., Nelson, K., & Trocsciano, T. (1995). Is the richness of our visual world an illusion? Transaccadic memory for complex scenes. *Perception*, **24**, 1075-1081.

Boulton, R. B., Singleton, V. L., Bisson, L. F., & Kunkee, R. E. (1999). *The maturation and aging of wines. From principles and practices of winemaking* (pp 382-426). New York, NY: Springer-Verlag Media.

Campbell, E. J. M., Campbell, D. M. E., & Roberts, R. S. (1994). Ability to distinguish whisky (uisge beatha) from brandy (cognac). *BMJ*, **309**, 1686-1688.

Cardello, A., & Maller, O. (1982). Acceptability of water, selected beverages and foods as a function of serving temperature. *Journal of Food Science*, **47**, 1549-1552.

Chadwick, S., & Dudley, H. (1983). Can malt whiskey be discriminated from blended whisky? The proof. A modification of Sir Ronald Fisher's hypothetical tea tasting experiment. *British Medical Journal*, **287**, 1912-1915.

Chartier, F. (2012). *Taste buds and molecules: The art and science of food, wine, and flavor* (translated by Levi Reiss). Hoboken, NJ: John Wiley and Sons.

Clarke, R. J. (2013). *Coffee volume 1 chemistry*. New York, NY: Springer.

Croijmans, I., & Majid, A. (2016). Not all flavor expertise is equal: The language of wine and coffee experts. *PLOS ONE*, **11(6)**:e0155845. https://doi.org/10.1371/journal.pone.0155845

Crolic, C., & Janiszewski, C. (2016). Hedonic escalation: When food just tastes better and better. *Journal of Consumer Research*, **43**, 388-406.

Deroy, O., Spence, C., & Noppeney, U. (2016). Causal metacognition: Monitoring uncertainty about the causal structure of the world. *Trends in Cognitive Sciences*, **20**, 736-747.

Ferreira, V. (2012a). Revisiting psychophysical work on the quantitative and qualitative odour properties of simple odour mixtures: A flavour chemistry view. Part 1. Intensity and detectability. A review. *Flavour and Fragrance Journal*, **27(2)**, 124-140.

Ferreira, V. (2012b). Revisiting psychophysical work on the quantitative and qualitative odour properties of simple odour mixtures: a flavour chemistry view. Part 2. Qualitative aspects. A review. *Flavour and Fragrance Journal*, **27(3)**, 201-215.

Fielden, C. (2009). *Exploring the world of wines and spirits*. London, UK: Wine & Spirit Education Trust.

699 Frank, M. E., Fletcher, D. B., & Hettinger, T. P. (2017). Recognition of the component odors
700 in mixtures. *Chemical Senses*, **42**, 537-546.

701 Freides, D. (1974). Human information processing and sensory modality: Cross-modal
702 functions, information complexity, memory, and deficit. *Psychological Bulletin*, **81**, 284-310.

703 Gallace, A., Ngo, M. K., Sulaitis, J., & Spence, C. (2012). Multisensory presence in virtual
704 reality: Possibilities & limitations. In G. Ghinea, F. Andres, & S. Gulliver (Eds.), *Multiple*
705 *sensorial media advances and applications: New developments in MulSeMedia* (pp. 1-40).
706 Hershey, PA: IGI Global.

707 Galmarini, M. V., Loiseau, A.-L., Visalli, M., & Schlich, P. (2016). Use of multi-intake
708 Temporal Dominance of Sensations (TDS) to evaluate the influence of cheese on wine
709 perception. *Journal of Food Science*, **81**, S2566-S2577.

710 García-Ogueta, M. I. G. (1993). Internal attentional switching: Effects of predictability,
711 complexity and practice. *Acta Psychologica*, **83**, 13-32.

712 Gill, V. (2008). A whisky tour-is this the most chemically complicated drink in the world?
713 Victoria Gill attempts to unlock some of the mysteries of scotch malt whisky. *Chemistry*
714 *World UK*, **5**, 40-44.

715 Goodstein, E. S., Bohlscheid, J. C., Evans, M., & Ross, C. F. (2014). Perception of flavor
716 finish in model white wine: A time-intensity study. *Food Quality and Preference*, **36**, 50-60.

717 Grabenhorst, F., Rolls, E. T., & Margot, C. (2011). A hedonically complex odor mixture
718 produces an attentional capture effect in the brain. *NeuroImage*, **55**, 832-843.

719 Harrington, R. J., & Hammond, R. (2005). The direct effects of wine and cheese
720 characteristics on perceived match. *Journal of Foodservice Business Research*, **8**, 37-54.

721 Hendrickson, J. B., Huang, P., & Toczko, A. G. (1987). Molecular complexity: A simplified
722 formula adapted to individual atoms. *Journal of Chemical Information and Modeling*, **27**, 63-
723 67.

724 Hincks, J. (2017). This is how it feels to eat 13-year-old steak. *Time*, **August 30th**.
725 http://time.com/4859696/aged-steak-beef-alexandre-polmard/.

726 Jain, A., Rakhi, N. K., & Baglerb, G. (2015). *Spices form the basis of food pairing in Indian*
727 *cuisine*. http://arxiv.org/ftp/arxiv/papers/1502/1502.03815.pdf.

728 Jakesch, M., & Leder, H. (2015). The qualitative side of complexity: Testing effects of
729 ambiguity on complexity judgments. *Psychology of Aesthetics, Creativity, and the Arts*, **9(3)**,
730 200-205.

731 Jinks, A., & Laing, D. G. (1999). Temporal processing reveals a mechanism for limiting the
732 capacity of humans to analyze mixtures. *Cognitive Brain Research*, **8**, 311-325.

733 Jinks, A., & Laing, D. (2001). The analysis of odor mixtures by humans: Evidence for a
734 configurational process. *Physiology & Behavior*, **72**, 51-63.

735 Kermen, F., Chakirian, A., Sezille, C., Joussain P., Le Goff, G., Ziessel, A., Chastrette, M.,
736 Mandairon, N., Didier, A., Rouby, C., & Bensafi, M. (2011). Molecular complexity
737 determines the number odour notes and the pleasantness of smells. *Scientific Reports*, **1**:206.

738 Kew, W., Goodall, I., Clarke, D., & Uhrín, D. (2017). Chemical diversity and complexity of
739 Scotch whisky as revealed by high-resolution mass spectrometry. *Journal of the American*
740 *Society of Mass Spectrometry*, **28**, 200-213.

741 Khan, R. M., Luk, C.-H., Flinker, A., Aggarwal, A., Lapid, H., Haddad, R., & Sobel, N.
742 (2007). Predicting odor pleasantness from odorant structure: Pleasantness as a reflection of
743 the physical world. *Journal of Neuroscience*, **27**, 10015-10023.

744 Kreitler, S. (1965). *Symbolschopfung und Symbolerfassung: Eine*
745 *experimentalpsychologische Studie*. Basel: Reinhardt.

746 Kreitler, S., Zigler, E., & Kreitler, H. (1974). The complexity of complexity. *Human*
747 *Development*, **17**, 54-73.

748 Laing, D. G., Cain, W. S., McBride, R. L., & Ache, B. W. (Eds.). (1989). *Perception of*
749 *complex smells and tastes*. San Diego, CA: Academic Press.

750 Laing, D. G., Link, C., Jinks, A., & Hutchinson, I. (2002). The limited capacity of humans to
751 identify the components of taste mixtures and taste–odor mixtures. *Perception*, **31**, 617-635.

752 Maarse, H. (Ed.). (1983). *Volatile compounds in food. Quantitative Data, Vol. 2* (Division for
753 Nutrition and Food Research, TNO-CIVO Food Analysis Institute, Zeist, The Netherlands,).

754 Marshall, K., Laing, D. G., Jinks, A. L., & Hutchinson, I. (2006). The capacity of humans to
755 identify components in complex odor-taste mixtures. *Chemical Senses*, **31**, 539-545.

756 Martin, D. (2007). *Évolution*. Lausanne: Editions Favre.

757 Maurer, D., Le Grand, R., & Mondloch, C. J. (2002). The many faces of configural
758 processing. *Trends in Cognitive Sciences*, **6**, 255-260.

759 McGann, J. P. (2017). Poor human olfaction is a 19th-century myth. *Science*, **356**:eaam7263.

760 Mendel Maraboli, M. (2011). *Perception de la qualité du vin par les consommateurs*
761 [Perception of wine quality by consumers]. PhD thesis. University of Burgundy, Dijon,
762 France.

763 Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our
764 capacity for processing information. *Psychological Review*, **63**, 81-97.

765 Miller, M., & Harrisson, J. (1991). *The great chile book*. Berkeley, CA: Ten Speed Press.

766 Mroczko-Wąsowicz, A. (2016). The unity and complexity of flavour perception:
767 Multisensory phenomenology and processing in human-food interactions. *MHFI'16*,
768 November 16th. Tokyo, Japan.

769 Okakura, K. (1989). *The book of tea*. London, UK: Kodansha International.

770 Parr, W. V. (2015). Unraveling the nature of perceived complexity in wine. *Practical Winery*
771 *& Vineyard*, **January**, 5-8.

772 Parr, W. V., Mouret, M., Blackmore, S., Pelquest-Hunt, T., & Urdapilleta, I. (2011).
773 Representation of complexity in wine: Influence of expertise. *Food Quality & Preference*, **22**,
774 647-660.

775 Passmore, N. (2015). Six great wines to pair with sushi. *Forbes*, **August 6th**.
776 https://www.forbes.com/sites/nickpassmore/2015/08/06/six-great-wines-to-pair-with-
777 sushi/#51d67abc655b.

778 Paulsen, M. T., Rognsa, G. H., & Hersleth, M. (2015). Consumer perception of food-
779 beverage pairings: The influence of unity in variety and balance. *International Journal of*
780 *Gastronomy and Food Science*, **2**, 83-92.

781 Piepers, D. W., & Robbins, R. A. (2012). A review and clarification of the terms "holistic,"
782 "configural," and "relational" in the face perception literature. *Frontiers in Psychology*, **3**:
783 559.

784 Pineau, N., Schlich, P., Cordelle, S., Mathonnière, C., Issanchou, S., Imbert, A., Rogeaux,
785 M., Etiévant, P., & Köster, E. (2009). Temporal dominance of sensations: Construction of the
786 TDS curves and comparison with time-intensity. *Food Quality and Preference*, **20**, 450-455.

787 Prescott, J. (1999). Flavour as a psychological construct: Implications for perceiving and
788 measuring the sensory qualities of foods. *Food Quality and Preference*, **10**, 349-356.

789 Rabin, M. D., & Cain, W. S. (1989). Attention and learning in the perception of odor
790 mixtures. In D. G. Laing, W. S., Cain, R. L. McBride, & B. W. Ache (Eds.), *Perception of*
791 *complex smells and tastes* (pp. 173-188). Sydney, Australia: Academic Press.

792 Rapp, A. (1990). Natural flavours of wine: Correlation between instrumental analysis and
793 sensory perception. *Fresenius' Journal of Analytical Chemistry*, **337**, 777-785.

794 Reinbach, H. C., Toft, M., & Moller, P. (2009). Relationship between oral burn and
795 temperature in chili spiced pork patties evaluated by time–intensity. *Food Quality &*
796 *Preference*, **1**, 42-49.

797 Ribéreau-Gayon, P., Glories, Y., A. Maujean, A., & Dubourdieu, D. (2006). Aging red wines
798 in vat and barrel: Phenomena occurring during aging. In *Handbook of enology: The chemistry*
799 *of wine stabilization and treatments*, Volume 2, 2nd Ed., Chichester, UK: John Wiley &
800 Sons.

801 Rudel, R. G., & Teuber, H.-L. (1975). Comment on "Human information processing and
802 sensory modality: Cross-modal functions, information complexity, memory, and deficit".
803 *Psychological Bulletin*, **82**, 947.

804 Schlich, P., Maraboli, M., Urbano, C., & Parr, W. V. (2015). Perceived complexity in
805 Sauvignon blanc wines: Influence of domain-specific expertise. *Australian Journal of Grape*
806 *and Wine Research*, **21**, 168-178.

807 Sezille, C., Ferdenzi, C., Chakirian, A., Fournel, A., Thevenet, M., Gerber, J., Hummel, T.,
808 Bensafi, M. (2014). Dissociated neural representations induced by complex and simple
809 odorant molecules. *Neuroscience*, **287**, 27-31.

810 Shankar, M., Simons, C., Shiv, B., Levitan, C., McClure, S., & Spence, C. (2010). An
811 expectations-based approach to explaining the influence of color on odor identification: The
812 influence of degree of discrepancy. *Attention, Perception, & Psychophysics*, **72**, 1981-1993.

813 Shepherd, G. M. (2012). *Neurogastronomy: How the brain creates flavor and why it matters*.
814 New York, NY: Columbia University Press.

815 Shogren, E. (2012). Thank the simple wasp for that complex glass of wine. *The Salt (NPR)*,
816 **August 31st**. http://www.npr.org/sections/thesalt/2012/08/02/157606554/thank-the-simple-
817 wasp-for-that-complex-glass-of-wine.

818 Singleton, V. L., & Ough, C. S. (1962). Complexity of flavour and blending of wines.
819 *Journal of Food Science*, **27**, 189-196.

820 Small, D. M. (2012). Flavor is in the brain. *Physiology and Behavior*, **107**, 540-552.

821 Smith, B. C. (2008). Is a sip worth a thousand words? *The World of Fine Wine*, **21**, 114-119.

822 Smith, B. (2012). Perspective: Complexities of flavour. *Nature*, **486**, S6.

Smith, B. (2014). Complexity and blending in wine. *Proceedings of Wine Active Compounds 2014* (Ed.) R. Gourgeon. Omiplura Press.

Smith, B. (2017). Beyond liking: The true taste of a wine. *The World of Fine Wine*, **58**, 138-147

Smith, B. C., Sester, C., Ballester, J., & Deroy, O. (2017). The perceptual categorisation of blended and single malt Scotch whiskies. *Flavour*, **6**:5.

Snitz, K., Arzi, A., Jacobson, M., Secundo, L., Weissler, K., & Yablonka, A. (2016). A cross modal performance-based measure of sensory stimuli intricacy. *PLoS ONE*, **11(2)**: e0147449. doi:10.1371/journal.pone.0147449

Sokolowsky, M., & Fischer, U. (2012). Evaluation of bitterness in white wine applying descriptive analysis, time-intensity analysis, and temporal dominance of sensations analysis. *Analytica Chimica Acta*, **732**, 46-52.

Spence, C. (2011). Crystal clear or gobbletigook? *The World of Fine Wine*, **33**, 96-101.

Spence, C. (2015). Just how much of what we taste derives from the sense of smell? *Flavour*, **4**:30.

Spence, C., Kettenmann, B., Kobal, G., & McGlone, F. P. (2001). Attention to olfaction: A psychophysical investigation. *Experimental Brain Research*, **138**, 432-437.

Spence, C., Smith, B., & Auvray, M. (2015). Confusing tastes and flavours. In D. Stokes, M. Matthen, & S. Biggs (Eds.), *Perception and its modalities* (pp. 247-274). Oxford, UK: Oxford University Press.

Spence, C., Wang, (Q.) J., & Youssef, J. (2017). Pairing flavours and the temporal order of tasting. *Flavour*, **6**:4. DOI 10.1186/s13411-017-0053-0 http://rdcu.be/pStQ

Steen, I., Waehrens, S. S., Petersen, M. A., Münchow, M., & Bredie, W. L. (2017). Influence of serving temperature on flavour perception and release of Bourbon Caturra Coffee. *Food Chemistry*, **219**, 61-68.

Stevenson, R. J., & Case, T. I. (2005). Olfactory imagery: A review. *Psychonomic Bulletin & Review*, **12**, 244-264.

Strother, L., & Kubovy, M. (2003). Perceived complexity and the grouping effect in band patterns. *Acta Psychologica*, **114**, 229-244.

Tao, Y. S., & Li, H. (2009). Active volatiles of cabernet sauvignon wine from Changli county. *Natural Science*, **1**, 176-182.

Thorngate, J. H., III (1997). The physiology of human sensory responses to wine – A review. *American Journal of Enology & Viticulture*, **48**, 271-279.

Wang, Q. (J.), Mesz, B., & Spence C. (2017). Analysing the impact of music on wine perception via TDS and TI. Poster presented at the *12th Pangborn Sensory Science Symposium*, 20-24th August, Providence, Rhode Island, USA.

Wang, Q. (J.), & Spence, C. (2018). Wine complexity: An empirical illustration. *Food Quality & Preference*, **68**, 238-244.

Weiss, T., Snitz, K., Yablonka, A., Khan, R. M., Gafsou, D., Schneidman, E., & Sobel, N. (2012). Perceptual convergence of multi-component mixtures in olfaction implies an olfactory white. *Proceedings of the National Academy of Sciences of the USA*, **109**, 19959-19964.

Wohlwill, J. F. (1975). Children's voluntary exploration and preference for tactually presented nonsense shapes differing in complexity. *Journal of Experimental Child Psychology*, **20**, 159-167.

Yarbus, A. L. (1967). Eye movements during perception of complex objects. In L. A. Riggs (Ed.), *Eye movements and vision* (pp. 171-196). New York, NY: Plenum Press.

Yeshurun, Y., & Sobel, N. (2010). An odor is not worth a thousand words: From multidimensional odors to unidimensional odor objects. *Annual Review of Psychology*, **61**, 219-241.

Zarzo, M. (2011). Hedonic judgments of chemical compounds are correlated with molecular size. *Sensors*, **11**, 3667-3686. doi:10.3390/s110403667