RUNNING HEAD: LOOKING FOR THE COMPLEXITY IN WINE

What does the term 'complexity' mean in the world of wine?

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ABSTRACT

Many people talk admiringly about the complexity of wine. However, it is often unclear what exactly they have in mind when using the term. In this review, we summarize why the appealing notion of chemical complexity is presumably not what is being referred to. Instead, we argue that a more plausible explanation is in terms of perceived complexity. It would appear that some writers use the term ‘complex’ on tasting a wine that exhibits a number of distinct, yet harmoniously-balanced, elements that may be experienced over the course of a single prolonged mouthful, over a glass, or over the lifetime of the wine as it ages in the bottle. However, another use of the term that has emerged from studies conducted on both experts and social wine drinkers relates to a single unitary perceptual experience of complexity. Perhaps, though, the latter account is better described as *inferred* rather than directly perceived complexity. Ultimately, according to the evidence that has been published to date, it would appear that different groups of consumers use the term ‘complexity’ consistently while, at the same time, describing something different in, or about, the wine. We focus, in particular, on differences in the usage of the term between wine experts and social wine drinkers.

KEYWORDS: COMPLEXITY; WINE; PERCEIVED; INFERRED; CHEMICAL.

Introduction

'Complexity' is a term that is often used to describe a quality wine. Given that the term is nearly always used as a positive descriptor,[1] it should come as little surprise to find that wine makers (for instance, some of those making New Zealand Sauvignon Blanc wines; see Parr, 2015) are apparently deliberately trying to make their wines more complex in the belief that they will find a market amongst a more-or-less discerning wine clientele. But what, exactly, are people referring to when they say this or that wine is *'complex'*? Is this, perhaps, a term like *'minerality'* that, if it has any meaning at all in the world of wine, turns out to mean different things to different interested parties (e.g., Evans, 2014; Heymann, Hopfer, & Bershaw, 2014; Maltman, 2013; Parr, Ballester, Peyron, Grose, & Valentin, 2015; Rodrigues, Sáenz-Navajas, Franco-Luesma, Valentin, Fernández-Zurbano, Ferreira, De La Fuente Blanco, & Ballester, 2017)? In this review, we assess various meanings that the term might have, including chemical complexity, perceived complexity, and inferred complexity. We also look at the question of how 'stimulus intricacy' (Snitz, Arzi, Jacobson, Secundo, Weissler, & Yablonka, 2016) relates to complexity, and at how neural measures relate to judgments of complexity in the chemical and other senses. At the end, we return briefly to highlighting the similarity between the use of the terms complexity and minerality in the world of wine. We also assess the different meanings given to the term complexity by expert and social drinkers.[2]

At the outset here, it is important to stress that while the focus of this review is squarely on complexity as it relates to wine, the conclusions likely also apply to any other flavourful substrate (such as specialty coffee or whisky). However, wine provides an excellent stimulus to focus on, given that it tends to attract far more research interest than pretty much any other food or beverage product.

Chemical complexity

One appealing way of grounding talk of complexity in the world of wine is to link it to the number of different volatile aromatic compounds that are present in the drink (cf. Jellinek &

[1] Going back more than half a century, for instance, 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 Palczak, Blumenthal, Rogeaux, & Delarue, 2019; Smith, 2014, on this theme).

[2] It is interesting here to consider Wittgenstein's (1953) pragmatic constitutive perspective, according to which rather than lexical/dictionary definitions, the most appropriate means of establishing the meaning of a term may be through word games and/or an analysis of actual language usage.

Köster, 1979, for a similar notion from the world of perfumery). This suggestion is based on the assumption that it is in the orthonasal and retronasal aromas where most of the information concerning the bouquet and flavour of a wine is to be found (see Spence, 2015, for a review). This, after all, would seem to be the way in which many use the term, as when arguing that wine and specialty coffee are more chemically complex than most other beverages. For instance, according to representative estimates, a quality wine will contain somewhere in the region of 600-1,000 volatile compounds (e.g., Rapp, 1990; Tao & Li, 2009), while there are something like 1,200 volatile compounds in specialty coffee (e.g., Clarke, 2013). Compare these figures to the mere 137 natural volatile compounds that one finds in apple juice (Maarse, 1983). Hence, if it were chemical complexity, or at least *this* version of chemical complexity,[3] that people had in mind, one would have to say that specialty coffee is more complex than wine, and that both drinks are much more complex than fruit juice. While the latter suggestion would seem to be relatively uncontroversial, the suspicion is that many in the world of wine would want to argue that a quality wine is actually *more* complex even than specialty coffee.

Appealing though this physical interpretation of complexity is, grounded as it is in the objectively measurable chemical properties of a liquid itself,[4] it is important to note that it has been estimated that no more than 30-40 of those many volatiles that are detectable in a drink (e.g., using variants of mass spectrometry; cf. Kew, Goodall, Clarke, & Uhrín, 2017) likely contribute to the aroma of the drink that is perceived (see Benzi, 2008). What is more, it is important to stress that there is certainly no one-to-one mapping between the number of volatiles contributing to the perceptual experience that is associated with a drink and the number of distinct elements that a taster can discern in the mix (Margot, 2009; cf. Jellinek & Köster, 1979). After all, complex combinations of many tens or even hundreds of different volatile organic molecules often give rise to a unitary perceptual experience, as when we describe an aroma by saying *'It smells like a rose'* (Sell, 2006; Yeshurun & Sobel, 2010). On the other hand, there are also certain volatile compounds that, even when presented in

[3] Note that, separately, researchers also talk about, and have objective measures for, the complexity of monomolecular odorants (e.g., Hendrickson, Huang, & Toczko, 1987). Furthermore, Kermen et al. (2011) have demonstrated that the chemical complexity of monomolecular odorants exhibits a logarithmic relationship with the average number of olfactory notes that are perceived/reported. See also Khan et al. (2007) and Zarzo et al. (2011), for evidence of a relationship between the molecular size of chemical compounds and ratings of hedonic pleasantness. Note, however, that none of these measures are directly applicable to the evaluation of wine, given that the latter always contain many hundreds of different volatile aromatic molecules, or at least they will if one isn't drinking one of Hervé This's 'note-by-note cuisine' wine creations (see Ashley, 2013; This, 2012, 2013).

[4] It is, in passing here, perhaps also worth noting that the equivalent attempt to detect minerals in those wines that some writers have been tempted to describe as expressing minerality has also failed (see Maltman, 2013).

isolation (i.e., as monomolecular odorants), can give rise to multiple odour descriptors (see Spence & Wang, 2018).[5]

Are blends perceived to be any more complex than their components?

Wang and Spence (submitted b) recently conducted a study inspired by the classic research of Singleton and Ough (1962). The latter evaluated people's quality ratings for 29 pairs of California wines and their blends. The surprising result to emerge from this early study was that the blends of two structurally similar single varietal wines led, in blind tasting, to a wine that was rated as being at least as high in quality as the average of the component wines, and often better than the best of the individual wines.[6] The authors posited that the higher quality ratings might have been due to increased perceived complexity in the blended wines, although this assertion was not specifically tested in the study. We therefore decided to repeat Singleton and Ough's approach, using three wines from the Dr. Frank winery based in the Finger Lakes region of upper New York State. In total, 87 tasters comprising a wide range of expertise[7] were given six wines to taste blind, the three single varietals (*Cabernet Sauvignon*, *Merlot*, and *Cabernet Franc*), and their three binary combinations. The participants were asked to describe the flavour of the wine and rate its quality and complexity, before eventually being asked to try and pick the blends from the single varietals. The idea here being that the mixture of any two wines must be, by definition, more chemically complex than either of the component wines. Intriguingly, however, the blends were not perceived as any more complex than the single varietal wines when tasted blind (see **Figure 1**). What is more, the wine experts were unable to discern the more chemically complex blends from the

[5] What would be ideal to know here, though what has not, at least not as far as we are aware been tested, is whether there is any meaningful relationship between the number of volatile olfactory compounds in a mixture and the average number of olfactory notes that people report. Were such a relationship to be obtained, perhaps similar to that described by Kermen et al. (2011) in relation to the complexity of monomolecular odorants, then it might suggest that the counterexamples mentioned in the text here are nothing more than idiosyncratic exceptions to the general rule. The work of Ferreira (2012a, b) perhaps comes closest to what we are after in terms of deconstructing a wine (i.e., by removing compounds), leaving just the non-volatile matrix, followed by the reintroduction of individual compounds with the aim of discovering the perceptual effect of the latter.

[6] It has been suggested by some (Karen McNeil, MW, *pers. comm*., March, 2018) that this result may say as much about the state of Californian wine-making, still in its infancy back then, as anything about blending and complexity *per se*.

[7] Out of 87 participants, 41 were wine novices (who identified most with the statement "I drink socially but don't know much about wine"), 30 were intermediates (who identified most with the statement "I know which wines I like and have been to some tastings"), and 16 were experts (who identified most with the statement "I have Wine and Spirits Education Trust (WSET) level 3 or higher certification or I regularly attend blind tastings").

single varietals, with the latter guessing “yes it’s a blend” 40% of the time for both the blended and single varietal wines.

Here it is worth noting that the failure to discriminate 50-50 blends from single varietal wines is consistent with a similar inability to discriminate between single malts and blended whiskies (Chadwick & Dudley, 1983; Smith, Sester, Ballester, & Deroy, 2017).[8] What such results, both in the worlds of wine and whisky, would appear to imply is that chemical complexity is certainly not what people are latching onto when they talk about a wine as complex.

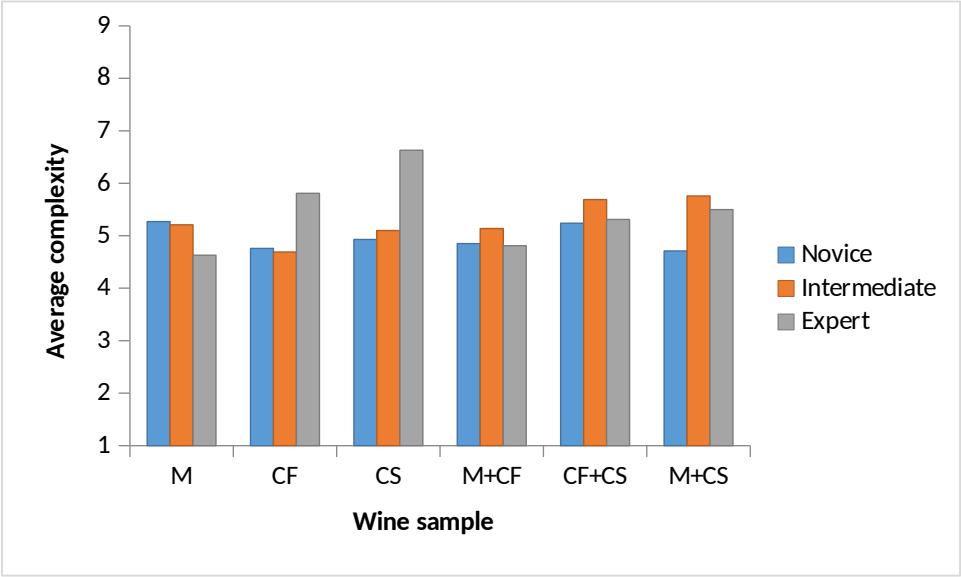


Figure 1. Average complexity ratings (on a 9-point scale) for the six wine samples tested by Wang and Spence (submitted b). M = Merlot, CF = Cabernet Franc, CS = Cabernet Sauvignon. All wines were from the 2015 vintage, from Dr Frank Winery. Error bars indicate standard error.

Neuronal measures of complexity in the chemical senses

Here it is perhaps also worth considering whether, rather than looking for some relatively objective physical measure of complexity in the chemical composition of the wine itself, one might look at the other end of the processing stream. That is, one might want to know something about what complex wines might be doing to the brain of the taster.[9] Are there any

[8] In fact, according to the evidence, many people may not even be able to distinguish whisky from brandy (cognac; Campbell, Campbell, & Roberts, 1994).

[9] There is an analogy here, of course, with the on-going debate about whether flavours reside in the food, or in the brain (see Prescott, 1999; Shepherd, 2012; Small, 2012; Smith, 2017).

physiological correlates of complexity in the world of wine? Along similar lines, in an early paper on complexity in the world of fragrance, one of the definitions of complexity that was put forward by Jellinek and Köster (1979) referred to physiological complexity, corresponding to the number of receptors that are stimulated by an odour. One might imagine that those wines whose complexity emerges from the time-evolving perception of multiple balanced/harmonized elements in the tasting experience would give rise to more neuronal activity than is seen when tasting a simpler wine where presumably there is just less going on to grab/hold our attention (see Grabenhorst, Rolls, & Margot, 2011; Schlich et al., 2015). As a point of reference here, neuroimaging studies have already demonstrated that complexity in the audiovisual realm is represented in early and associative sensory areas, such as the parahippocampal place for visual scenes, and the posterior regions of superior temporal gyrus and sulcus for complexity in language and music (Gücçlütürk, Güçlü, van Gerven, & van Lier, 2018).

The notion that complex wines might evoke more physiological/neural activity is certainly not a new idea. Indeed, the idea has been hinted at previously by a number of commentators. Take, for example, Duccio Cavalieri, a professor of microbiology at the University of Florence in Italy, who believes that the complexity of a wine is mirrored in the network of brain activation that results on tasting it: *"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 has also been suggested 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"."* An intriguing neuroimaging study reported by Sezille, Ferdenzi, Chakirian, Fournel, Thevenet, Gerber, Hummel, and Bensafi (2014) has, in fact, provided some initial support for the notion that experiences in the chemical senses that people find complex (in the sense of comprising multiple perceptible elements) do have a certain neural correlate/signature. Using functional Magnetic Resonance Imaging (fMRI), these cognitive neuroscientists were able to demonstrate that more complex odorant molecules give rise to a more distributed network of neural activation. In particular, activity in the anterior cingulate appeared to correlate with molecular complexity. That is, 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.

Sezille et al.'s (2014) intriguing results therefore provide a potential bridge between a certain kind of chemically-measurable complexity and how complexity is actually experienced in the brain. That said, one might also wonder whether the increased neural activation seen in the anterior cingulate might indicate increased conflict between different possible olfactory descriptors for what is being experienced, rather than necessarily an increase in perceived complexity (as in the number of distinct olfactory components that a person is aware of). As we have seen already, more complex odour molecules typically give rise to a greater number of odour descriptors (Kermen et al., 2011). And, there is presumably more chance for conflict concerning the identity of what exactly one is smelling/tasting when there are more alternative competitors to be discriminated between. Indeed, it has been suggested previously, at least according to certain authors, that complexity in the chemical senses might well be related to the difficulty in identifying or discriminating the elements (e.g., Porcherot & Issanchou, 1998; Ruijschop, Boelrijk, Burgering, de Graaf, & Westerterp-Plantenga, 2009). As a practical example, both Sauvignon Blanc and Albariño wines can exhibit a floral sweet smell that may be interpreted as white peach (in the case of Albariño) or fresh grass (in the case of Sauvignon Blanc). As a blind wine taster, it can be difficult to decipher what exactly one is smelling, without using other supporting information from the wine (e.g., the presence of oak-related aromas would indicate Sauvignon Blanc, which would then lead the taster to infer that they were smelling grass rather than peach). Or to take another example, Araujo, Rolls, Velazco, Margot, and Cayeaux (2005) have demonstrated that the same odour (isovaleric acid with cheddar cheese flavor) as much more unpleasant when it was labeled as "body odor" than when it is labeled as "parmesan cheese". In this case, the ambiguity in smell might stem from the fact that the same bacteria that is used to ripen many cheeses also lives on the human skin. The results showed that contextual information was used by the participants to resolve the ambiguity in olfactory identification.

Perceived complexity: Does the term refer to the same thing in the different senses?

While the *chemical* complexity of a drink can, in some sense at least, be measured objectively, its relation to *perceived* complexity is far from clear (see also Palczak et al., 2019). Assuming, therefore, that what those in the world of fine wine who use the term 'complexity' are really referring to is the *perceived*, rather than the *chemical*, variety, one can ask what kinds of perceptual experiences are liable to give rise to such a description.[10] One intuitive way to think about this, by analogy with talk of complexity in the other senses, such as, for example, vision or audition (e.g., Donderi, 2006; Freides, 1974; Marin & Leder, 2013), is that those stimuli having more discrete perceptual components present in the experience are those that will be more likely to be described as complex. The seminal early work of Berlyne on the notion of complexity in the field of visual aesthetics is worth mentioning here (as highlighted by Palczak et al., 2019). For instance, Berlyne (1960 pp. 38-39) argued that aesthetic complexity follows three rules: (1) 'Other things being equal, complexity increases with the number of distinguishable elements'; (2) 'If the number of elements is held constant, complexity increases with dissimilarity between elements'; and (3) 'Complexity varies inversely with the degree to which several elements are responded to as a unit.'

As far as the chemical senses are concerned, it should, however, be noted that people can only identify a very limited number of elements of multi-odour/tastant mixtures, even if they are familiar with all of the individual components when presented in isolation. In fact, according to the psychophysicists, this limit is at three elements at most (see Jinks & Laing, 1999, 2001; Laing, 1991; Laing, Link, Jinks, & Hutchinson, 2002; Lawless, 1999; Marshall, Laing, Jinks, & Hutchinson, 2006; see also Ferreira, 2012a, b).[11] As such, it is more likely to be the number of discrete elements that are experienced over a more *prolonged* tasting experience that elicits the use of the term complexity here (cf. Jellinek & Köster, 1979, for a similar multiple perceived element view from the world of fragrance research).

What is also relevant to any discussion of the meaning(s) of the term perceived complexity, as it applies to the different senses, is the fact that the bandwidth of the chemical senses is far lower than that seen for the so-called 'higher' spatial senses (see Gallace, Ngo, Sulaitis, &

[10] In fact, when a writer really wants to refer to the chemical complexity they often seem to preface the term 'complexity', with the term 'chemical' (e.g., see Gill, 2008; Thorngate, 1997, for a couple of representative examples), as if implying that whenever the term complexity is used normally, it is indeed being used to refer to something other than chemical complexity.

[11] It is important to bear in mind here that in Laing's experiments, he would give a single odour stimulus to the judges, so that the sniffer could, in fact, have only a single sniff. Under such conditions, the amount of information that can be processed is understandably quite limited.

Spence, 2012). Such physiological/information-processing constraints mean that while multiple stimuli can be perceived/maintained in awareness simultaneously in the 'higher' senses of vision and audition, complexity, at least when the term is used to refer to multiple elements, is more likely to play out sequentially in the 'lower' senses of touch, taste, and smell. Relevant here, one might consider the temporally evolving complexity in wine – think only of the bouquet/aroma, followed, on tasting by the attack, mid-palate, and finish (see Todd, 2018).

At the same time, however, it should perhaps also be noted that the traditional pejorative view of the fundamentally limited nature of human olfaction has, in recent years, seen a radical re-evaluation. It turns out that human olfaction is a far more discriminating sense than many scientists had given credit for (see McGann, 2014, for a thorough reappraisal of this much maligned sense). As just one example of this changing perspective, note only how the historical claim that people could discriminate a maximum of no more than 10,000 odours has recently been revised to a theoretical maximum of one trillion (Bushdid, Magnasco, Vosshall, & Keller, 2014). At the same time, however, it should also not be forgotten that in their early work, Engen and Pfaffmann (1959) found that, when it came to odour intensity, the estimated channel capacity of 1.5 bits/stimulus implied that humans, on average, could accurately identify only about three levels of odour intensity, compared to seven or more for other sensory modalities (Lawless, 1999).

To the extent that what people are referring to when talking about complexity in the chemical senses is *perceived* complexity, one might hope that the notion ought to bear some meaningful relation to the way in which people talk about the perceived complexity of visual, auditory, and/or tactile stimuli. One objective measure of the complexity of visual and auditory stimuli that has been proposed is in terms of the compression ratio (e.g., Marin & Leder, 2013; see also Henriques, Gonçalves, Antunes, Matias, Bernardes, & Costa-Santos, 2013). Indeed, computer scientists have, for a number of years, been interested in trying to develop objective methods to classify the complexity of visual images (e.g., see Corchs, Ciocca, Bricolo, & Gasparini, 2016). However, at least to our way of thinking, it is difficult to see how such a metric could be directly applied to the world of wine. Perhaps there would be some meaningful measure of the compressibility of the read-out from the mass spectrometer that might provide an interesting starting point (subject to the limitations highlighted earlier). Though again, perhaps such an approach is less likely to succeed given that the majority of information that is specified in jpegs and MP3 files etc. presumably

relates to the perceptible components of the image or sound file, so specified. By contrast, the mass-spectroscopy read-out just provides a direct description of what is present in the stimulus itself, and hence is much further removed from defining the minimum requirements needed to recreate the odour percept (as opposed to the odour stimulus).

An intriguing alternative approach, however, to measuring complexity that has emerged from the world of visual aesthetics research is to think of visual complexity in terms of the amount and variety of elements, the way these elements are organised, and in terms of asymmetry (e.g., Nadal, Munar, Marty, & Cela-Conde, 2010). It is certainly easier to see how this kind of approach could be translated into the world of wine, e.g., in terms of the number and variety of elements. Meanwhile, one could perhaps relate the notion of asymmetry to balance, or the lack thereof, in wine. One might also consider whether this could include asymmetry in the sensations associated with attach, mid-palate, and finish of a wine, say. The literature on visual aesthetics has embraced the connection between perceived complexity and hedonic value (Berlyne, 1970; Casti & Kariqvist, 2003), suggesting the existence of an inverted U-shaped function linking complexity and hedonic valence, with maximum pleasantness lying somewhere between too little and too much complexity (Berlyne, 1970; see also Mielby, Kildegaard, Gabrielsen, Edelenbos, & Thybo, 2012). It would, therefore, be interesting to test whether this relationship also holds true to the world of wine, where complexity is seen to be a monotonically increasing positive trait (Parr, 2015; Schlich et al., 2015; Wang & Spence, 2018).

The question which nobody has so far addressed is, can too much complexity in wine be a bad thing? Visual complexity, note, has always been thought of as a ‘collative’ property, meaning that it is influenced by the prior experiences of the viewer (see Cupchik & Berlyne, 1979; Giacalone, Duerlund, Bøegh-Petersen, Bredie, & Frøst, 2014; Palzak et al., 2019). It is something of an open question as to how true this basic claim is (though see Marin, Lampatz, Wandl, & Leder, 2016, for recent supportive evidence), and to the extent that it does apply in the world of visual aesthetic appreciation. Separately, there is a question as to whether it also applies to the world of wine too. Here it is worth noting that it is always possible that the stimuli that happen to have been chosen for evaluation (e.g., the wines studied by Wang & Spence, 2018, for instance), might end-up falling near the top of the inverted U-shape curve, where differences in hedonic response are likely to be slight, hence resulting in a “flat” function (Giacalone et al., 2014).

On the temporal evolution of complexity in wine

Given the bandwidth limitations on information-processing in the chemical senses, it makes little sense to try and limit the perception of complexity to the number of distinguishable elements in a mouthful of wine (at a given moment in time; see Spence & Wang, 2018, on this 'snapshot' view of complexity). Instead, one might legitimately want to consider how the taster's experience changes as a wine evolves in the glass or decanter. One might, of course, even want to extend the relevant timeframe here and consider how the wine ages in the bottle over some quite considerable period of time (e.g., Ribéreau-Gayon, Glories, Maujean, & Dubourdieu, 2006)

The view that complexity in the chemical senses is, in part, something that often emerges when a product is deliberately aged, fits well with the use of the term that one finds in other domains, such as in those talking about aging meat (Hincks, 2017) or those talking about the complexity that often emerges on drying chiles (Miller & Harrison, 1991, p. 77).[12] It also fits with the widespread belief that aged spirits, like whisky tend to be thought of as more complex than other non-aged spirits such as gin. Note that while the latter may well comprise many tens of exotic botanicals, hence presumably being really rather chemically complex, it is not a product that is typically aged (see Spence, 2018).

Indeed, it is presumably *only* when this more temporally prolonged notion of tasting is considered that quality wines start to distinguish themselves as perhaps being much more complex than other drinks such as, for instance specialty coffee. For while the latter may indeed be more chemically complex than wine, at least in terms of the number of volatiles that are present (which, as we have seen already, is not the same as the number of volatiles that will be detectable by the taster, nor even contribute directly to the tasting experience), it can be argued that there is far less development of the flavour profile in the cup (of coffee; see Dugas, Pineau, & Folmer, 2012). Furthermore, the notion of aging the beans, or the coffee itself, will likely only lead to a degradation/loss of flavour, and not to the emergence of additional layers of complexity (or at least of development) as one hopes to see in the case of wine.

[12] There may also be a link back to Berlyne's (1960) ideas here, given that the flavours that ageing delivers are usually so distinct from the flavours that we associate with the fresh products/ingredients themselves.

Here it is interesting to note that those sensory analysis techniques such as the Temporal Dominance of Sensations (TDS), or Time-Intensity analysis (TI), that are designed to capture the complex evolution of tasting experiences over time, have proved capable of capturing the dynamic interaction of many flavours over even just a prolonged mouthful of wine (e.g., see Wang, Mesz, & Spence, 2017; see also Galmarini, Loiseau, Visalli, & Schlich, 2016; Meillon, Viala, Medel, Urbano, Guillot, & Schlich, 2010; Pineau, Schlich, Cordelle, Mathonnière, Issanchou, Imbert, Rogeaux, Etiévant, & Köster, 2009). The temporal evolution approach has, it is worth noting, also been applied successfully to a number of other complex food experiences (e.g., Larsen, Tang, Ferguson, & James, 2016; Tang, Larsen, Ferguson, & James, 2016, 2017). In the future, it would therefore be interesting to compare how this temporally-evolving complexity in a mouthful, glass, or even a bottle of wine compares to what one sees in a mouthful of coffee, in a cafetiere, or over the life of a bag of coffee beans (see also Wen, Lopez, & Ferreira, 2018)? One of the ways in which wine may be qualitatively different from coffee relates to the fact that the alcohol in wine tends to provide a particularly effective vehicle for the capture and delivery of different olfactants (Voilley & Lubbers, 1998). Given the neuronal measures we proposed earlier, it may also be worth considering whether such a temporally-evolving sequence of sensations might also be associated with a distinctive neural profile. One interesting point here concerns the experience of complexity in the moment, versus the inference of complexity when reflecting back on a tasting experience. Another important point is that it is not only how much but also the stage at which the sensory experience is experienced as complex. Relevant here to judgments of complexity may therefore be the character of the odorants' temporal evolution rather than merely their number, assuming they tend to happen to have similar temporal properties.

Two other terms that often crop up in informal discussion with wine experts who favour the multiple perceptible elements view of complexity in the chemical senses are *balance* and *harmony* (e.g., Medel, Viala, Meillon, Urbano, & Schlich, 2009; Schlich, Maraboli, Urabano, & Parr, 2015).[13] Note here that balance, at least according to the Wines and Spirits Education Trust (WSET), refers to whether the structural elements, sugar, alcohol, and fruitiness on the one hand versus acidity and tannins on the other are balanced. A wine that is particularly high or low in the first group needs to be balanced by something equally high or low in the second group. Harmony, by contrast, is thought to refer to whether the non-structural (i.e. flavourful)

[13] Note that the notion of unity in variety – and balance, also crops up in the world of food-beverage pairing (see Paulsen, Rognsa, & Hersleth, 2015).

elements go well together. If a complex wine has many flavours (e.g., honeysuckle, rose, lychee, and apricot in a Gewürztraminer), are they all in harmony? Perhaps, then, this idea of harmony is what is needed if one wants to use the term 'perceived complexity' as a *positive* descriptor of a given quality wine.

Different views on perceived complexity

Wendy Parr and her colleagues have provided some intriguing insights into complexity in the world of wine (e.g., Parr, 2015; Parr, Mouret, Blackmore, Pelquest-Hunt, & Urdapilleta, 2011). These researchers have conducted research highlighting the different ways in which wine experts and social drinkers use the term 'complexity' when describing wine. Importantly, it would appear that different groups of individuals use the same term quite differently. Social drinkers, for instance, tend to associate complexity with a wine's image/brand as well as how much they like the wine. Here, it should also be borne in mind that non-experts might be using the term 'complex' to describe a wine when they cannot find any other term to describe their experience (see also Tempere, Hamtat, de Revel, & Sicard, 2016, on expert vs. non-expert differences in olfactory identification). Experts, by contrast, are apparently more likely to use the same descriptor in relation to inferred methods of viticulture and wine production. Furthermore, Schlich et al. (2015) conducted a study with French wine professionals and consumers that revealed that while wine experts associated complexity with the number of flavours, with harmony, with balance, with the length of finish (duration of aftertaste remaining in the mouth), and with familiarity; connoisseurs and consumers correlated complexity with intensity instead. The ease of identifying individual flavours, however, turned out surprisingly not to be correlated with perceived complexity.

Such findings led Wendy Parr and her colleagues to conclude that sometimes complexity might actually be a descriptor that is associated with a unitary sensation (imagine the seamless stony/saline/citrus flavour of a *Grand Cru Chablis*; Robinson & Harding, 2015). It is at this point, when trying to explain how a single percept could be described as complex, that Parr and others tend to invoke the notion of *configural processing* (Jinks & Laing, 2001; Parr, 2015; Romagny, Coureaud, & Thomas-Danguin, 2018; Smith, 2014). The idea behind the latter term is that we are aware of the whole (e.g., that the face that I am looking at is of my wife Barbara), while at the same time also being able to individuate the elements (such as the colour of her eyes, the size and shape of her nose, and so on; see Maurer, Le Grand, &

Mondloch, 2002; Piepers & Robbins, 2012). In other words, a single percept/descriptor identifying a person actually contains within it many more granular details (or elements) held together as a configural whole.[14] This, at least, is the notion of configural processing that emerges from the visual literature.

However, while it is certainly true that configural information processing occurs in many situations (e.g., with the prototypical example being facial recognition), to our way of thinking, this approach does not necessarily seem like the best way in which to describe the unitary percepts that give rise to judgments of complexity in the world of wine. The reason being that while people might identify the configuration of aromas/flavours presented by a wine as complex, that does not necessarily seem to mean that they have the ability to clearly identify all of the individual elements in the bouquet or on the palate (Laing, 1991; Laing et al., 2002) in the way that the configural account, at least as taken from the literature on visual perception, would seem to imply. Just imagine the seamless stony/saline/citrus flavour of a *Grand Cru Chablis* (Robinson & Harding, 2015) mentioned earlier. It isn't clear that this unitary 'complex' flavour, what some refer to as "oyster-shell-like", can be broken down into multiple distinguishable elements. That said, a closer reading of both Jinks and Laing (2001, p. 61) and Parr (2015, p. 7, column 3, final paragraph) would seem to suggest that they agree. Namely, when they use the term 'configural', they do not wish to suggest that each of the elements contributing to the unitary percept can necessarily always be identified individually by the perceiver. (Note that while allowing this for binary and ternary mixtures, Jinks and Laing argue for an indivisible unitary percept for quaternary and more complex odour mixtures.) As such, the latter's use of the term configural might unfortunately be adding confusion to discussion in this area (at least to those who are more familiar with the frequent use of the term 'configural' in vision research).

Rather, there would appear to be a sense in which the presence of a certain aroma or flavour – perhaps one derived from winemaking or ageing (e.g., yoghurt or leather), rather than from the primary flavours stemming from the grape itself – which allows the knowledgeable taster to *infer* some of what must have taken place in order to create that particular attribute in the wine. The use of the term complexity then, in this use of the term, would seem to shift the focus away from a description of the end perceptual experience associated with the sensory experience on tasting the wine itself. Instead, the term is used more to acknowledge the

[14] Here, one can also think of this in relation to the notion of chunking (Kreitler, 1965, cited in Kreitler, Zigler, & Kreitler, 1974; Miller, 1956).

complex processes that went into delivering a particular aroma or flavour in the wine (Parr et al., 2011; cf. Adapon, 2008, for a similar notion of complexity from the world of Mexican cuisine). It is in this sense, therefore, that the notion of *inferred* complexity starts to sound increasingly appealing. One might, then, want to contrast this with the directly perceived complexity that is apparent in wines whose multiple elements reveal themselves over time. Both versions of complexity would *a priori* seem to constitute equally legitimate uses of the term 'complexity'. Here, it is important to stress that we take Parr and colleagues discussion of 'perceived complexity' (see Parr, 2015; Schlich et al., 2015) to be more similar to our notion of 'inferred complexity' than to the notion of 'directly perceived complexity'. This is because while Parr et al. do not explicitly mention inferential processing in their account, they did allow for the possibility of top-down cognitive processing (such as inferential reasoning), especially in the case of wine professionals.

We have also recently conducted an experiment to look at the way in which wine experts and social drinkers think about complexity in the case of wine (see Wang & Spence, 2018, submitted b). In one study, for instance, three flights of wines (eight wines in total, comprising three dry white, three reds, and two sweet dessert wines, chosen to showcase various aspects of complexity) were given to 18 social wine drinkers (17 of whom self-reported a novice level of wine expertise, while the remaining participant claimed an intermediate level of expertise; Wang & Spence, 2018). The participants were tasked with associating the relevant aroma/flavour descriptors to each of the wines, at the various stages of smelling, tasting, and aftertaste.[15] They also rated perceived quality and liking for the wines, and were asked to decide whether they found the wines to be simple or complex, using a 9-point response scale anchored with the descriptors 'Extremely simple' and 'Extremely complex'.[16] Intriguingly, however, and contradicting the suggestions of the directly perceived multi-element view of complexity, the results failed to reveal any correlation between the number of flavour descriptors given to a particular wine by the participants in our study and the attribution of complexity, and least not once liking and quality had been controlled for (see **Figure 2**).

[15] Note that the participants were all provided with an aroma wheel (Noble, Arnold, Masuda, Pecore, Schmidt, & Stern, 1984) to help with the generation of aroma/flavour descriptors. Importantly, however, the social drinkers were not restricted to the use of the terms provided by the aroma wheel.

[16] Though note that some commentators have suggested that the opposite of simple is, in fact, difficult rather than necessarily complex (see Muller, 2004).

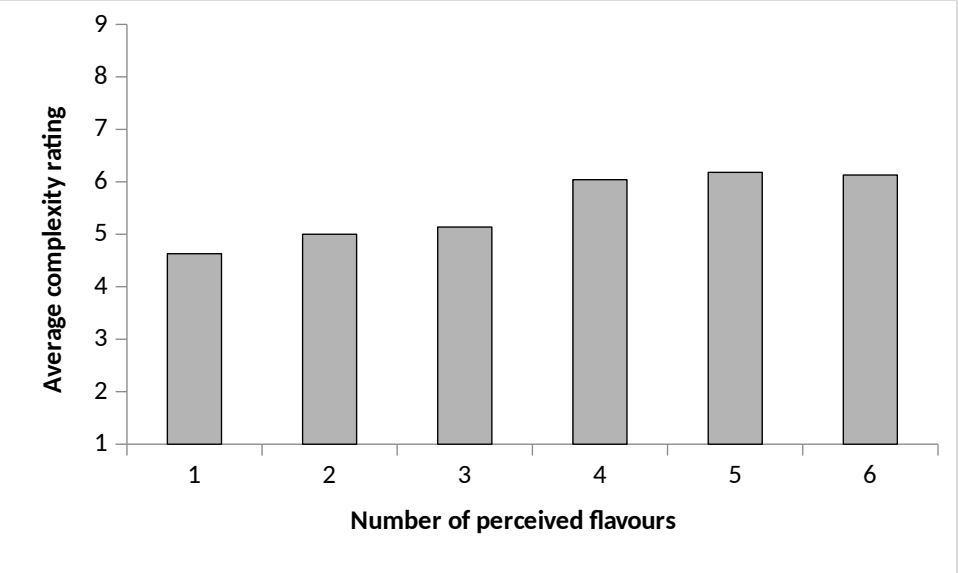


Figure 2. Average complexity rating of wines based on number of flavours perceived by the participants in Wang and Spence (2018). Error bars indicate standard error.

Intriguingly, however, further natural language processing of the social drinkers' responses in Wang and Spence's (2018) study using a Naïve Bayes classifier revealed that, for the three red Bordeaux blends at least, it was those wines that were described by flavours associated with oak ageing (such as 'smoke'), which were more likely to be labelled as complex. Given that oak ageing flavours are usually distinct from the fruity (and sometimes floral/vegetal) primary flavours, this result can be seen as agreeing with Berlyne's (1960) early discussion of complexity, whereby complexity is believed to increase with increasing dissimilarity between the elements. What is also of note, the social drinkers tested in this particular study tended to use more consistent vocabulary to describe those wines that they perceived as being more complex, compared to those other wines that they found relatively more simple stands in direct contrast to Snitz et al.'s (2016) suggestion that increased 'stimulus intricacy' (about which, more below) actually correlates with reduced agreement amongst observers. As we will see below, though, this inconsistency supports Snitz et al.'s further suggestion that stimulus intricacy is, in fact, something quite distinct from stimulus complexity.

Wine education and the meaning of complexity

At this point, one might be asking *"So what, exactly, are wine professionals taught about complexity?"* For a professional trade perspective, one need look only at the Wine and Spirits Education Trust (WSET), a globally accredited provider of education and qualifications in both wine and spirits. According to the WSET, complexity relies on the analysis of the wine's bouquet or aromas. Complexity can either result from fruit character alone – when the flavours span multiple categories such as floral, herbaceous, citrus fruit, stone fruit, etc. – or, in terms of an aged wine, from a combination of primary (fruit-based), secondary (from wine-making), or tertiary (from bottle ageing) aromas (WSET Level 4 Diploma candidate assessment guide). This follows Parr et al.'s (2011) model of complexity, where the wine professional is trained to think about how the flavours are linked to wine production (i.e., yeast, lees, MLF, barrel, volatile acidity) as well as intrinsic qualities in the wine. The fact that the term 'complexity' is so rigorously defined in wine education may, of course, also help to explain why it is that wine experts tend to agree on flavours that they associate with the term.[17] In fact, one benefit of such professional training may stem from the role of dialogue and discussions to build a common vocabulary of technical wine language (see Herdenstam, Hammarén, Ahlström, & Wiktorsson, 2009; Herdenstam, Nilsen, Öström, & Harrington, in press).

Perceived versus imagined/inferred sensory characteristics

One topic that has not yet been brought up in this (or in any previous) discussion of complexity in the world of wine relates to mental imagery. Here, it is important to note that not everything that the wine-taster perceives, or at least imagines that they perceive, in a wine need necessarily be chemically present in the wine (Smith, 2007). So, for example, should an experienced wine-taster know that they are drinking an aged claret, then even before tasting the wine, they may well be expecting to detect notes of blackcurrant, well-hung game, and tobacco. It is possible that not all of these will necessarily be present in the wine. But even if some of them are not, the expectation that they *should* be there, might give rise to a mental impression of those flavour notes in the taster's experience. Could it be that such imagined odours are in some sense actually indistinguishable from the sensorially-induced version of

[17] One of the four possible definitions of complexity that were put forward by Jellinek and Köster (1979) when considering the complexity of a perfume corresponded to the variety of notes created by the perfume, which may be approached with sophistication. This sounds a little like the expert wine-taster's appreciation of the multiple elements in a complex wine.

that percept (Sugiyama, Ayabe-Kanamura, & Kikuchi, 2006; see also Gilbert, Crouch, & Kemp, 1998).[18]

More than a century of experimental psychology has, after all, revealed time-and-again how people sometimes fail to discriminate visual and auditory mental imagery from visual and auditory perception (e.g., Perky, 1910; Segal, 1971). Furthermore, neuroimaging studies have convincingly demonstrated that even reading a taste word such as 'salt' or 'cinnamon' can activate many of the same areas as when the actual taste or aroma is actually experienced in the mouth (see Barrós-Lóscertales et al., 2012; Djordjevic, Zatorre, Petrides, & Jones-Gotman, 2004; González, Barros-Loscertales, Pulvermüller, Meseguer, Sanjuán, Belloch, et al., 2006; see Spence, 2016, for a review). Moreover, it has frequently also been shown that imagined stimuli can interact perceptually with those stimuli that are actually perceived (e.g., Berger & Ehrsson, 2013; Eardley & Pring, 2011; Ishai & Sagi, 1995; Pearson, Clifford, & Tong, 2008). Further complicating matters here is the phenomenon of perceptual filling-in, which has been reported previously in the visual, auditory, and tactile modalities (e.g., Gallace & Spence, 2014; Pessoa & de Weerd, 2003). Given that perceptual filling-in has been reported in the other senses, one might well expect that the same phenomenon would be observed in the chemical senses as well. As an example of olfactory filling-in, just take Laska and Hudson's (1992, p. 411) early demonstration that, in a task in which their participants were asked to discriminate odour mixtures with one component omitted, 20-40% of them thought that the two samples were identical. In other words, they completely missed the fact that one of the odours was missing from the mixture.

Separately, one might also consider to what extent wine tasting, especially in a group setting[19], can be considered shared tasting experiences. In other words, a wine-taster's decision about what a wine tastes like might not depend solely on the activation of their taste buds, their olfactory receptors, and so on. Perhaps social decision-making, which has emerged as a fascinating topic elsewhere in the field of perception research in recent years, shows that two minds really can be better than one (e.g., Trouche, Sander, & Mercier, 2014;

[18] One might also draw an analogy with the memory effect whereby if a list of terms is constructed based on a prototype, but the prototype itself is missing from the list, the majority of people will be convinced that they had heard the prototype when trying to recall the words in the list (see Whittlesea, 2002). Might wine-tasters, on recalling a wine, do something similar?

[19] Although tasting a wine alone while reading the notes of wine critics and, increasingly, fellow wine enthusiasts (e.g. cellartracker.com) can also constitute a shared tasting experience.

see also Valeriani, Cinel, & Poli, 2017). The same presumably might also be true of the world of wine – though we are not aware of anyone having published on this theme as yet.[20]

Brochet and Dubourdieu (2001) proposed their prototype theory, whereby an experienced taster might form an idea of what a wine ought to smell and taste like, based on prior information (such as from visually inspecting the glass or the label), before they even come to tasting the wine itself. Their suggestion was that this prototype might then interfere with the actual perceptual experience of wine tasting. Multiple studies have, for instance, demonstrated that wine tasters, especially experts, tend to fall victim to colour-induced olfactory biases (Morrot, Brochet, & Dubourdieu, 2001; Parr, White, & Heatherbell, 2003).[21] Perhaps most dramatically, a large study (N=168) that we recently conducted at a Wine and Brain Symposium in Barcelona revealed that experienced wine tasters were found to voluntarily assign red fruit aromas and flavours to a white wine that was coloured pink (Wang & Spence, submitted a).

Given all of the above, when an experienced wine-taster is convinced that they can 'perceive' multiple elements leading to the attribution of complexity in a wine, we should perhaps remain open to the possibility that some of what is contributing to their judgment might, in fact, actually be partly imagined mentally, as a function of what they infer, expect, or have read should be there in the wine. Combining the rich time-evolving multisensory perceptual inputs, together with the expected, imagined, and possibly also filled-in aromas/flavours, one can perhaps begin to understand, despite the psychophysical data to the contrary (this is the bandwidth limitation; Gallace et al., 2012), how wine writers like David Schildknecht are able to write 1000+ word tasting notes about a single wine (Smith, 2008).

Complexity vs. Sensory Intricacy

Given the widely-acknowledged difficulties associated with the definition of complexity in the chemical senses, as evidenced here (see also Palczak et al., 2019), not to mention previously documented in the other senses (e.g., see Kreitler, Zigler, & Kreitler, 1974), it is perhaps worth considering whether it might be preferable to use an alternative term to complexity. In this regard, Snitz et al. (2016) talk of 'sensory intricacy' to capture what they

[20] Prof. Barry Smith has been working on the question of whether two tasters combined can do better at guessing vintages of mature Burgundies than guessing separately.

[21] There may also be a fruitful link to the notion of crossmodal mental imagery (Spence & Deroy, 2013).

551 claim to be an objectively measurable stimulus property that operates across more than one
552 sensory modality. At first glance, 'sensory intricacy' might sound as if it were synonymous
553 with sensory complexity. However, the authors themselves are careful to distance their
554 measure from notions of complexity, which their research shows behaves somewhat
555 differently under careful empirical testing conditions. Intriguingly, Snitz et al. found that the
556 objectively measurable degree of disagreement about the most appropriate way in which to
557 categorize an odorous stimulus (in other words, the variance in people's ratings across a
558 number of descriptive scales, such as artificial–natural, or curved–angular) correlates with
559 how intricate they classify that stimulus. What is more, in a separate experiment, Snitz et al.
560 were able to demonstrate that the objectively measurable degree of sensory intricacy, when
561 applied to visual stimulus patterns, predicted the size of the attentional blink, another
562 objective measure of some fundamental aspect of human information processing (e.g.,
563 Raymond, Shapiro, & Arnell, 1992).

564 Would there be benefit, one wonders, in describing a wine as 'intricate'? Might such a
565 description be used to capture the variance that a given wine generates amongst a group of
566 wine tasters, and would such a descriptor carry any more meaning than all the current talk of
567 'complexity'? One of the obvious benefits of using such a descriptor is that it would appear to
568 be objectively quantifiable, in a way that perceived complexity has yet to be, at least as far as
569 the chemical senses are concerned. However, as we have seen already, those wines that the
570 social drinkers classified as 'complex' in Wang and Spence's (2018) recent study were also
571 the wines where there was *more* agreement about the sensory descriptors that captured the
572 wine's aroma/flavour, hence supporting Snitz et al.'s own suggestion that sensory intricacy is
573 something quite distinct from complexity. Relevant here too, both Chollet et al. (2011) and
574 Schlich et al. (2015) also reported greater within-group agreement in complexity ratings
575 amongst domain-experts. Furthermore, it is also easy to imagine how the wine experts would
576 also tend to agree on the judgements of complexity, especially given the well-defined
577 presentation of complexity in wine education mentioned earlier. As such, therefore, there
578 would currently seem to be few robust grounds for replacing the notion of complexity in the
579 chemical senses with discussion of sensory intricacy, intriguing though the latter notion
580 undoubtedly is.

581

582 **Conclusions**

In conclusion, while people, especially wine writers, are often tempted to describe the term a wine as ‘complex’, one would be more than justified in asking quite what is meant by the term. Having ruled out ‘chemical’ complexity as a meaningful physical grounding for the term, there would appear to remain two quite distinct notions of ‘perceived’ complexity. On the one hand, there is the intuitive notion of a wine being described as complex if there is ‘a lot going on’ in it, a lot to individuate and perhaps capture our attention. That said, the timeframe over which complexity is considered is rarely specified. However, given the bandwidth limitations on information processing that have been proposed for the chemical senses, the likelihood would seem to be that one has to be talking about the multiple elements that are available to introspection in a temporally-dynamic flavour profile that one discerns over the course of a glass or bottle, once the latter has been opened and allowed to breathe (see Spence & Wang, 2018). Think here also of attack, mid-palate, and finish. Indeed, this is how the term would appear to be being used by certain wine writers who have appeared in print talking about the complexity of wine (e.g., Kramer, 2012).

Given the oft-highlighted limitations in the ability to identify more than two or three elements in artificially-constructed multi-odour/odour-taste mixtures (see Ferreira, 2012a, b; Jinks & Laing, 1999, 2001; Laing, 1991; Laing et al., 2002; Lawless, 1999; Marshall et al., 2006), the longer timescale would appear to be the more appropriate way in which to think about the perceived complexity of wine-tasting experiences that involve multiple different perceptually identifiable elements. Of course, one might also be talking about the elemental complexity that one finds over the lifetime of a wine as it ages gracefully in the barrel and thereafter in the bottle (Ribéreau-Gayon et al., 2006). There would also seem to be implicit in the use of the descriptor in this sense of the term the suggestion that the elements in the flavour experience were in some sense intentionally designed, rather than reflecting a wholly natural (or, in some sense, arbitrary) process of aging/degradation (see Spence & Wang, 2018).

However, as this review of the literature has hopefully made clear, this is certainly not the only way in which people (both wine experts and social drinkers) talk about perceived complexity. The growing body of laboratory research also makes clear that wine experts and social drinkers (e.g., Parr, 2015; Schlich et al., 2015; Wang & Spence, submitted a) also use the term to describe a certain singular unitary note in a wine. Both uses of the term perceived complexity, complexity in multiplicity of sensations, and complexity in a unitary sensation, would seem, *a priori*, to be equally valid. (Separately, the intriguing suggestion that sensory intricacy might replace complexity has been ruled out as a plausible alternative.) Hence,

perhaps the most appropriate question to ask the next time that someone tells you that a particular wine is 'wonderfully complex' is to ask whether they are referring to complexity in unity or a unity in complexity. And, looking to the future, it will be interesting to assess the extent to which hedonic response and judgments of complexity interact, and whether wine, like the visual arts, confirms to Berlyne's inverted U-shape function between valence and complexity (or arousal).

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REFERENCES

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

Ashley, S. (2013). *Synthetic food: Better cooking through chemistry*. http://www.pbs.org/wgbh/nova/next/physics/synthetic-food-better-cooking-through-chemistry/.

Barrós-Loscertales, A., González, J., Pulvermüller, F., Ventura-Campos, N., Bustamante, J. C., Costumero, V., ... Ávila, C. (2012). Reading salt activates gustatory brain regions: fMRI evidence for semantic grounding in a novel sensory modality. *Cerebral Cortex*, **22**, 2554-2563.

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

Berger, C. C., & Ehrsson, H. H. (2013). Mental imagery changes multisensory perception. *Current Biology*, **23**, 1367-1372.

Berlyne, D. E. (1960). *Conflict, arousal and curiosity*. Martino Fine Books.

Berlyne, D. E. (1970). Novelty, complexity and hedonic value. *Perception & Psychophysics*, **8**, 279-286.

Brochet, F., & Dubourdieu, D. (2001). Wine descriptive language supports cognitive specificity of chemical senses. *Brain and Language*, **77**, 187-196.

Bushdid, C., Magnasco, M. O., Vosshall, L. B., & Keller, A. (2014). Humans can discriminate more than 1 trillion olfactory stimuli. *Science*, **343**, 1370-1372.

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

652 Casti, J., & Karlqvist, A. (2003). *Art and complexity*. Amsterdam, NL: Elsevier.

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

656 Chollet, S., Lelievre, M., Abdi, H., & Valentin, D. (2011) Sort and beer: everything you
657 wanted to know about the sorting task but did not dare to ask. *Food Quality and Preference*
658 **22**, 507-520.

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

660 Corchs, S. E., Ciocca, G., Bricolo, E., & Gasparini, F. (2016). Predicting complexity
661 perception of real world images. *PLoS ONE*, **11(6)**:e0157986.

662 Cupchik, G. C., & Berlyne, D. E. (1979). The perception of collative properties in visual
663 stimuli. *Scandinavian Journal of Psychology* **20**, 93-104.

664 de Araujo, I. E., Rolls, E. T., Velazco, M. I., Margot, C., & Cayeux, I. (2005). Cognitive
665 modulation of olfactory processing. *Neuron*, **46**, 671-679.

666 Donderi, D. C. (2006). Visual complexity: A review. *Psychological Bulletin*, **132**, 73-97.

667 Djordjevic, J., Zatorre, R. J., Petrides, M., & Jones-Gotman, M. (2004). The mind's nose:
668 Effects of odor and visual imagery on odor detection. *Psychological Science*, **15**, 143-148.

669 Dugas, V., Pineau, N., & Folmer, B. (2012). *Evaluating whole cup experience in gourmet*
670 *espresso coffee by using dynamic methods*. Eurosense Symposium.

671 Eardley, A. F., & Pring, L. (2011). Exploring the impact of sucking sweets on flavour
672 imagery. *Journal of Cognitive Psychology*, **23**, 811-817.

673 Engen, T., & Pfaffmann, C. (1959). Absolute judgments of odor intensity. *Journal of*
674 *Experimental Psychology*, **58**, 23-26.

675 Evans, S. J. (2014). Minerality in wine: What does it mean to you? *Decanter*, **December 11th**.
676 https://www.decanter.com/premium/minerality-in-wine-what-does-it-mean-to-you-245668/.

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

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

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

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

689 Gallace, A., & Spence, C. (2014). *In touch with the future: The sense of touch from cognitive*
690 *neuroscience to virtual reality*. Oxford, UK: Oxford University Press.

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

694 Giacalone, D., Duerlund, M., Bøegh-Petersen, J., Bredie, W. L. P., & Frøst, M. B. (2014).
695 Stimulus collative properties and consumers' flavor preferences. *Appetite*, **77**, 20-30.

696 Gilbert, A. N., Crouch, M., & Kemp, S. E. (1998). Olfactory and visual mental imagery.
697 *Journal of Mental Imagery*, **22**, 137-146.

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

701 González, J., Barros-Loscertales, A., Pulvermüller, F., Meseguer, V., Sanjuán, A., Belloch,
702 V., et al. (2006). Reading *cinnamon* activates olfactory brain regions. *NeuroImage*, **32**, 906-
703 912.

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

706 Güccçlütürk, Y., Güçlü, U., van Gerven, M., & van Lier, R. (2018). Representations of
707 naturalistic stimulus complexity in early and associative visual and auditory cortices. *Nature*
708 *Scientific Reports*, **8**:3439.

709 Hendrickson, J. B., Huang, P., & Toczko, A. G. (1987). Molecular complexity: A simplified
710 formula adapted to individual atoms. *Journal of Chemical Information and Modeling*, **27**, 63-
711 67.

712 Henriques, T., Gonçalves, H., Antunes, L., Matias, M., Bernardes, J., & Costa-Santos C.
713 (2013). Entropy and compression: Two measures of complexity. *Journal of Evaluative and*
714 *Clinical Practice*, **19**, 1101-1106.

715 Herdenstam, A. P. F., Hammarén, M., Ahlström, R., & Wiktorsson, P.-A. (2009). The
716 professional language of wine: Perception, training and dialogue. *Journal of Wine*
717 *Research*, **20:1**, 53-84. DOI: 10.1080/09571260902978543

718 Herdenstam, A. P. F., Nilsen, A. N., Öström, Å., & Harrington, R. J. (in press). Sommelier
719 training – Dialogue seminars and repertory grid method in combination as a pedagogical tool.
720 *International Journal of Gastronomy & Food Science*.

721 Heymann, H., Hopfer, H., & Bershaw, D. (2014). An exploration of the perception of
722 minerality in white wines by projective mapping and descriptive analysis. *Journal of Sensory*
723 *Studies*, **29**, 1-13.

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 Ishai, A., & Sagi, D. (1995). Common mechanisms of visual imagery and perception.
727 *Science*, **268(5218)**, 1772-1774.

728 Jellinek, J. S., & Köster, E. P. (1979). Perceived fragrance complexity and its relation to
729 familiarity and pleasantness. *Journal of the Society of Cosmetic Chemists*, **30**, 253-262.

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

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

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

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

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

743 Kramer, M. (2012). How to really taste wine. *Wine Spectator*, **December 18th**.
744 http://www.winespectator.com/webfeature/show/id/47792.

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

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

749 Laing, D. G. (1991). Characteristics of the human sense of smell when processing odor
750 mixtures. In D. G. Laing, R. L. Doty, & W. Breipohl (Eds.), *The human sense of smell* (pp.
751 241-259). Berlin, Germany: Springer-Verlag.

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

754 Larsen, D. S., Tang, J., Ferguson, L. R., & James, B. J. (2016). Increased textural complexity
755 in food enhances satiation. *Appetite*, **105**, 189-194.

756 Laska, M., & Hudson, R. (1992). Ability to discriminate between related odor mixtures.
757 *Chemical Senses*, **17**, 403-415.

758 Lawless, H. T. (1999). Descriptive analysis of complex odors: Reality, model or illusion?
759 *Food Quality and Preference*, **10**, 325-332.

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

762 Maltman, A. (2013). Minerality in wine: A geological perspective. *Journal of Wine Research*,
763 **24**, 169-181. https://doi.org/10.1080/09571264.2013.793176.

764 Margot, C. (2009). A noseful of objects. *Nature Neuroscience*, **12**, 813-814.

765 Marin, M. M., Lampatz, A., Wandl, M., & Leder, H. (2016). Berlyne revisited: Evidence for
766 the multifaceted nature of hedonic tone in the appreciation of paintings and music. *Frontiers*
767 *in Human Neuroscience*, **10**, 1-20.

768 Marin, M. M., & Leder, H. (2013). Examining complexity across domains: Relating
769 subjective and objective measures of affective environmental scenes, paintings and music.
770 *PLoS ONE*, **8(8)**:e72412.

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

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

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

Medel, M., Viala, D., Meillon, S., Urbano, C., & Schlich, P. (2009). *A questionnaire for assessing the perceived complexity of wine. Application to the study of the effect of expertise on perception of wine complexity*. Florence, Italy: 8th Pangborn Sensory Science Symposium.

Meillon, S., Viala, D., Medel, M., Urbano, C., Guillot, G., & Schlich, P. (2010). Impact of partial alcohol reduction in Syrah wine on perceived complexity and temporality of sensations and link with preference. *Food Quality and Preference*, **21**, 732-740.

Mielby, L. H., Kildegaard, H., Gabrielsen, G., Edelenbos, M., & Thybo, A. K. (2012). Adolescent and adult visual preferences for pictures of fruit and vegetable mixes – Effect of complexity. *Food Quality and Preference*, **26**, 188-195.

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

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

Morrot, G., Brochet, F., & Dubourdieu, D. (2001). The color of odors. *Brain and Language*, **79**, 309-320.

Muller, K. (2004). *Prédiction de l'évolution des préférences des consommateurs dans le temps en fonction de facteurs sensoriels et plus particulièrement de la complexité perçue et de la familiarité et de facteurs individuels: application à deux gammes de produits*. Institut national d'agronomie de Paris Grignon.

Nadal, M., Munar, E., Marty, G., & Cela-Conde, C. (2010). Visual complexity and beauty appreciation: Explaining the divergence of results. *Empirical Studies of the Arts*, **28**, 173-191.

Noble, A. C., Arnold, R. A., Masuda, B. M., Pecore, S. D., Schmidt, J. O., & Stern, P. M. (1984). Progress towards a standardized system of wine aroma terminology. *American Journal of Enology and Viticulture*, **35**, 107-109.

Palczak, J., Blumenthal, D., Rogeaux, M., & Delarue, J. (2019). Sensory complexity and its influence on hedonic responses: A systematic review of applications in food and beverages. *Food Quality and Preference*, **71**, 66-75.

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

Parr, W. V., Ballester, J., Peyron, D., Grose, C., & Valentin, D. (2015). Perceived minerality in Sauvignon wines: Influence of culture and perception mode. *Food Quality & Preference*, **41**, 121-132.

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

Parr, W. V., White, K. G., & Heatherbell, D. (2003). The nose knows: Influence of colour on perception of wine aroma. *Journal of Wine Research*, **14**, 79-101.

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

Pearson, J., Clifford, C. W. G., & Tong, F. (2008). The functional impact of mental imagery on conscious perception. *Current Biology*, **18**, 982-986.

Perky, C. W. (1910). An experimental study of imagination. *American Journal of Psychology*, **21**, 422-452.

Pessoa, L., & De Weerd, P. (2003). *Filling-in: From perceptual completion to cortical reorganization.* Oxford, UK: Oxford University Press.

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

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

Porcherot, C., & Issanchou, S. (1998). Dynamics of liking for flavoured crackers: Test of predictive value of a boredom test. *Food Quality and Preference*, **9**, 21-29.

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

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

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception & Psychophysics*, **18**, 849-860.

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

Robinson, J., & Harding, J. (Eds.). (2015). *The Oxford companion to wine* (4th Ed.). Oxford, UK: Oxford University Press.

Rodrigues, H., Sáenz-Navajas, M. P., Franco-Luesma, E., Valentin, D., Fernández-Zurbano, P., Ferreira, V., De La Fuente Blanco, A., & Ballester, J. (2017). Sensory and chemical drivers of wine minerality aroma: An application to Chablis wines. *Food Chemistry*, **230**, 553-562.

Romagny, S., Coureaud, G., & Thomas-Danguin, T. (2018). Key odorants or key associations? Insights into elemental and configural odour processing. *Flavour and Fragrance Journal*, **33**, 97-105.

Ruijschop, R. M. A. J., Boelrijk, A. E. M., Burgering, M. J. M., de Graaf, C., & Westerterp-Plantenga, M. S. (2009). Acute effects of complexity in aroma composition on satiation and food intake. *Chemical Senses*, **35**, 91-100.

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

Segal, S. J. (1971). Processing of the stimulus in imagery and perception. In S. J. Segal (Ed.), *Imagery: Current cognitive approaches*. New York, NY: Academic.

Sell, C. (2006). Structure-odor relationships: On the unpredictability of odor. *Angewandte Chemie International Edition*, **45**, 6254-6261.

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

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

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

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

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

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

Smith, B. C. (2008). Same compounds: Different flavours? In D. Chassagne (Ed.), *Proceedings of Wine active compounds 2008* (pp. 98-102). University of Bourgogne, Oenopluria Media.

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.

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

Spence, C. (2016). The neuroscience of flavor. In B. Piqueras-Fiszman & C. Spence (Eds.), *Multisensory flavor perception: From fundamental neuroscience through to the marketplace* (pp. 235-248). Oxford, UK: Elsevier.

Spence, C. (2018). The complexion of complexity. *Class Magazine*, **Summer**, 72-73.

Spence, C., & Deroy, O. (2013). Crossmodal mental imagery. In S. Lacey & R. Lawson (Eds.), *Multisensory imagery: Theory and applications* (pp. 157-183). New York, NY: Springer.

Spence, C., & Wang, Q. (J.) (2018). On the meaning(s) of complexity in the chemical senses. *Chemical Senses*, **43**, 451-461.

Sugiyama, H., Ayabe-Kanamura, S., & Kikuchi, T. (2006). Are olfactory images sensory in nature? *Perception*, **35**, 1699-1708.

Tang, J., Larsen, D. S., Ferguson, L. R., & James, B. J. (2016). The effect of textural complexity of solid foods on satiation. *Physiology & Behavior*, **163**, 17-24.

Tang, J., Larsen, D. S., Ferguson, L., & James, B. J. (2017). Textural complexity model foods assessed with instrumental and sensory measurements. *Journal of Texture Studies*, **48**, 9-22.

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

Tempere, S., Hamtat, M.-L., de Revel, G., & Sicard, G. (2016). Comparison of the ability of wine experts and novices to identify odorant signals: A new insight in wine expertise. *Australian Journal of Grape & Wine Research*, **22**, 190-196.

This, H. (2012) *La cuisine note à note en 12 questions souriantes* (Note-by-note cuisine in 12 smiling questions). Paris, France: Belin.

This, H. (2013) Molecular gastronomy is a scientific discipline, and note by note cuisine is the next culinary trend *Flavour*, **2**:1.

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

Todd, C. (2018). Tasting in time: The affective and temporal dimensions of flavour perception. *The Monist*, **101**, 277-293.

Trouche, E., Sander, E., & Mercier, H. (2014). Arguments, more than confidence, explain the good performance of reasoning groups. *Journal of Experimental Psychology: General*, **43**, 1958-1971.

Valeriani, D., Cinel, C., & Poli, R. (2017). Group augmentation in realistic visual-search decisions via a hybrid brain-computer interface. *Scientific Reports*, **7**:7772.

Voilley, A. & Lubbers, S. (1998). Flavor-matrix interactions in wine. In A. L. Waterhouse & S. E. Ebeler (Eds.), *Chemistry of wine flavor* (pp. 217-229). American Chemical Society Symposium Series.

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 investigation. *Food Quality and Preference*, **68**, 238-244.

Wang, Q. J., & Spence, C. (submitted a). Drinking through rosé-coloured glasses: Influence of wine colour on the perception of aroma and flavour in wine experts and novices. *Australian Journal of Grape & Wine Research.*

Wang, Q. J., & Spence, C. (submitted b). Is complexity worth paying for? Investigating the perception of wine complexity for single varietal and blended wines in consumers and experts. *Australian Journal of Grape and Wine Research*.

Wen, Y., Lopez, R., & Ferreira, V. (2018). An automated gas chromatographic-mass spectrometric method for the quantitative analysis of the odor-active molecules present in the vapors emanated from wine. *Journal of Chromatography A*, **1534**, 130-138.

Whittlesea, B. W. (2002). False memory and the discrepancy-attribution hypothesis: The prototype-familiarity illusion. *Journal of Experimental Psychology: General*, **131**, 96-115.

Wittgenstein, L. (1953). *Philosophical investigations*. Oxford, UK: Wiley-Blackwell.

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.

938 Zarzo, M. (2011). Hedonic judgments of chemical compounds are correlated with molecular
939 size. *Sensors*, **11**, 3667-3686.