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Abstract: The present study was aimed at increasing the understanding of red wine mouthfeel by investigating the potential cross-modal effect of aroma and establishing relationships between sensory dimensions and chemical measurements. Investigations involved a set of 42 non-wooded red wines that were described with a novel application of rate-all-that-apply sensory methodology by a group of Spanish wine experts under two conditions: 1) with no aroma perception (using nose clips) and 2) with aroma perception. In parallel, ethanol content, pH, titratable acidity, chemical activity, concentration of tannins, and spectroscopic measures of wines were determined. Results suggest that aroma does not play a main effect on taste or mouthfeel perception of red wines, except for oily mouthfeel, which was hypothesised to be masked by earthy aromas and enhanced by alcoholic nuances. Independent and non-correlated mouthfeel dimensions such as dry/silky and sticky, grainy, prickly or oily were also identified. Tannin activity was shown to be highly positively correlated to dry on the palate, and tannin concentration with both overall dry and dry on the palate. A significant partial least squares regression model showed that tannin concentration and activity (positive contribution) as well as pH values (negative) were good predictors of the mouthfeel dimension mainly related to dry and sticky terms.

Highlights

- Aroma does not have a main effect on taste or mouthfeel perception of red wines
- The only effect of aroma was observed for oily mouthfeel
- Oily mouthfeel was masked by earthy aromas and enhanced by alcoholic nuances
- Independent dimensions were related to dry/silky, grainy, prickly and oily
- Tannin concentration and activity and pH drove wine dryness

**Effect of aroma perception on taste and mouthfeel dimensions of red
wines: Correlation of sensory and chemical measurements**

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Abstract

The present study was aimed at increasing the understanding of red wine mouthfeel by investigating the potential cross-modal effect of aroma and establishing relationships between sensory dimensions and chemical measurements. Investigations involved a set of 42 non-wooded red wines that were described with a novel application of rate-all-that-apply sensory methodology by a group of Spanish wine experts under two conditions: 1) with no aroma perception (using nose clips) and 2) with aroma perception. In parallel, ethanol content, pH, titratable acidity, chemical activity, concentration of tannins, and spectroscopic measures of wines were determined. Results suggest that aroma does not play a main effect on taste or mouthfeel perception of red wines, except for oily mouthfeel, which was hypothesised to be masked by earthy aromas and enhanced by alcoholic nuances. Independent and non-correlated mouthfeel dimensions such as dry/silky and sticky, grainy, prickly or oily were also identified. Tannin activity was shown to be highly positively correlated to dry on the palate, and tannin concentration with both overall dry and dry on the palate. A significant partial least squares regression model showed that tannin concentration and activity (positive contribution) as well as pH values (negative) were good predictors of the mouthfeel dimension mainly related to dry and sticky terms.

Keywords: astringency; cross-modal interaction; drying; polyphenol; partial least squares regression; rate-all-that-apply; tannin activity; tannin concentration

1. Introduction

Product flavour is the result of the interaction between sensory modalities including colour, aroma, taste and mouthfeel (Prescott, 2012). In complex systems, the sensation of mouthfeel is overall the least understood, and this is especially true in the case of red wine. Indeed, studies that relate wine appreciation of either experts or consumers with sensory properties tend to be limited to measuring a few mouthfeel-related terms such as overall astringency, hot sensation, body or viscosity (Hopfer & Heymann, 2014; Sáenz-Navajas et al., 2016; Sáenz-Navajas, Ballester, Pêcher, Peyron, & Valentin, 2013), in contrast to the array of aroma terms employed to characterise wines (Noble et al., 1987). However, wine experts, communicators and regular consumers use a wide range of terms related to mouthfeel cues to describe wines, and even relate them to wine judgements (e.g., rough, dry, strong, astringent, harsh, body, hard or tannin) (Gawel, Oberholster, & Francis, 2000; Sáenz-Navajas et al., 2016; Vidal, Giménez, Medina, Boido, & Ares, 2015). This disconnect between scientific literature and popular use of mouthfeel-related terms can be attributed to the fact that the specific compounds driving such properties have not been adequately defined. This generates a situation where there are no appropriate reference materials illustrating the different mouthfeel attributes, which results in the lack of a stable lexicon to characterise the whole continuum of mouthfeel perceptions for red wines.

In the last decades, different authors have worked on developing mouthfeel vocabulary for wines based either exclusively on consumers' memory (Vidal et al., 2015) or on perception (i.e., with product exposure) (Gawel, Iland, & Francis, 2001; Gawel et al., 2000; Kang, Niimi, Muhlack, Smith, & Bastian, 2019; Pickering & Demiglio, 2008; Sáenz-Navajas et al., 2017). The studies involving perception have succeeded in finding mouthfeel differences among wines by both static or dynamic approaches, and acknowledged the fact that astringency and its subqualities change with time (Kang et al., 2019; Watrelot, Heymann, & Waterhouse, 2019). Most of these descriptive works have been carried out by trained participants with the aim of achieving consensus among them by presenting specific reference materials or definitions

1 illustrating each attribute. The fact that the specific molecule or defined group of compounds
2 eliciting mouthfeel-related sensations is still relatively unknown means that the reference
3 materials may in some cases be confusing for panellists. Such confusion can be attributed in
4 part to the fact that some reference standards are multidimensional and elicit more than one
5 sensory property, including different astringent subqualities such as roughing, drying, and
6 constricting or puckering (Kershaw & Running, 2019). For example, alum generates a dryness
7 sensation together with sweet and sour tastes, and proanthocyanidin extracts elicit mouthfeel
8 sensations due to different classes of flavan-3-ols, and have residual aromas, are bitter, and in
9 some cases sour too.

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11 As an alternative to conventional descriptive analysis and to overcome the limitation of the
12 absence of appropriate reference materials, a consumer-based rate-all-that-apply (RATA)
13 methodology has been proposed to describe wines using an expert panel (Sáenz-Navajas et al.,
14 2018; Sáenz-Navajas et al., 2017). Globally, consumer-based methods are not aimed at
15 achieving consensus among participants, and consequently, participants are not trained: it is
16 assumed that they are able to describe and find differences among products (Valentin, Chollet,
17 Lelievre, & Abdi, 2012; Varela & Ares, 2012). RATA in particular has the advantage of
18 requiring a smaller number of panellists compared to other consumer-based approaches such as
19 check-all-that-apply (CATA) – which generates counts rather than rankings or intensities –
20 especially if the panellists are trained or experts (Giacalone & Hedelund, 2016). It works under
21 the assumption that wine experts have constructed a specific prototype-based language to
22 describe wines (Brochet & Dubourdieu, 2001).

23
24 Astringency is an important property of red wine and is arguably the most studied mouthfeel
25 attribute (Cheynier et al., 2006; García-Estévez, Pérez-Gregorio, Soares, Mateus, & De Freitas,
26 2017; Gawel, 1998; Soares, Brandão, Mateus, & de Freitas, 2017). The perceptual phenomenon
27 driving astringent-related mouthfeel is a source of controversy in the scientific literature, but
28 interactions between various phenolics and salivary proteins seem to be the most accepted
29 mechanism (García-Estévez, Ramos-Pineda, & Escribano-Bailón, 2018; Soares et al., 2017). As

an alternative to sensory methods, different chemical measures have been proposed for assessing astringency. These include simple measures such as the classical absorbance at 280 nm or the more recently proposed wavelength at 230 nm (Boulet, Ducasse, & Cheynier, 2017; Boulet et al., 2016), measures based on precipitation with proteins or methylcellulose (Aleixandre-Tudo, Buica, Nieuwoudt, Aleixandre, & Du Toit, 2017), or more sophisticated measurements such as tannin activity based on the enthalpy of interaction between tannins and a hydrophobic surface (Revelette, Barak, & Kennedy, 2014; Sáenz-Navajas et al., 2019). Notwithstanding, the sensory percept of astringency has been reported to be influenced by other wine components such as alcohol, pH or acidity (Fontoin, Saucier, Teissedre, & Glories, 2008), polysaccharides (Watrelet, Schulz, & Kennedy, 2017), polyphenolic profile via interaction with oral components (i.e., saliva, mucosa and oral receptors), and cognitive processing (Canon, Neiers, & Guichard, 2018) through aroma-astringency or taste-astringency interactions (Sáenz-Navajas, Campo, Avizcuri, et al., 2012; Sáenz-Navajas, Campo, Valentin, Fernández-Zurbano, & Ferreira, 2012; Saenz-Navajas, Ferreira, Campo, Fernandez-Zurbano, & Valentin, 2010; Sereni, Osborne, & Tomasino, 2016). However, the effect of aroma on taste or mouthfeel perception has been limited to the study of a reduced number of real wines or the exclusive evaluation of the global term astringency (Arvisenet, Guichard, & Ballester, 2016; de-la-Fuente-Blanco, Fernández-Zurbano, Valentin, Ferreira, & Sáenz-Navajas, 2017; Sáenz-Navajas, Campo, Avizcuri, et al., 2012).

Considering the importance of mouthfeel to red wine quality, the present study aimed to increase the understanding of red wine mouthfeel by exploring the hypotheses that interactions exist between aroma and mouthfeel perceptions and that tannin measures would correlate with mouthfeel characters. Addressing this, the effect of aroma on taste and mouthfeel properties of a set of 42 red young wines was investigated by 18 wine experts who described them by means of a RATA method (Sáenz-Navajas et al., 2017) under two conditions: with and without nose clips. In addition, relationships were assessed between mouthfeel and chemical measures

including activity and concentration of tannins, and spectroscopic measures at both 280 nm and 230 nm.

2. Material and methods

2.1. Wines

A total of 42 non-wooded commercial and non-commercial red wines were selected. Commercial wines were purchased online, and non-commercial (still unblended) wines were provided by wineries. These were monovarietal wines elaborated from one of 14 different varieties, and were of different origins (mainly from Spain, but also from Argentina and France) and vintages. A detailed list of wine characteristics (origin, variety, vintage and conventional oenological parameters) is presented in Table A.1 of Appendix A.

2.2. Sensory analysis

2.2.1. Participants

A volunteer sensory panel was comprised of 18 established winemakers from the Rioja area, Spain (15 women and 3 men, ranging in age from 23 to 54, with an average of 38 years old). They had extended experience in wine production and tasting (average of 13 years) and were considered to be experts according to Parr, Heatherbell, and White (2002).

2.2.2. Procedure

Samples were characterised by rate-all-that-apply (RATA) with a list of 23 taste and mouthfeel-related attributes (Table 1) that were developed previously (Sáenz-Navajas et al., 2017) and another 20 aroma attributes (Table 2) obtained from the literature (Noble et al., 1987; Sáenz-Navajas, Gonzalez-Hernandez, Campo, Fernández-Zurbano, & Ferreira, 2012).

Participants attended four sessions on four different days, either at 12:00 pm or 6:00 pm. Each session was split into two sub-sessions (ca. 40 min each), which were separated by an imposed pause of 20 min. In each sub-session, panellists were presented with 10 or 11 wine samples with a 10-min break every 5 samples. In the first sub-session, nose-clips were employed and only

1 taste and mouthfeel (list of attributes in Table 1) were characterised for the wines. In the second
2 sub-session, orthonasal aroma (list of attributes in Table 2) was evaluated for the same wines as
3 well as taste and mouthfeel attributes.
4

5 All participants evaluated the 42 wine samples. In the first sub-session (with nose clips), they
6 were instructed to take a sip of wine and slightly distribute it all over the mouth cavity,
7 including palate and gums. Then, they had to select a maximum of 5 terms that applied to the
8 sample and rate their intensity on a seven-point scale (1 = not intense; 7 = very intense)
9 according to RATA methodology (Ares et al., 2014; Reinbach, Giacalone, Ribeiro, Bredie, &
10 Frøst, 2014). In the second sub-session, they were instructed to firstly smell samples
11 orthonasally and describe each sample by the RATA method, then proceed as explained above
12 for taste and mouthfeel properties. Terms that did not apply to the sample were allocated a value
13 of zero when collecting data. To avoid bias due to order of presentation, terms in the list
14 appeared in different and randomised order for each assessor.
15

16 Participants tasted samples in a sequential monadic manner and had to follow a sip (rinsing
17 solutions: water and 1 g L⁻¹ pectin solution) and spit protocol between each sample (Colonna,
18 Adams, & Noble, 2004). Twenty-mL samples were poured 30 minutes prior to the session and
19 served in normalised (German Institute for Normalisation, DIN) dark wine glasses (Sensus,
20 Schott Zwiesel, Germany) labelled with random three-digit codes (different for each condition)
21 and covered with plastic Petri dishes. The order of presentation of wines was the same under the
22 two conditions (with and without nose clips) but different for each participant attending to a
23 randomised order. Samples were served at room temperature and evaluated in a ventilated and
24 air-conditioned tasting room at around 20 °C under ambient light. Participants were not
25 informed about the nature of the samples nor the objective of the study.
26

27 *2.3. Chemical analysis*

28 Reducing sugars, ethanol content, pH and titratable acidity were analysed using Fourier
29 Transform infrared spectrometry with a WineScanTM FT 120 (FOSS®, Barcelona, Spain),
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which was previously calibrated with the official OIV methods (International Organisation of Vine and Wine, 2019).

Absorbances at 280 and 230 nm of wines diluted between 1:100 and 1:400 in deionised water (to obtain absorbance units in the range of 0.2-0.9) were measured in 1-cm quartz cuvettes with a Shimadzu UV-spectrophotometer (UV-1800).

Concentration and activity of tannins were determined using HPLC-UV-vis following the method proposed by Revelette et al. (2014).

All chemical analyses were carried out in duplicate.

2.4. Data analysis

2.4.1. Effect of aroma perception on taste and mouthfeel attributes

To evaluate the effect of aroma on taste and mouthfeel attributes, a three-way ANOVA (participants as random factor and wines and evaluation condition as fixed factors), considering all main effects and interactions, was calculated on the 23 taste and mouthfeel attributes. The degree of similarity between the mouthfeel characterisation carried out under the two conditions (with and without nose clips) was assessed by calculating RV coefficients (Robert & Escouffier, 1976). The significance of the RV coefficient was estimated by an approximation of the exact distribution of the RV statistic with the Pearson type III approximation (Kazi-Aoual, Hitier, Sabatier, & Lebreton, 1995).

For the characterisation of wines, a two-way ANOVA (participants as random factor and wines as fixed factor) was calculated on the aroma, taste and mouthfeel attributes evaluated under the condition with access to aroma (WA). Principal component analysis (PCA) was conducted on the correlation matrix of mean ratings over the 18 panellists for significant aroma, taste and mouthfeel attributes obtained under the condition without nose clips with the 42 wines of the study. Further hierarchical cluster analysis with the Ward criteria was performed on all the dimensions of the PCA. The three clusters identified by truncating the tree diagram were

consolidated by aggregation around mobile centres. To identify the terms that best characterised each cluster, firstly a two-way ANOVA with panellists as random factor and clusters as fixed factors was calculated, then for significant attributes, a pair-wise comparison (Fischer) test was applied ($\alpha = 0.05$).

To identify the aroma attributes possibly involved in the oily perception, a two-way ANOVA for aroma terms was calculated with the five wines (SM4, SM8, SM37, SM38, SM40) that presented a significant effect of the evaluation condition for the term oily. For significant ($P < 0.05$) aroma terms (earthy and alcoholic) pair-wise comparison (Fischer) tests were applied.

Analyses were carried out using XLSTAT (version 19.03).

2.4.2. Correlations between physicochemical variables and mouthfeel attributes

Pearson correlation coefficient (r) and its significance were calculated between significant mouthfeel-related attributes (mean sensory scores of the 18 wine experts) and physicochemical variables (ethanol content, pH, titratable acidity, tannin activity, tannin concentration, and absorbance at 280 and 230 nm). Analyses were carried out using XLSTAT (version 19.03).

Partial least squares regression models (PLSR1) were calculated to predict dimension 1 (derived from PCA calculated with RATA scores) from chemical variables (tannin activity, TPI-280, TPI-230, tannin concentration, pH, titratable acidity, ethanol content). Analyses were carried out using Unscrambler (version 9.7).

3. Results and discussion

3.1. Effect of aroma on taste and mouthfeel properties

The first aim of the study was to evaluate the effect of aroma on taste and mouthfeel properties of a variety of red wines. This was addressed with expert panellists using RATA on a broad selection of wines obtained with the intention of having samples with important sensory variability in terms of both aroma and palate properties (taste and mouthfeel). Notably, this appeared to be the first time that this sensory methodology has been applied for mouthfeel

description of a relatively wide range of diverse red wines. Table 1 shows significant main effects ($P<0.05$) for wine in three out of the four tastes evaluated (salty, bitter and sour), with a tendency ($P<0.1$) observed for sweetness. Eight out of the 19 mouthfeel-related terms were also significant ($P<0.05$), with the three dryness-related terms among the most significant, together with sticky and prickly, followed by unctuous, grainy and oily. A tendency was observed ($P<0.1$) for the term silky. Table 2 shows that among the 20 aroma terms evaluated, 15 presented significantly different scores among the wines. Significant terms included those related to a range of fruit nuances along with floral, spice, vegetal and developed attributes. Fig. 1 shows the cluster analysis calculated with significant attributes. Three main clusters of wines with important sensory differences could be identified among the 42 wines studied. The first cluster included 11 wines elaborated with a diversity of varieties and from different origins (Table S1 of the Supporting Information). Cluster 1 was mainly characterised by aroma terms linked *a priori* to low quality according to expert and consumer judgements (Sáenz-Navajas et al., 2013), such as vegetal and animal, as well as bitter taste and dry and sticky mouthfeel. The second cluster presented *a priori* quality-related attributes such as fruity (yellow, red and black fruits) and floral aromas. Interestingly, the three Bobal wines belonged to this cluster, which was well in accordance with previous works that found red and cassis aromas in wines elaborated with this variety and also coming from La Mancha region (East-central Spain) (García-Carpintero, Sánchez-Palomo, & González Viñas, 2010). The third and largest cluster, containing more than 50% of wines studied, presented dried fruit/compote, roasted and alcoholic aromas, and unctuous mouthfeel. Wines elaborated with Bonarda (Argentina), Carignan (Northeast Spain), Prieto Picudo (Northwest, Spain), Syrah (Northeast, Spain) and Grenache (4 out of 5, Northeast Spain) were included in this last cluster, which provides information about the sensory profile of wines elaborated with these specific varieties and origins. Notably, even though the literature highlights that both the variety and origin of grapes are important factors affecting sensory profile and thus typicality of wines (Parr, 2009; Picard, Tempere, de Revel, & Marchand, 2015; Picard, Thibon, et al., 2015), to the best of our knowledge there was no systematic scientific study aimed at describing the sensory profiles of

wines as a function of both variety and origin. Thus, further studies should be carried out to evaluate such effects on wine sensory profiles. The present results also revealed that a non-specifically trained panel of wine experts who described wines with a pre-established list of aroma, taste and mouthfeel terms according to RATA methodology (Sáenz-Navajas et al., 2017) was successful in discriminating among the set of wines studied.

A significant effect of the evaluation condition (with (WA) and without (NA) aroma perception, using a nose clip for the latter) was evident for 4 out of the 23 taste and mouthfeel-related terms evaluated (Table 1). Evaluation condition was especially significant for grainy (average scores for the 42 wines and the 18 participants under the two conditions: WA = 0.08; NA = 0.22) and coarse (WA: 0.44; NA: 0.64) ($P < 0.01$) mouthfeel attributes, followed by bitter taste (WA = 1.11; NA = 1.35) ($P < 0.05$). A tendency was also observed for sour taste (WA = 1.32; NA = 1.48) ($P < 0.1$). It is noteworthy that the scores of these four attributes were higher under the nose-clip condition regardless of the wine evaluated. This could be attributed to the fact that in the absence of aroma perception, participants were exposed to a lower number of stimuli, which could have made them to focus their attention on mouthfeel and taste attributes leading to check and rate a higher number of these terms. This hypothesis is supported by the fact that the number of citations is significantly higher ($P < 0.05$ based on chi-square test) under the nose clip condition than for the condition that permitted olfaction, especially for sour taste (WA = 265; NA = 332; difference = 67), followed by bitter taste (WA = 253; NA = 295; difference = 42), coarse (WA = 89; NA = 126; difference = 37), and silky (WA = 61; NA = 88; difference = 27). Thus, the increase of the scorings for these four palate-related attributes in the absence of aroma could be attributed to an attentional effect produced by the tasting condition. Similar cross-modal interactions have been reported in the literature (Arvisenet et al., 2019; Bult, de Wijk, & Hummel, 2007; Sáenz-Navajas, Campo, Avizcuri, et al., 2012), where an increase in the complexity of the sensory stimuli (i.e., palate stimuli only vs palate and aroma simultaneously) increased the level of cross-modal interactions. This has been attributed to the difficulty of even trained panellists to disentangle unitary flavour stimuli when those occur simultaneously.

However, the present results cannot be attributed to other cross-modal interactions more usually observed in other works and related to the enhancement of tastes by congruent aromas (e.g., sweet taste-fruity aroma, sour taste-citrus aroma, or bitter taste-animal aroma) (Arvisenet et al., 2016; de-la-Fuente-Blanco et al., 2017; Saenz-Navajas et al., 2010). These last interactions can be ruled out in the present work because if this had been the case, significant effects of condition $\times$ wine would have been observed for taste or mouthfeel attributes, given the high aroma variability presented by the studied wines.

Concerning interactions between wine and evaluation condition, only the term oily was significantly different when comparing the sensory results with and without aroma perception. Pair wise *post-hoc* tests of significance showed significant effects ($P < 0.05$) of evaluation condition only for 5 out of the 42 wines studied (SM4, SM8, SM37, SM38, SM40). Fig. 2 shows that for SM4 and SM8, the term oily is higher under the nose clip condition, thus the presence of aroma stimuli seems to mask the oily perception. The contrary is observed for wines SM37, SM38 and SM40, in which aroma stimulus seems to significantly ($F = 2.22$; $P < 0.05$) enhance oily mouthfeel. Further ANOVA calculated considering these two groups of wines as fixed factors showed that wines SM4 and SM8 presented significantly higher scores for earthy aroma ($F = 7.98$; $P < 0.01$), whereas SM37, SM38 and SM40 had higher scores for the term alcohol ($F = 5.55$; $P < 0.05$). These results would suggest that the presence of earthy aromas could be masking the oily mouthfeel whereas alcoholic nuances can enhance the attribute in the studied wines. The use of a nose clip avoided any effect of volatile molecules on in-mouth sensory perceptions, and consequently the results should be exclusively attributable to cognitive interactions (Poinot, Arvisenet, Ledauphin, Gaillard, & Prost, 2013). Similar trigeminal-odour interactions have been reported (Labbe, Gilbert, & Martin, 2008; Spence, 2016) and certain aromas have been shown to enhance mouthfeel properties such as viscosity through associative learning (Stevenson & Mahmut, 2011). Thus, it can be hypothesised that the oily sensation perceived for some wines may be associated with a congruent effect between mouthfeel and

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aroma stimuli. Notwithstanding, further research experiments should be carried out to confirm the hypothesis that has arisen from the presented data set.

The RV coefficient, which can be understood as a correlation coefficient between two individual sample spaces and varies from 0 (full disagreement) to 1 (perfect agreement), was calculated between the sensory space generated by taste and mouthfeel properties under the two conditions (with and without nose clip) and found to be 0.617 ($P < 0.01$). This suggested that both sensory spaces were not significantly different, which was in good accordance with the ANOVA results, in which only a significant effect of condition $\times$ wine was observed for oily mouthfeel. Notably, this contrasted with previous work carried out with reconstituted wines, where a significant effect of the fruity aroma extract of a white wine was observed for astringent perception elicited by the non-volatile matrix of both white and red wines (Saenz-Navajas et al., 2010). However, the lack of effect of aroma on the astringency of red wines observed in the present work is well in line with previous results obtained with model red wines (de-la-Fuente-Blanco et al., 2017; Sáenz-Navajas, Campo, Avizcuri, et al., 2012). All this suggesting that aroma seems to play a significant effect on palate properties, but such effect would be only predominant in white wines, while in red wines the effect would be secondary if any.

3.2. Taste and mouthfeel dimensions

Table 3 shows the correlation matrix calculated with the significant palate-related attributes among the studied wines. Some mouthfeel terms were highly correlated, such as dry and dry on the palate ($r = 0.64$, $P < 0.001$) and both terms negatively correlated with silky ($r = -0.52$, $P < 0.01$ and $r = -0.42$, $P < 0.01$, respectively). This would suggest that the terms dry and dry on the palate present similar meanings for wine experts and were redundant. The highly significant ($P < 0.001$) negative correlation of silky and dry (and dry on the palate) was notable, and suggested that these terms were part of the same mouthfeel dimension and that panellists used them to score high or low intensity of that perceived characteristic. This may mean that in future these terms could be denoted dry-sticky/silky to avoid redundancy among the terms in a list. Also of interest was the significant correlation observed for the terms unctuous and oily ($r =$

0.36, $P < 0.05$), which could suggest that both terms are part of the same sensory dimension. They are most probably redundant terms that belong to the same category and thus it can be suggested to unify both terms under the same name, for example unctuous. The positive correlations of bitter taste with dry ($r = 0.40$, $P < 0.01$) could be attributed to an indirect effect related to the fact that wine polyphenols elicit both sensations simultaneously (Ma et al., 2014; Soares et al., 2017).

In order to further understand the sensory dimensions arising from the RATA methodology employed in the present work, PCA was conducted with significant attributes (4 for taste and 9 for mouthfeel, Table 1) for the 42 wines under the two evaluation conditions (Fig. 3). Among the 13 PCs explaining 100% of the original variability, the first six dimensions were mostly contributed (based on highest squared cosines of the variable for each PC) by at least one of the 13 significant sensory attributes and explained 72% of the variance. The necessity of a relatively high number of PCs to explain the original variance suggests that the sensory approach employed was able to disclose a wide range of non-correlated and independent palate sensations, mainly involving six sensory dimensions (or PC) that are built from different taste or mouth-feel related attributes. Fig. 3a shows that the first sensory dimension, PC1 (explaining 28% of variance), was mainly contributed by three attributes associated with dryness along with stickiness, and the term silky (along with salty and sour to a lesser extent). As suggested above, this dimension could be denoted as dry-sticky/silky. PC2 (explaining 13%) was mainly built by the terms grainy and unctuous in the positive direction, which were non-correlated and thus independent terms ($r = 0.020$). Both PC3 and PC4, which respectively explained 9% and 8% of original variance, were mainly contributed by tastes: sweet opposing bitter for PC3 and sour opposing salty for PC4 (Fig. 3b). On the other hand, PC5 and PC6, both explaining 7% of variance, were mostly related to the terms prickly and oily, respectively (Fig. 3c).

Leaving aside the four tastes, these results suggest that the chosen sensory approach was able to identify four independent and non-correlated mouthfeel dimensions for this set of red wines (PC1, PC2, PC5 and PC6), which represented sensory aspects that go beyond the most common

mouthfeel term astringency, including: dry-sticky/silky, grainy, prickly and unctuous. This valuable information will help to open a new path of experiments aimed at identifying the molecules responsible for these mouthfeel dimensions. The first insight into the chemical drivers of these sensory properties is described next, and together with the RATA results, will contribute to the ultimate goal of obtaining reference materials that will enable the training of sensory panels.

3.3. Relationships between mouthfeel properties and physicochemical measurements

The second aim of the work was to further understand the relationships between some chemical variables and the specific sensory mouthfeel descriptors and/or the mouthfeel dimensions identified. Addressing this aim, different chemical and spectrometric variables including ethanol content, pH, titratable acidity, absorbance at 280 nm and 230 nm, tannin concentration, and tannin activity were measured and correlated with the sensory data.

The highest significant correlation ($r = 0.70$, $P < 0.001$, Table 4) was found between the chemical variable tannin concentration and the first sensory dimension (dry-sticky/silky) of the PCA (PC1, Fig. 3a). Accordingly, tannin concentration was significantly ($P < 0.001$) and equally correlated with both dryness and dryness on the palate ($r = 0.65$). These results suggested that the first PC, which was mainly positively contributed by the terms dry, dry on the palate and sticky, and negatively by silky, was most probably related to the global attribute astringency. This percept is accepted to be mainly driven by the interaction between tannins and salivary proteins (García-Estévez et al., 2017; Soares et al., 2017). In this regard, different strategies have been developed to predict overall astringency from chemical measures of tannins (Kennedy, Ferrier, Harbertson, & Peyrot Des Gachons, 2006; Umali et al., 2015), showing that tannin concentration is only one of the tannin features involved in astringency. Thus, tannin activity has been defined in an attempt to identify other properties of tannins involved in the perception of astringency, (Revelette et al., 2014). Tannin activity, which is related to the thermodynamics of interaction between tannins and a hydrophobic surface (polystyrene

divinylbenzene HPLC column) (Barak & Kennedy, 2013), was found to have a significant ($p < 0.001$) correlation with dry on palate ($r = 0.64$, Table 4).

Table 4 shows that both spectroscopic measurements at 280 nm and 230 nm presented significant ($P < 0.01$) but weaker correlations ($r \leq 0.60$ in all cases) with PC1 (dry-sticky/silky) and the individual terms dry and dry on palate than did tannin concentration or activity. Besides, the spectroscopic measures did not correlate with any other mouthfeel-related attribute, although this was not too surprising. Even if these global measures are often used to evaluate polyphenol content in wines and are further related to astringency perception, there is a wide range of phenolics that absorb in the UV-region that are not involved or have a limited role in the modulation of wine astringency. These include low molecular weight flavan-3-ols (monomers or dimers), phenolic acids, flavonols, and anthocyanins among others components.

Besides tannin properties, other factors such as pH, acidity or ethanol content have been shown to modulate astringency (Fontoin et al., 2008). Even if no direct linear correlation was observed between these three variables and the sensory properties evaluated (Table 4), a PLSR1 model (with 3 PCs and explaining 71% of the original variance by cross-validation, Figure 4) was able to predict the first sensory dimension (which mainly referred to global astringency) in part from these chemical measures. Tannin concentration was the main variable contributing to the model (weighted regression coefficient (wrc) = 0.928), followed by a negative contribution of pH ($wrc = -0.597$), and then tannin activity ($wrc = 0.263$). The involvement of tannin activity in astringency perception is of interest, but outcomes can be variable and more understanding is required. A previous study could not establish a link in Cabernet Sauvignon wines (Watrelet, Byrnes, Heymann, & Kennedy, 2016), which was attributed to the presence of other compounds such as polysaccharides or even to the presence of cross-modal interactions of astringency with aroma. In contrast, a relationship between tannin activity and astringency was recently confirmed by a machine learning modelling approach (Sáenz-Navajas et al., 2019). As for the effect of wine pH, the increase of astringency with decreases in pH was previously observed with model wines (Fontoin et al., 2008) and was attributed to an effect of pH on rheological

properties of saliva. Low pH values have been suggested to decrease viscosity and thus increase astringent perception (Luck et al., 1994).

4. Conclusions

A RATA-based sensory methodology employed with wine experts was successful in discriminating among the taste and mouthfeel sensory properties of a relatively wide range of red wines. Different independent and non-correlated mouthfeel dimensions could be identified, encompassing perceptions associated with dry-sticky/silky, grainy, prickly and oily. Moreover, the effect of aroma on palate sensations was studied using RATA methodology with and without nose clips, which confirmed in the main that aroma did not have an effect on taste or mouthfeel perception of red wines. However, an aroma-mouthfeel interaction was identified for the term oily, which was hypothesised to be masked by earthy aromas and enhanced by alcoholic nuances.

Concerning the correlation of mouthfeel properties and chemical variables, tannin activity was shown to be a good predictor of wine dryness on the palate, and tannin concentration correlated with both dry (in general) and dry on the palate terms (as well as with PC1, which was driven by these attributes). However, the results provided evidence that there are (at least three) other independent mouthfeel dimensions (related or not to drying) identified in the present work that are not linked to the other chemical variables studied, which highlights the need for deeper investigation. Furthermore, although simple spectroscopic measurements (280 nm and 230 nm) were positively correlated to wine dryness, the correlations were poor compared to tannin specific estimations.

Overall, the study has increased knowledge of the mouthfeel perception of red wines, which is valuable for both wine researchers and the wine industry. RATA was shown to be a useful sensory tool to be directly used in the wine industry to evaluate differences in taste and mouthfeel properties of wine. Besides, this work provides the basis for an important field of research aimed at identifying the molecules or groups of molecules that elicit the different

1 sensory dimensions identified in the present work. This is not a trivial undertaking and is part of
2 a longer term strategy, where the most different wines from among the selected 42 are being
3 fractionated and further characterised, to identify sensory-active fractions related to different
4 mouthfeel dimensions.
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24 **Appendix A. Supplementary information**

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26 Supplementary information associated with this article can be found online at Supplementary
27 data to this article can be found online at <https://doi.org/10.1016/j.foodres>.
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1 **Figure captions**

1 **Fig. 1.** Tree diagram showing the three wine clusters derived from hierarchical cluster analysis calculated on
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3 all dimensions of the PCA performed with the 42 studied wines and using significant aroma, taste and
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5 mouthfeel attributes. Attributes describing each cluster are those with significantly higher scores in the given
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7 cluster.
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11 **Fig. 2.** Average sensory scores of 18 participants for the oily attribute, evaluated with no aroma perception
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13 (NA) using nose clips compared to aroma perception (WA), for wines presenting a significant effect of
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15 aroma perception on oily scores. Error bars represent the standard error of the mean. Different letters indicate
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17 the existence of significant differences between samples ($P < 0.05$, pairwise Fischer post hoc test).
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21 **Fig. 3.** Two-dimensional loadings plots derived from PCA of significant taste and mouthfeel attributes that
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23 were calculated with the average scores of 18 participants who evaluated 42 wines with and without nose
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25 clips, showing a) PC1 vs PC2, b) PC3 vs PC4, and c) PC5 vs PC6. Underlined attributes are significantly
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27 correlated with one of the PCs (i.e. independent sensory dimensions) represented.
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31 **Fig. 4.** PLS regression plot of predicted vs measured scores of sensory dimension 1 (PC1: dry-sticky/silky).
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Figure 1

Figure 2

Figure 3

Figure 4.

Table 1. List of taste and mouthfeel attributes obtained from Sáenz-Navajas et al. (2017) used to evaluate the wines with RATA. Three-way ANOVA (participants as random factor, wine and condition of evaluation as fixed factors) calculated to evaluate the effect of evaluation condition (C) (with and without aroma perception) on taste and mouthfeel sensory properties of the 42 red wines studied (F values; P-significance: *P<0.1, **P<0.05, ***P<0.01, ****P<0.001; fd: freedom degrees; ns: not significant).

	wine (W) fd = 41		condition (C) fd = 1		wine (W) × condition (C) fd = 41	
	F	P	F	P	F	P
salty	1.453	**	2.473	ns	1.021	ns
bitter	1.873	***	6.350	**	1.100	ns
sweet	1.523	*	0.376	ns	0.987	ns
sour	2.618	****	3.712	*	0.947	ns
dry	3.804	****	0.161	ns	1.171	ns
dry on tongue side	2.132	****	0.346	ns	0.683	ns
dry on palate	3.480	****	1.905	ns	0.742	ns
sticky	1.633	****	0.782	ns	0.743	ns
dusty	0.863	ns	0.888	ns	1.212	ns
grainy	4.439	**	9.230	***	0.769	ns
sandy	1.240	ns	1.227	ns	0.697	ns
coarse	1.130	ns	7.178	***	0.737	ns
unctuous	1.828	***	0.835	ns	1.020	ns
oily	1.576	**	0.800	ns	1.523	**
fleshy	1.011	ns	0.238	ns	0.635	ns
mouthcoating	1.178	ns	1.280	ns	0.935	ns
silky	1.388	*	1.316	ns	0.935	ns
gummy	1.164	ns	0.092	ns	1.093	ns
watery	1.190	ns	0.052	ns	1.263	ns
burning	0.941	ns	1.702	ns	1.057	ns
hot	1.204	ns	2.219	ns	0.981	ns
prickly	1.616	****	0.509	ns	1.123	ns
persistent	0.824	ns	0.510	ns	1.070	ns

Table 2. List of aroma attributes employed during wine description by RATA and two-way ANOVA (participants as random factor, and wine as fixed factor) calculated to evaluate the discrimination effect of aroma attributes among the 42 red wines studied (F values; P-significance: *P<0.1, **P<0.05, ***P<0.01, ****P<0.001; ns: not significant).

aroma attribute	F	P
white fruit (apple, pear, quince)	1.763	***
yellow fruit (peach, apricot)	1.805	***
tropical fruit (banana)	1.996	***
red fruit (strawberry, raspberry, cherry)	2.557	****
black fruit (blackberry, blueberry)	1.358	*
dried fruit/compote (raisin, prune)	1.341	*
floral (violet, rose, acacia)	2.519	****
alcohol	1.612	**
spices (clove, black pepper, cinnamon, vanilla, liquorice)	1.631	***
roasted (coffee, toast, toffee, cacao)	2.051	***
vegetal (green pepper, fresh grass)	1.453	**
cooked vegetables (artichoke, asparagus, olive)	2.430	****
earthy (mushroom, truffle)	1.629	***
reduction (rotten egg, cauliflower)	1.730	***
animal (leather, stable)	2.820	****
citrus (lemon, orange)	0.942	ns
nuts (walnut, hazelnut, almond)	1.189	ns
balsamic (eucalyptus, menthol)	1.143	ns
mouldy (cork, mould)	0.720	ns
lactic (milk, yogurt, cream)	1.249	ns

Table 3. Correlation matrix calculated for average scores (of 18 panellists) of taste and mouthfeel attributes for the 42 wines evaluated under the two conditions with and without noseclips. Significant correlations ($P < 0.05$) are marked with an asterisk (P-significance: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$).

	salty	bitter	sweet	sour	dry	dry on tongue side	dry on palate	sticky	grainy	unctuous	oily	silky	prickly
salty	1.00	-0.31	0.01	0.07	-0.24	-0.27	-0.34	-0.12	-0.12	0.24	0.12	0.25	0.12
bitter	-0.31	1.00	-0.22	-0.30	0.40**	0.32	0.24	0.08	0.32	-0.18	0.01	-0.18	0.03
sweet	0.01	-0.22	1.00	-0.07	-0.20	-0.02	-0.01	-0.05	0.20	0.19	0.04	0.07	0.12
sour	0.07	-0.30	-0.07	1.00	-0.27	-0.33	-0.32	-0.14	-0.09	0.12	0.06	0.25	0.07
dry	-0.24	0.40	-0.20	-0.27	1.00	0.41**	0.55***	0.32	0.28	-0.33	-0.33	-0.52***	-0.14
dry on tongue side	-0.27	0.32	-0.02	-0.33	0.41	1.00	0.44**	0.19	0.28	0.05	-0.18	-0.26	-0.08
dry on palate	-0.34	0.24	-0.01	-0.42	0.55	0.44	1.00	0.32	0.43**	-0.28	-0.11	-0.42**	-0.15
sticky	-0.12	0.08	-0.05	-0.14	0.32	0.19	0.32	1.00	0.11	-0.30	-0.21	-0.22	-0.11
grainy	-0.12	0.32	0.20	-0.09	0.28	0.28	0.43	0.11	1.00	0.02	0.07	-0.14	0.18
unctuous	0.24	-0.18	0.19	0.12	-0.33	0.05	-0.28	-0.30	0.02	1.00	0.36*	0.32	0.29
oily	0.12	0.01	0.04	0.06	-0.33	-0.18	-0.11	-0.21	0.07	0.36	1.00	0.30	0.16
silky	0.25	-0.18	0.07	0.25	-0.52	-0.26	-0.42	-0.22	-0.14	0.32	0.30	1.00	0.15
prickly	0.12	0.03	0.12	0.07	-0.14	-0.08	-0.15	-0.11	0.18	0.29	0.16	0.15	1.00

Table 4. Pearson correlation coefficient (r) calculated between chemical variables and tastes, mouthfeel attributes and sensory dimensions (i.e., principal components derived from PCA). Significant correlations (P<0.05) are marked with an asterisk (P-significance: *P<0.05, **P<0.01, ***P<0.001).

	tannin activity	tannin conc.	TPI-280 (au)	TPI-230 (au)	ethanol content (%v/v)	pH	titratable acidity
salty	-0.20	-0.31	-0.28	-0.18	-0.27	-0.11	0.11
bitter	0.07	0.32	0.27	0.30	0.27	0.30	-0.34
sweet	0.10	-0.07	-0.04	-0.06	0.04	0.05	0.02
sour	-0.39*	-0.50**	-0.40*	-0.42	-0.20	-0.52	0.34
dry	0.51**	0.65***	0.51**	0.56**	0.15	0.38	-0.17
dry on tongue side	0.28	0.43*	0.36	0.30	0.18	0.10	0.01
dry on palate	0.64***	0.65***	0.57**	0.59**	0.02	0.26	-0.08
sticky	0.39*	0.36	0.31	0.28	0.08	-0.03	0.13
grainy	0.22	0.26	0.18	0.21	-0.09	0.00	-0.07
unctuous	-0.21	-0.24	-0.24	-0.24	-0.17	0.01	-0.04
oily	-0.29	-0.20	-0.18	-0.16	-0.15	0.09	-0.19
silky	-0.36	-0.34	-0.30	-0.30	-0.28	-0.04	-0.05
prickly	-0.18	-0.06	-0.09	0.01	-0.07	-0.02	-0.04
PC1 (dry-sticky/silky)	0.59**	0.70***	0.60**	0.59**	0.26	0.28	-0.12
PC2 (grainy)	0.00	0.12	0.06	0.11	-0.07	0.19	-0.22
PC4 (prickly)	0.32	0.04	0.05	0.02	-0.05	-0.12	0.26
PC5 (unctuous)	-0.09	-0.12	-0.07	-0.12	0.01	-0.32	0.15

EXPERIMENTAL

42 red wines

SENSORY description by RATA with a preestablished list of descriptors under 2 conditions:
1) with nose clip
2) without nose clip

CONCLUSIONS

1. No important effects of aroma on taste or mouthfeel perception of red wines
2. The only effect of aroma was observed for oily mouthfeel. It is masked by earthy aromas and enhanced by alcoholic nuances
3. Independent dimensions were related to dry/silky, grainy, prickly and oily
4. Tannin concentration and activity and pH drove wine dryness

Descriptor/wine	Wine 579								
Salty (<i>salado</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Bitter (<i>amargo</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Sweet (<i>dulce</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☒	☒	☐	☐
Sour (<i>ácido</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Dry (<i>secante</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Dry (side of tongue) (<i>secante lados de la lengua</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Dry (palate) (<i>secante en el paladar</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☒	☐	☐	☐	☐	☐	☐
Sticky (<i>pegajoso</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Dusty (<i>polvoriento</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Granular (<i>granuloso</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Sandy (<i>arenoso</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Coarse (<i>rugoso</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☒	☒	☐	☐	☐	☐	☐
Greasy (<i>graso</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fleshy (<i>carnoso</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Mouth-coating (<i>envolvente</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Silky (<i>sedoso</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Gummy (<i>gomoso</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☒	☒	☐
Watery (<i>acuoso</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Unctuous (<i>untuoso</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Burning (<i>ardiente</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☒	☒	☐	☐	☐	☐	☐
Hot (<i>picante</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Persistent (<i>persistente</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☐	☐	☐	☐	☐	☐	☐
Sharp (<i>punzante</i>)	1	2	3	4	5	6	7	8	9
	☐	☐	☒	☒	☐	☐	☐	☐	☐

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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