Crossmodal Correspondence between Color, Shapes, and Wine Odors & Sensitivity to Subtle Changes in Wine Odor

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Michelle Lynn Heatherly
December 2018

Abstract

Wine odor is a key component of wine quality and is one of the most complex food odors humans perceive. This thesis used two separate studies to answer the following questions: first, how is wine odor perception influenced by visual cues on packaging (i.e. wine label)? And second, how sensitive are humans to subtle changes in wine odor? In the first study odor-color-shape crossmodal interactions with complex odor stimuli (chardonnay odors) and visual stimuli were investigated. The results showed that most chardonnay odors were grouped similarly; however, the vegetable-forward wine was more associated with sharper shapes. In general, yellow labels tended to be better matched with all odors, except the vegetable-forward wine, which was matched equally to all colors; indicating that, regardless of odor character, chardonnay is mostly associated with a yellow colored label. Interestingly, results also indicated that not all correspondences aligned with the most common color association of an odor character's (i.e., vegetative was not strictly associated with green, nor smoky with brown, etc.). Significant correlations between stimuli liking and matching scores indicate that many of the correspondences are explained by hedonics. In a second study, designed to assess general human sensitivity to changes in wine odor, a model wine odor was used to gauge the discriminatory ability of experts and novices. Panelists as a whole were not able to discriminate between either the addition or subtraction samples compared to their base counterparts. Furthermore, expertise did not seem to play a role in discriminatory abilities either, with experts and novices producing similar d' values. Overall, the d' values were consistently low and demonstrate that the stimuli were challenging to discriminate between. Taken together, these studies show that specific wine odor characteristics do correspond with specific visual stimuli and human sensitivity to changes in odor mixtures is not extremely high, even in wine experts.

Table of Contents

INTRODUCTION 1
What is Olfaction, and why is it Important? 1
Wine Aroma 2
Color Perception 2
Odor- Visual Crossmodal Correspondence 3
Discrimination in a Complex Mixture 4
CHAPTER I Crossmodal Correspondence between Color, Shapes, and Wine Odors 6
Abstract 7
Introduction 8
Experiment 1. 12
Materials and Methods 12
Results 16
Discussion 25
Experiment 2. 26
Materials and Methods 26
Results 29
Discussion 32
Conclusion 36
CHAPTER II Sensitivity to Subtle Changes in Wine Odor 37
Introduction 39
Materials and Methods 41
Results 49
Discussion 53
Conclusion 55
CONCLUSION 56
REFERENCES 57
VITA 70

List of Tables

Table 1. Odorants used to spike chardonnay wine for aroma stimuli 13
Table 2. Pearson's correlations among the distance matrices of colors and odors 17
Table 3. Pearson's correlations among the distance matrices of shapes and odors. 21
Table 4. Hedonic scores of wine aromas, colors, and shapes for projective mapping study. 22
Table 5. Aroma and angularity matching scores for label study. 30
Table 6. Aroma and color matching scores for label study. 31
Table 7. Hedonic scores of wine aromas, colors, and angularities for label study. 32
Table 8. Odorants in the odor model base 45
Table 9. Odorants added to the wine base at detection thresholds 45
Table 10. Intensity, pleasantness, and familiarity scores of wines and modifiers 52

List of Figures

Figure 1.Visual stimuli used in projective mapping experiment. 14
Figure 2. Confidence ellipses for projective mapping of color and odor spiked wines..... 16
Figure 3. Confidence ellipses for projective mapping of shapes and odor spiked wines. 18
Figure 4. Cluster dendrogram of odor spiked wines and shape from distance matrices. 19
Figure 5. Correspondence analysis of words describing placement of color stimuli. 23
Figure 6. Correspondence analysis of words describing placement of shape stimuli 24
Figure 7. Wine label stimuli..... 28
Figure 8. Wine odor character on label angularity matching..... 30
Figure 9. Wine odor character on label color matching..... 31
Figure 10. d’ values for n + 1 & n – 1 samples for each expertise level. 49
Figure 11. d' values for n + 1 addition samples for each added modifier..... 50
Figure 12. d' values for n - 1 subtraction samples for each modifier..... 51

INTRODUCTION

What is Olfaction, and why is it Important?

Smell, or olfaction, is one of the five basic senses of humankind. The main purpose of olfaction is to alert us to possible hazards around us (such as noxious fumes or spoiled food) and also to bring our attention towards positive items (e.g. nourishing foods) (Croy, Nordin, & Hummel, 2014). There are two pathways by which odor information reaches the olfactory epithelium: through the nostrils, during sniffing, and up through the back of the throat, during eating and drinking (Negoias, Visschers, Boelrijk, & Hummel, 2008). More specifically, when we process olfactory stimuli orthonasally, stimuli from the external environment travels up the nostrils towards the olfactory mucosa (Negoias et al., 2008). Amazingly, when perceived orthonasally, it appears that there is no limit to the number of smells that can be perceived, this is especially important because it provides us with information about the environment around us- particularly in regards to food, danger, or social interactions (Spors & Grinvald, 2002).

Alternatively, retronasal olfaction is typically related to the mouth and throat (Murphy & Cain, 1977), and is responsible for smell-taste confusions (Murphy & Cain, 1980; Murphy et al., 1977; Rozin, 1982). While chewing, volatile molecules are released. During breathing or swallowing the volatiles travel up to the nasal cavity through the pharynx, stimulating receptors in the olfactory cleft. (Hummel & Nordin, 2005). It has been determined that different airflow patterns are the cause of perceptual differences between the two pathways (Mozell, 1970), as well anatomical differences in compartments of the nose (Damm, Vent, Schmidt, Theissen, Eckel, Lötsch, & Hummel, 2002; Leopold, 1988; Sobel, Khan, Saltman, Sullivan, & Gabriel, 1999; Zhao, Scherer, Hajiloo, & Dalton, 2004; Raudenbush & Meyer, 2001). Surprisingly, the sense of smell, especially retronasal olfaction, is quite important to our quality of life (Hummel et al., 2005).

People with impaired, or without a sense of smell of all, experience difficulties in many areas of their life, including food consumption, security, hygiene, and in their sexual life (Tennen, Affleck, Mendola, 1991; Van Toller, 1999; Hummel et al, 2005). In regard to food preparation and consumption, one study found that 69% of patients reported lower enjoyment of foods after the onset of their disorder (Ferris & Duffy, 1989). It has also been reported that preparing food is difficult, especially with problems detecting burning foods, or spoiled foods

(Miwa, Furukawa, Tsukatani, Costanzo, DiNardo, & Reiter, 2001; Temmel, Quint, Schickinger-Fischer, Klimek, Stoller, & Hummel, 2002). As far as safety is concerned, 61% of patients reported a failure to detect fire, gas, or smoke (Miwa et al., 2001). Additionally, patients experience complications related to personal hygiene; they cannot smell their own body odor, or bad breath, and have concerns about their children's hygiene as well (Temmel et al., 2002).

The sense of smell is especially important in the realm of food and beverages, particularly in regard to quality. Our ability to determine when, how much, and what specifically we want to eat is often related to olfactory mechanisms (Nordin, 2009). A divergence between expectations formed prior to consumption and perceived flavor can lead to rejection of the food.

Wine Aroma

Wine aroma is a large determinant of quality in the eye of the consumer, especially when determining the perceived quality and acceptability. Acceptability of a wine is typically determined by the presence or absence of a complex but well-balanced aroma profile (Marais, 1983). Volatile compounds play a vital role in the aromas and flavors present in wine. There are over 800 volatiles in wine, but only a relatively small number of these have been identified by sensory analysis (Maarse & Vischer, 1989). Volatile components in wine aroma are classified as either primary, secondary, or tertiary aromas. Primary aromas are produced directly from the grapes or from modifications during grape processing. Secondary aromas are formed by the fermentation process, and tertiary aromas or the "bouquet" are a result from the aging process (Rapp and Mandery, 1986). Wine aromas are extremely complex matrices, with interactions occurring among many compounds, which can highly influence how the aroma is perceived (Robinson, Ebeler, Heymann, Boss, Solomon, & Trengover, 2009; Jones, Gawel, Francis, & Waters, 2008).

Color Perception

As outlined in Goldstein's *Sensory and Perception* (2014), color vision is an important component of the overall perception of our environment. Evolutionarily, good color vision facilitates finding objects, specifically foods, from our surroundings. It has been proposed that human vision evolved mainly for finding fruit (Mollon, 1989, 1997; Sumner & Mollon, 2000; Walls, 1942). Color also helps serve as a signaling agent, indicating when food is no longer safe

to eat, or when it is safe to cross an intersection (Goldstein, 2014). Color also helps with recognition and identification. A study from Tanaka & Presnell (1999) demonstrated that participants were able to more rapidly and accurately label objects that were in their proper colors, than those that were in inappropriate colors (Tanaka & Presnell, 1999).

We can describe all the colors in our visible spectrum in terms of blue, green, yellow, and red, or any combination of these (i.e. bluish-green) (Abramov & Gordon, 1994; Hurvich, 1981). Color perception itself, however, is usually attributed to the physical properties of wavelength, with colored objects determined by the wavelengths that are reflected off the objects into our eyes.

Researchers in the 1960s determined that there are three different cone pigments responsible for color vision, short-wavelength pigment (S), middle-wavelength pigment (M), and long-wavelength pigment (L) (Goldstein, 2014). These pigments are made up of large protein components called opsin, and differences within this structure are responsible for different absorption spectra (Nathans et al., 1986). Furthermore, there are two types of neurons that have been credited with color perception. Single-opponent cells are important for color perception within specific regions, double-opponent cells are responsible for perceiving boundaries between different colors (Johnson et al., 2008).

Contrary to popular belief, most problems with color perception only involve partial loss of color vision, and is termed color deficiency. This deficiency is often assessed through tests similar to the Ishihara color test in which plates with numbers of varying degrees of color are presented and the participant must identify the number. If someone is a monochromat, they only see in shades of gray. If someone is a dichoromat, they are a two-pigment observer. Finally, if someone is an anomalous trichromat, they mix wavelengths in different proportions, and are not as good at color discrimination

Odor- Visual Crossmodal Correspondence

Vision has the capability to alter odor perception. In a phenomenon known as crossmodal correspondence, humans associate information from one sensory feature with another feature from a different sensory modality (Marks, 1978; Spence & Deroy, 2013). Both color and shapes have been shown to be associated with odors. People have the ability to clearly match colors to odors (Demattè, Sanabria, & Spence, 2006). Also, more intense odors tend to be associated with

darker colors (Kemp & Gilbert, 1997). Along those same lines, floral perfume has been more highly associated with a bright print as opposed to a darker one (Fiore, 1993).

Angular, or sharp, shapes are generally associated with bitter and sour or “sharp” tastes, while round shapes are more associated with sweet and rich tastes (Ngo, Misra, & Spence, 2011). Pale ale served from rounded glasses were reported as being fruitier (Mirabito, Oliphant, Van Doorn, Watson, & Spence, 2017). Angular shapes tend to be more related to intense and unpleasant aromas, and rounded shapes tend to be associated with more faint, or pleasant aromas (Demattè et al., 2006; Hanson-Vaux, Crisinel, & Spence, 2013; Adams & Doucé, 2017).

The work that has been done on odor-visual interactions has not been extensively studied in complex odor matrices, typically only occurring with single odor stimuli, and it is unclear whether crossmodal correspondences would manifest themselves in the same way within a subset of complex odors- such as wine.

Discrimination in a Complex Mixture

Not much is understood about odor mixture discrimination. What is known, is that humans have difficulty discriminating between odor stimuli, especially when in the context of odor mixtures (Engen, 1970; Laing & Francis, 1989). People tend to want to detect differences in mixtures when none actually exist, and in a study that used identical stimuli, approximately 28% of participants reported a difference when they received identical perfumes and an additional 17% of subjects reported a difference when presented with distilled water (Eisenson, Fisichelli, & Welch, 1954). Odor discrimination is difficult for even highly experienced chemists and perfumers, who rely heavily on their sense of smell. They have been shown to experience difficulty when forced to discriminate between stimuli on smell alone (Jones, 1968).

Alternatively, it has been shown that it only requires a very small change in the ratio of the perceived intensities of individual components to shift the perception of the mixture largely in the direction of the stronger component (Laing & Wilcox, 1983), indicating perceived intensities of constituents is relevant to mixture perception. There have been findings in the perfume and food industries that demonstrate that changes in odor mixtures can have significant perceptual consequences, which can make quality control difficult (Persaud & Dodd, 1982; Reineccius & Anandaraman, 1984; Dodd, 1988).

We want to better understand wine odor perception and, because of this, the experiments reported in this thesis have two general aims. Firstly, to investigate more deeply odor-color-shape crossmodal interactions, specifically with a complex odor matrix using both abstract and realistic stimuli. Secondly, to provide a clearer picture of the differences in discriminative performance between wine experts and novices particularly in regards to odor mixtures and the complexity of odorants present.

CHAPTER I
CROSSMODAL CORRESPONDENCE BETWEEN COLOR, SHAPES, AND WINE ODOR

A version of this chapter is published in *Food Quality and Preference* by Michelle Heatherly, Melissa Foley, John P. Munafo and Curtis R. Luckett:

Abstract

Crossmodal correspondence is of scientific and commercial interest in regard to the packaging of food and beverages. Research has shown that colors and shapes can be associated with certain aromas, but these interactions have been less extensively studied with authentic visual stimuli (i.e., packaging), or with complex food odors in a matrix. This study investigated odor-color-shape crossmodal interactions with complex odor stimuli (wine odors) and wine labels. The present research used projective mapping with 3D shapes and colors, along with a wine label matching study, to test whether chardonnay odors of different character (buttery, citrus, floral, smoky, and vegetable) were associated with certain colors and shapes. In the projective mapping experiment, most chardonnay odors were grouped similarly; however, the vegetable-forward wine was more associated with sharper shapes. In the label experiment, yellow labels tended to be better matched with all odors, except the vegetable-forward wine, which was matched equally to all colors. These findings indicate that, regardless of odor character, chardonnay is mostly associated with a yellow colored label. Interestingly, results also indicated that not all correspondences aligned with the most common color association of an odor character's (i.e., vegetative was not strictly associated with green, nor smoky with brown, etc.). Significant correlations between stimuli liking and matching scores indicate that many of the correspondences are explained by hedonics. Overall, the present research demonstrates evidence for odor-color-shape correspondences in complex odors and realistic visual stimuli, but not as strongly as in controlled environments and simplistic stimuli.

Introduction

There is a growing body of research regarding crossmodal correspondence and the role it can play in consumer experience. Crossmodal correspondence is the name given to the phenomenon of associating information from one sensory feature with another sensory feature from a different sensory modality (Marks, 1978; Spence & Deroy, 2013). These correspondences have been associated with synesthesia in the past, however a general definition of crossmodal correspondences is acquired, malleable, relative, and in transitive pairings between sensory dimensions (Deroy & Spence, 2013) These cases are frequent (if not universal) in the population (Levitan, Ren, Woods, Boesveldt, Chan, McKenzie, Dodson, Levin, Leong, & van den Bosch, 2014), are stable across time (Gilbert, Martin, & Kemp, 1996), and appear to exist among all combinations of sensory modalities (Deroy, Crisinel, & Spence, 2013).

Three main mechanisms for crossmodal correspondences have been outlined by Schifferstein & Tanudjaja (2004), the first of which is that humans have an inherent ability to perceive the synesthetic quality of stimuli directly. Along these lines, it has been proposed that natural biases might exist across sensory systems (Deroy et al. 2013). Moreover, perceptual learning may drive the development of crossmodal correspondences. For example, over repeated exposure humans learn that the odor of lemons comes from the characteristically yellow fruit. Similarly, it has been hypothesized that culture and prior experience play a role in deciding our perception (Ayabe-Kanamura, Schicker, Laska, Hudson, Distel, Kobayakawa, & Saito, 1998; Ferdenzi, Schirmer, Roberts, Delplanque, Porcherot, Cayeux, Velazco, Sander, Scherer, & Grandjean, 2011; Spence & Van Doorn, 2017) and as a result, odor-color associations may be connected with the culture in which people live or have grown up in (Jacquot, Noel, Velasco, & Spence, 2016). Lastly, some correspondences may stimulate a particular association, which could prompt the concept of a specific color (Schifferstein et al., 2004).

In regard to food and beverage much of the research in this field has focused on how visual and auditory stimuli can influence more food specific sensations such as flavor perception. For example, the visual appearance of the packaging itself has been shown to influence perception of the product inside (Cheskin, 1957; Esterl, 2011). Cheskin reported an increase in lemony/lime flavor in soda as more yellow color was added to the can (Cheskin, 1957). More recently it was found that a green label on a beer bottle led to significantly higher ratings in terms

of quality, taste, and dominance of fruity/citrus notes present in the beer, as opposed to a brown label (Barnett & Spence, 2016). In popular culture, Coca-Cola® experienced customer complaints that their cola tasted different when drank from white-colored holiday cans (Esterl, 2011). In another (unpublished) study, Deliza concluded that background packaging color can influence taste ratings (1996). More specifically, sweetness scores were increased by manipulating the amount of orange color on orange juice packaging (Deliza, 1996). Similarly, switching potato chips that were commonly associated with a blue packet, to a new green packet affected flavor perception, with participants often reporting erroneous flavors as a result (Piqueras-Fiszman & Spence, 2011). These examples tend to focus on basic tastes or single attributes, but all demonstrate that label manipulation can influence the perception of the contents within a package or product.

While color and flavor/taste interactions have been the focus of considerable research, associations between visual cues and olfaction have been much less explored. Demattè found that people have the ability to explicitly match colors to odors (Demattè, Sanabria, & Spence, 2006). Also from this study, an implicit association test was administered where participants made speeded discrimination responses between odors and color patches. Participants responded more quickly and correctly when odor-color pairings were highly associated than in those that had a weak association (i.e., strawberry odor and pink, as opposed to turquoise). Also, stronger odors are typically associated with darker colors (Kemp & Gilbert, 1997). Alternatively, in an older example, floral perfume was found to be more highly associated with a print based on light colors (Fiore, 1993). There are also indications of hedonic scores mediating crossmodal interactions of odors and colors. Namely, bright colors tend to be rated as pleasant, while darker colors tend more to be found unpleasant, and all of these are correlated to color/odor choices (Maric & Jacquot, 2013).

Some research has demonstrated that applying images to a drink container, as well as manipulating the colors of the label, can influence the hedonic or sensory properties of the product (Mizutani, Okamoto, Yamaguchi, Kusakabe, Dan, & Yamanaka, 2010; Piqueras-Fiszman et al., 2011). Sparkling water has been shown to be better matched with angular shapes, and still water with organic shapes (Spence & Gallace, 2011), which is interesting in the context of packaging as sparkling water sometimes has an image of a star on the label (e.g. San Pellegrino), and still water is sometimes accompanied by a more organic fluer-de-lis on the label

(e.g. Acqua Panna) (Ngo, Piqueras-Fiszman, & Spence, 2012). However, in general, work exploring crossmodal interactions regarding shapes and basic tastes/aromas has used abstract visual shapes with varying degrees of sharpness/roundness, typically involving line scales anchored with 2D shapes, in which a subject will indicate how sharp or round a basic taste or aroma seems (Köhler, 1929; Ramachandran & Hubbard, 2001). Other studies have employed multiple 2D abstract shapes (Seo, Arshamian, Schemmer, Scheer, Sander, Ritter, & Hummel, 2010) or even allowed participants the freedom to draw shapes in order to visualize their odor associations (Kaeppler, 2018).

One way to explain crossmodal correspondences of shapes and flavor is that consumers are primed to notice to certain sensory attributes that are related to certain tastes/flavors based on the shapes presented (regardless of whether they are seen or touched), which enhances the perception of those attributes (Spence, 2012). Angular shapes are generally associated with bitter and sour or "sharp" tastes, while round shapes are more associated with sweet and rich tastes (Ngo, Misra, & Spence, 2011). Manipulation of the shape of the receptacle itself may influence how complex odors are perceived (Hummel, Delwiche, Schmidt, & Hüttenbrink, 2003; Delwiche & Pelchat, 2002), and angular packaging has shown increased intensity of taste sensations (Becker, Van Rompay, Schifferstein, & Galetzka, 2011). Furthermore, it was demonstrated that when cola was presented in a cola glass, it was rated as sweeter, more intense and more pleasant than when presented in a water glass or bottle (Cavazzana, Larsson, Hoffmann, Hummel, & Haehner, 2017). One study involving craft beer and the shape of glass found that Yenda Pale Ale was rated as significantly fruitier when served from a rounded glass as opposed to one with straight sides (Mirabito, Oliphant, Van Doorn, Watson, & Spence, 2017). In another study, surfaces of cup holders were manipulated, influencing ratings of bitter coffee and sweet hot-chocolate, with bitterness ratings ~27% higher for an angular surface, and sweetness ratings ~18% higher for a rounded surface pattern (Van Rompay, Finger, Saakes, & Fenko, 2016). Crossmodal correspondences have also been reported in the serving plates of desserts, where rounder plates resulted in higher sweetness scores (Chen, Woods, & Spence, 2018; Stewart & Goss, 2013)

Interactions in shape and aroma have also been documented. Angular shapes have been shown to be associated with more intense and unpleasant aromas (Dematte et al., 2006). Rounded shapes have been associated with less intense or more pleasant aromas (Hanson-Vaux,

Crisinel, & Spence, 2013; Adams & Doucé, 2017). Recently, curved shapes were shown to be associated with vanilla aroma, and angular shapes with citrus (Blazhenkova, & Kumar, 2018).

There has been evidence to support some level of association between visual cues and aromas at the basic level, but the visual stimuli have remained simple in kind. Visual stimuli have typically included simple color chips or fabric swatches and line scales anchored with 2D shapes of varying sharpness/roundness with which to test interactions. More complex visual stimuli have been investigated only in a few select studies (Seo et al., 2010; Kaeppler, 2018). And, it appears that the intricacy and multi-dimensional features that underlie odor-color correspondences are not yet fully understood (Jacquot et al., 2016).

The work on odor-visual interactions thus far has not been studied extensively in a complex odor matrix. With this gap in understanding, it is unclear whether crossmodal correspondence between visual cues and aroma manifest themselves within a subset of complex odors. Furthermore, there is little data on crossmodal correspondences that include realistic nuances in aroma character. The flavor of whisky, which shares wine odor complexity and nuance in character across the product category, was found to be modulated by visual and audio stimuli (Spence et al., 2013). These crossmodal effects were observed by modifying the environment, but, to most food and beverage producers, the most accessible method of controlling visual stimuli would be through packaging. Food and beverage packaging, such as wine labels, are often the first impression a consumer has of a product and are known to influence preference and purchasing behavior. Like many products, wine packaging needs to communicate relevant and appropriate information about the quality of the liquid within (Tootelain & Ross, 2000). Using packaging to enhance the impression and perception of quality of the wine is a key component to the maximizing of the consumer experience.

This study sought to investigate more deeply odor-color-shape crossmodal interactions, specifically with a complex odor matrix. Chardonnay wine was chosen as the odor matrix on the basis of a relatively wide range of odor profiles existing within the category; also some key aroma-active compounds have been characterized. As well it has also been shown that changing the shape of a wine glass exerts a direct impact on the perception of wines (Hummel et al., 2003; Delwiche et al., 2002; Hüttenbrink, Schmidt, Delwiche, & Hummel, 2001), and leads to the hypothesis that certain wine aromas might be matched better to certain shapes/colors. The

present research also sought to explore odor-color-shape crossmodal correspondences in a complex odor matrix, using both abstract stimuli and realistic visual stimuli (i.e., wine labels).

Experiment 1.

Materials and Methods

Participants

Fifty participants (32 females; 18 males) with a mean age of 32 years (range of 20-60) took part in the study. All the participants were recruited based on their answers to an online pre-screening questionnaire. Potential participants who reported no visual or smell impairments and who had consumed white wine in the past 6 months were invited to participate. Additionally, all participants were checked for colorblindness, as determined by the Ishihara test for color deficiency (Ishihara, 1917). Sessions took place over the course of three days, and all 50 participants completed the study in its entirety. The study was conducted according to the Declaration of Helsinki—Ethical Principles for Medical Research Involving Human Subjects and approved by the University of Tennessee Institutional Review Board (IRB # UTK IRB-18-04258-XP).

Stimuli

Five odorants were used in the experiment to create: buttery, citrus, floral, smoky, and vegetable-forward wines (2,3-pentanedione, L-linalool, 2-phenylethanol, 2-methoxyphenol, and 2-isobutyl-3-methoxypyrazine, respectively). All odorants were purchased from Sigma Aldrich (St. Louis, Missouri). These wine odors were based off key attributes found in white wines, including chardonnay (Guth, 1997; Ryan, Watkins, Smith, Allen, & Marriott, 2005; Postel, & Güvenc, 1976; Lee, Seung-Joo, & Noble, 2003; Buettner, 2004). All odorants were diluted in 100 ml of 2016 Kendall Jackson Chardonnay (Santa Rosa, California) to their respective serving concentrations, found in Table 1. Concentrations were determined based on natural concentrations of odorants in selected white wines including chardonnay and then, through preliminary experimentation, the odorant concentration was increased until the odor attribute was just perceivable (Guth, 1997; Ryan et al., 2005; Postel et al., 1976; Lee et al., 2003; Buettner, 2004). More specifically, the research team determined the necessary level of each odorant to

modify the odor's character just enough that it could be reliably differentiated from the base wine.

Table 1. Odorants used to spike Chardonnay wine for aroma stimuli

Odorants	Aroma Quality	Average serving Conc. (ppb) [a]
2,3-pentadione	Buttery	1055
L-linalool	Citrus	550
2-phenylethanol	Floral	66035
2-methoxyphenol	Smoky	15.4
2-isobutyl-3-methoxypyrazine	Vegetable	0.07

[a] Calculated as the mean value of triplicates.

The visual stimuli consisted of 2 sets of 3D printed shapes found in Figure 1. One set contained four colored hemispheres (A). The colored hemispheres were measured for color by means of a HunterLab colorimeter (MiniScan XE Plus, Hunter Associates Laborities, Inc., Reston, VA) to obtain L*a*b coordinates, and converted to L*C*H (lightness, chroma, hue) coordinates, to get the exact position in the CIELAB color space (LCH values for color stimuli: Yellow- 81, 70, 81; Red- 32, 52, 38; Green- 43, 31, 159; Brown- 45, 24, 52). The other set (B) contained 4 different shapes (hemisphere, methane molecule, pyramid, and star) all white in color. The visual stimuli were designed to account for possible effects of object complexity. More specifically, both a complex (methane, star) and a simple (hemisphere, pyramid) were provided to each participant. Shapes were designed using Inventor® (AutoDesk Inc., San Rafael, California) and 3D printed using a uPrint SE Plus® (Stratasys, Eden Prairie, Minnesota). All shapes were roughly matched for size by equalizing the longest axis measurement across the stimuli (hemisphere: 7.8cm x 7.8cm x 4.2cm; methane: 7.6cm x 7.6cm x 7.6cm; pyramid: 6.5cm x 6.5cm x 6.5cm; star: 7.8cm x 7.8cm x 3.0cm).

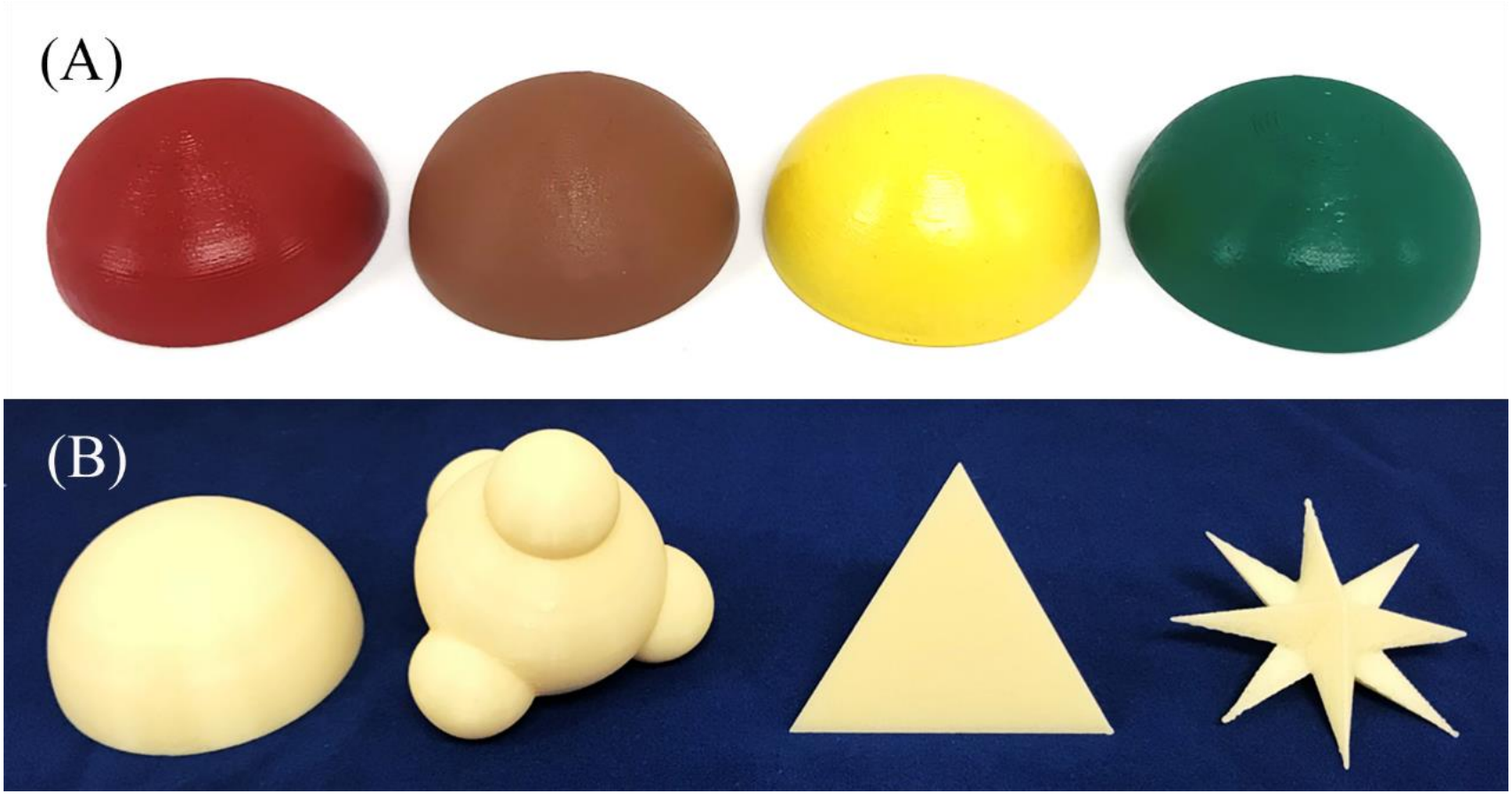


Figure 1.Visual stimuli used in projective mapping experiment. Set 1 (A): 3D printed colored hemispheres. Set 2 (B): 3D printed round and sharp shapes

Procedure

Upon arriving, the participants were given a brief training session on projective mapping. During evaluations, a sensory space (91cm x 91cm) was laid out, and all five wine samples were presented simultaneously with randomized 3-digit codes in covered wine glasses. Using Red Jade® software (Redwood City, California), participants were instructed to smell the headspace of the wines and distribute them on the sensory space based on similarities and differences. Wines that were considered similar in odor were to be placed closer together, and those that were considered different were to be placed further apart, and relative distances between samples would represent how extensive the participants perceived their similarities or differences. Participants were encouraged to use the whole space. After wine placement was completed, participants received one set of 3D objects (either colors or shapes) and were instructed to distribute them among the wines based on how well the objects matched the odors. Participants were then asked to transpose their projected map onto the provided tablets and explain how they made their placement decisions. The shapes were then removed from the sensory space, leaving the wines in their original position, and the next set of objects was presented for another similar evaluation. In all procedures the stimuli were provided to the participants as a set, in a random arrangement. Pleasantness scores for all wines and 3D objects were collected after the task was completed (9-point hedonic scale: 1=not at all pleasant, 9=extremely pleasant).

Statistical Analysis

X and Y coordinates were collected for all colors, shapes, and odors across all participants. R version 3.3.3 (R Core Team, Vienna, Austria) with the SensoMineR package version 1.23 (Husson, Le, & Cadoret, 2017) was used to run Multifactor Analysis (MFA) for odors, colors, and shapes. The MatrixCorrelation package version 0.9.2 (Liland, Naes, & Indahl, 2017) and the Hmisc package version 4.1-1 (Harrell, Dupont, and others, 2018) were used to generate a distance matrix, containing the Euclidean distances between points, taken pairwise, between the odors and colors, and the odors and shapes. Cluster analysis was then performed on the distance matrices to generate dendrogram plots to show the similarity among observations. Correlation analysis was also run on the distance matrices between odors and colors, as well as aromas and shapes to determine the strength of the associations. Analysis of variance (ANOVA) was run for the hedonic scores collected for all odors, shapes, and colors with Tukey HSD

adjustment using JMP 13.0.0 (SAS, Cary, NC). Open ended comments were coded into one-word descriptors and multiple correspondence analysis was used to analyze the descriptors about placements using JMP 13.0.0 (SAS, Cary, NC).

Results

Color/Odor Mapping

The MFA confidence ellipses for the projective mapping task for color and odor-spiked wines can be found in Figure 2. Yellow and green colors overlapped heavily with all chardonnay odors except vegetable, indicating that most variants of chardonnay odor were associated with these two colors. Dimensions 1 and 2 for color and odor mapping were of similar magnitude (19.7% and 19.1%, respectively).

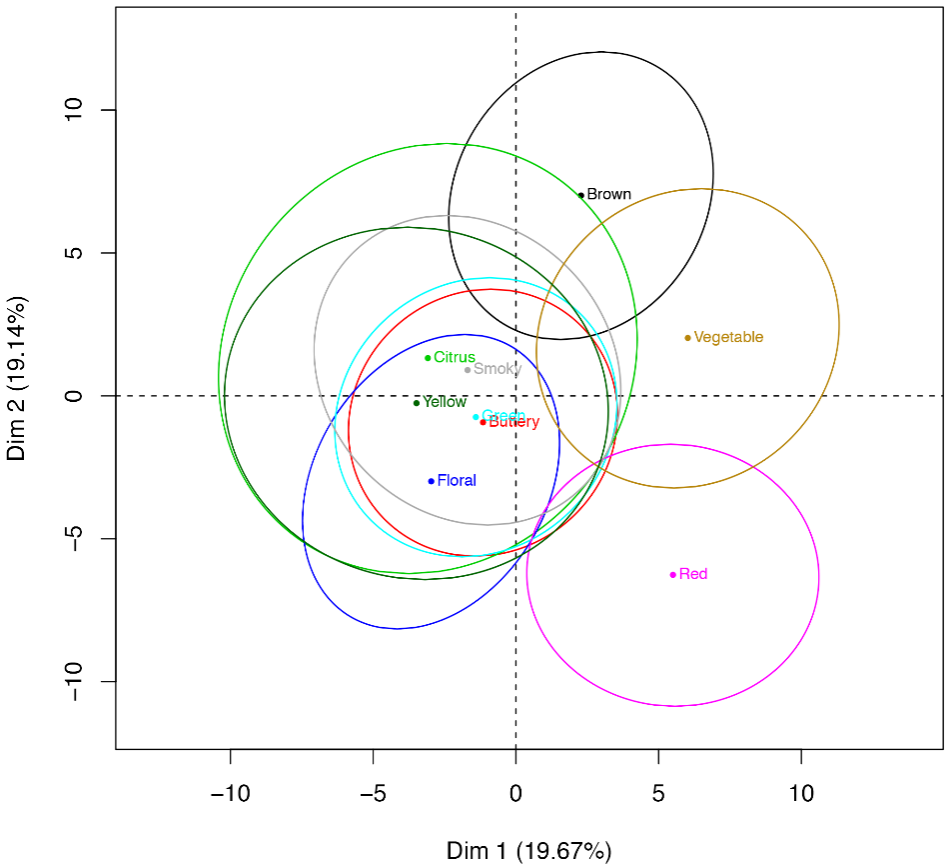


Figure 2. Confidence ellipses for modified projective mapping configuration for color and odor spiked wines.

Color/Odor Correlations

Pearson's correlations between the distance matrices for all odors and colors can be found in Table 2. Several significant pairwise comparisons were found between color and odor coordinates. The most notable correlation was a positive association between the smoky chardonnay and yellow ($r = 0.48$, $p < 0.0001$). Floral and green were also positively correlated ($r = 0.33$, $p = 0.0007$), as were citrus and green ($r = 0.27$, $p = 0.0068$). Citrus and brown were positively correlated ($r = 0.26$, $p = 0.0085$), as were buttery and yellow ($r = 0.20$, $p = 0.0417$). Lastly, a weak correlation was found for the vegetable chardonnay odor and red ($r = 0.22$, $p = 0.0267$). There was also a notable negative correlation between the vegetable and citrus chardonnays ($r = -0.22$, $p = 0.0303$).

Table 2. Pearson's correlation coefficients (r) among the distance matrices of 3D printed colors and odor-spiked wines.

	Buttery	Floral	Citrus	Vegetable	Smoky	Yellow	Green	Red	Brown
Buttery	-	0.12	-0.01	0.04	0.19	0.20	0.16	-0.03	0.01
Floral		-	0.16	-0.04	-0.02	0.08	0.33**	0.09	-0.06
Citrus			-	-0.22*	0.06	0.05	0.27**	-0.08	0.26**
Vegetable				-	0.17	0.12	0.14	0.22*	0.14
Smoky					-	0.48***	0.14	0.06	0.14
Yellow						-	0.12	0.02	-0.12
Green							-	0.04	0.06
Red								-	-0.16
Brown									-

*Significant at the 0.05 level.
**Significant at the 0.01 level.
***Significant at the 0.0001 level.

Shape/Odor Mapping

The MFA confidence ellipses for the projective mapping task of shapes and odors can be found in Figure 3. Round shapes (hemisphere and methane molecule) were heavily overlapped with citrus, floral, buttery, and smoky spiked wines, indicating that most of the chardonnay odor profiles were associated with rounder shapes. Sharp shapes (star and pyramid) were moderately grouped with the vegetable-spiked wine as indicated by the moderate overlap between them, but also in the distinct separation from the other grouping. Dimensions 1 and 2 for shape and odor accounted for 28.6% and 15.8% of the variance in mapping, respectively.

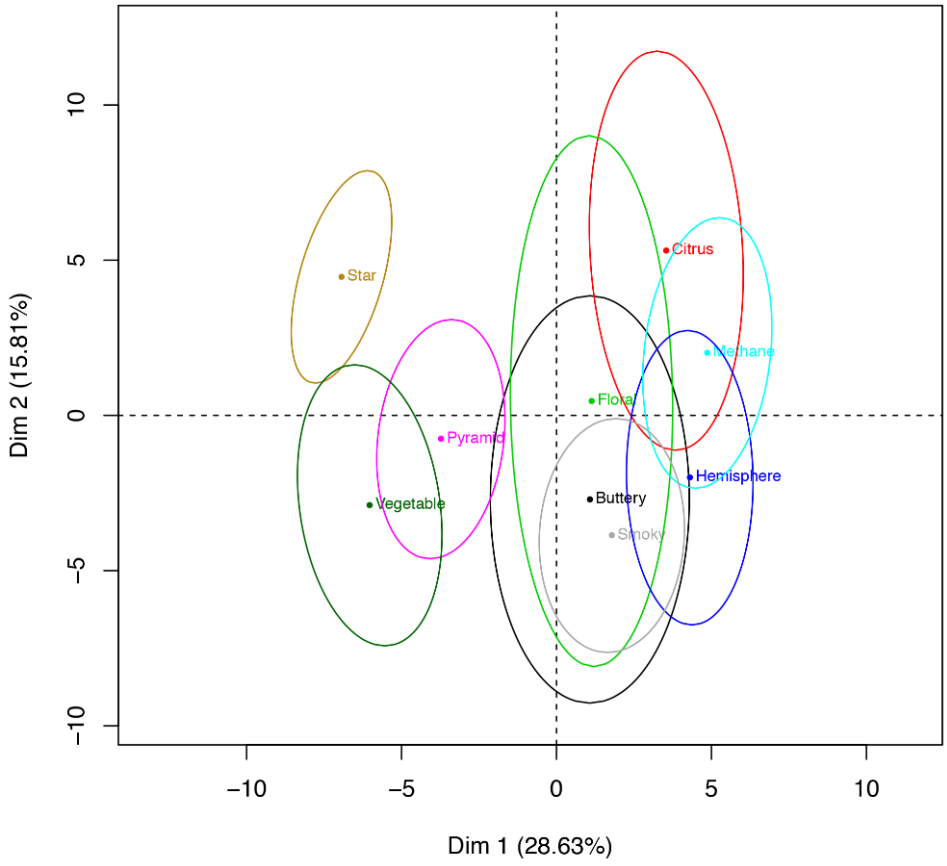


Figure 3. Confidence ellipses for modified projective mapping configuration for shapes and odor spiked wines.

The cluster dendrogram for the distance matrices of odors and shapes can be found in Figure 4 and is in agreement with the confidence ellipses indicating that two distinct clusters emerged, a “sharp” cluster and a “round” cluster. In the sharp cluster, it can be seen that the vegetable-forward chardonnay was associated with the sharper shapes (star and pyramid). In the round cluster, it can be seen that all other chardonnay odors (citrus, floral, buttery, and smoky) were associated with the rounder shapes (methane and hemisphere).

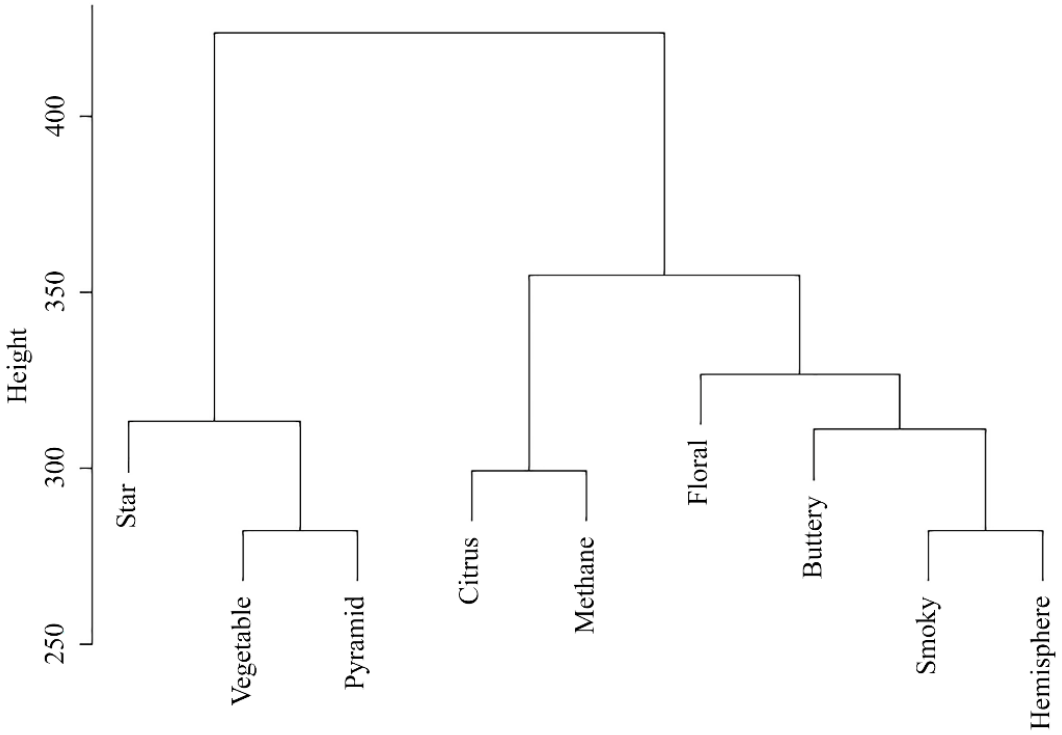


Figure 4. Cluster dendrogram of odor spiked wines and 3D printed shape and distance matrices.

Shape/Odor Correlations

There were also several significant correlations found between wine odor and shape of 3D objects. Pearson's correlations for distance matrices of all odors and shapes can be found in Table 3. The strongest correlation found was a positive relationship between the vegetable chardonnay and the pyramid ($r = 0.35$, $p = 0.0003$). Similarly, moderate positive correlations were found between vegetable chardonnay and the star ($r = 0.30$, $p = 0.0023$). Positive correlations were found between the citrus-forward wine and the methane ($r = 0.31$, $p = 0.0019$) and hemisphere ($r = 0.35$, $p = 0.0004$). Similarly, moderate positive correlations were found between the smoky-forward wine and the methane ($r = 0.30$, $p=0.0024$) and hemisphere ($r = 0.31$, $p = 0.0018$). Buttery chardonnay and methane had a positive correlation ($r = 0.27$, $p = 0.0069$), as well as floral chardonnay with methane ($r = 0.29$, $p = 0.0037$). Along those same lines, the floral chardonnay was also positively correlated with the other round shape, hemisphere ($r = 0.20$, $p = 0.0458$). As might be expected, the sharp shapes (star and pyramid) were positively correlated with each other ($r = 0.20$, $p = 0.0429$), and the round shapes (methane and hemisphere) were positively correlated with each other ($r = 0.36$, $p = 0.0002$). Additionally, the star and both round shapes were negatively correlated (star/methane: $r = -0.20$, $p = 0.0411$; star/hemisphere: $r = -0.33$, $p = 0.0008$).

Table 3. Pearson's correlation coefficients (r) among the distance matrices of the 3D printed shapes and odor-spiked wines.

	Buttery	Floral	Citrus	Vegetable	Smoky	Pyramid	Star	Methane	Hemisphere
Buttery	-	0.12	-0.02	0.05	0.18	0.08	-0.13	0.27**	0.15
Floral		-	0.12	-0.03	0.03	0.03	-0.02	0.29**	0.20*
Citrus			-	-0.20*	0.05	-0.07	-0.06	0.31**	0.35**
Vegetable				-	0.14	0.35**	0.30**	-0.03	-0.04
Smoky					-	0.14	-0.15	0.30**	0.31**
Pyramid						-	0.20*	-0.08	-0.15
Star							-	-0.20*	-0.33**
Methane								-	0.36**
Hemisphere									-

*Significant at the 0.05 level.
**Significant at the 0.01 level.

Hedonic Ratings

Round shapes were rated more pleasant than sharp shapes ($p < 0.0001$). Differences were found between odor pleasantness ($p < 0.0001$) with smoky, floral, and buttery odor characteristics were rated the most pleasant, whereas vegetable spiked wine was rated the least pleasant. Differences were also detected between color pleasantness ($p < 0.0001$) with green and yellow rated as the most pleasant colors, and brown rated as the least pleasant color. Hedonic mean values are reported in Table 4.

Table 4. LSMeans differences with Tukey HSD adjustment and standard error for hedonic pleasantness scores of wine aromas, colors, and shapes for projective mapping study.

		Mean ± Std. Error	p-value
Wine Aroma	Smoky	7.2 ± 0.2 A	< 0.0001
	Floral	6.7 ± 0.2 AB	
	Buttery	6.5 ± 0.3 AB	
	Citrus	6.1 ± 0.3 B	
	Vegetable	4.8 ± 0.4 C	
Color	Green	6.9 ± 0.2 A	< 0.0001
	Yellow	6.6 ± 0.2 A	
	Red	5.5 ± 0.3 B	
	Brown	4.5 ± 0.3 C	
Shapes	Round	6.5 ± 0.2 A	< 0.0001
	Sharp	5.5 ± 0.2 B	

Means in a column followed by like letters do not differ (α=0.05). 1= not at all pleasant; 9=extremely pleasant

Participant Reasoning for Sorting

Multiple correspondence analyses can be found in Figures 5 and 6. The comments from the color task revealed that people tended to associate brown with wines that had rotten, weak, boring, and earthy aromas. Yellow and green tended to be associated with chardonnays that were perceived to be balanced, fresh, mild, and neutral. Red was associated with the wines that had a more distinct aroma. However, only about 6% of the variation was explained by Dimension 1, and about 5.6% more variation was explained by Dimension 2.

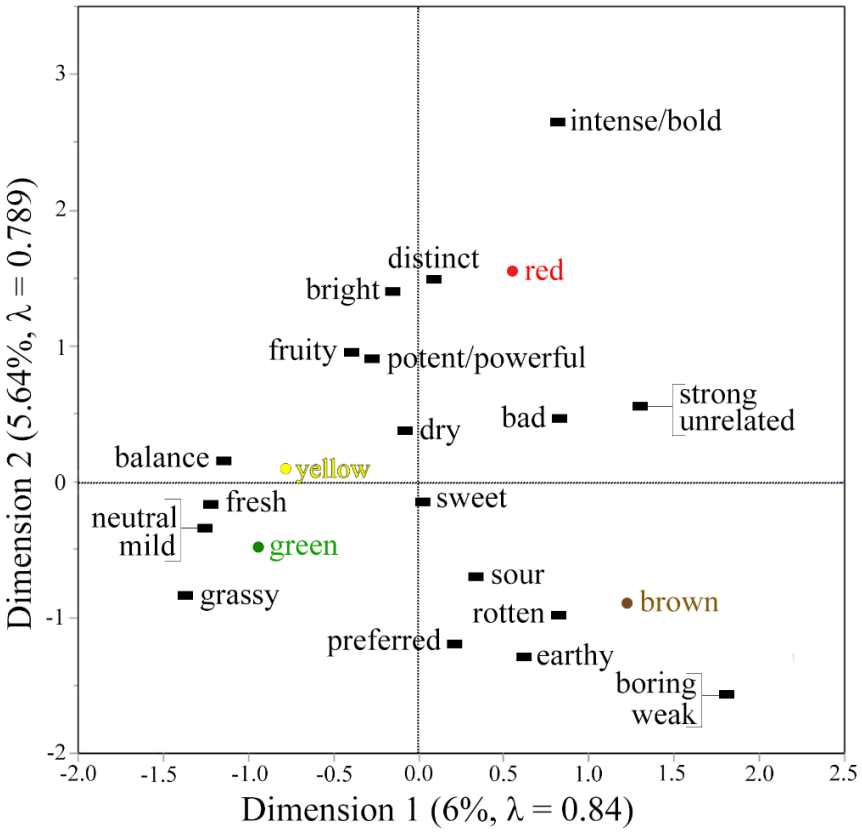


Figure 5. Correspondence analysis of words used by participants in describing their placement of the color stimuli.

The comments from the shape task revealed that people tended to associate the sharp shapes (pyramid and star) similarly, and the round shapes (methane and hemisphere) relatively similarly. Sharper shapes were associated with chardonnay aromas that were seen as pungent, strong, bitter, astringent, and bold. The rounded shapes were more associated with aromas seen as smooth, sweet, gentle, and floral. But again, only around 6.1% of the variation was explained by Dimension 1, and about 5% of variation by Dimension 2.

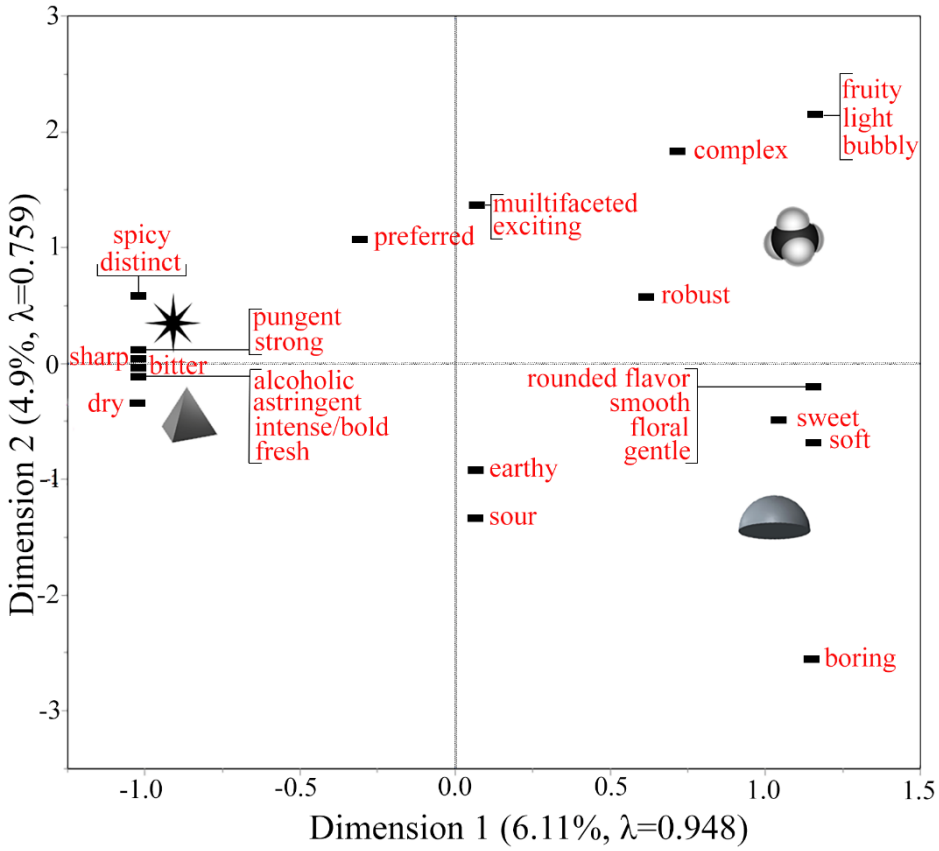


Figure 6. Correspondence analysis of words used by participants in describing their placement of shape stimuli

Discussion

The results from Experiment 1 provide some evidence of crossmodal correspondences between complex odors and colors and shapes. Moreover, the present work confirms such correspondences within a product category with nuanced differences between aroma profiles, which has received little attention apart from perfume applications (Fiore, 1993; Kim, 2011). Chardonnay odors as a whole were grouped similarly with yellow and green colors, regardless of odor character. When participants recognize an odor, they will select a color that characterizes the known olfactory source (Néhmé, Barbar, Maric, & Jacquot, 2016). Typically, results from other odor-color crossmodal studies tend to attribute odor and color matching based on the color of the origin of odor, but that isn't always the case (see Deroy et al., 2003, Jacquot et al., 2016, for examples). Associations with odor origin color were not consistently shown in the present study. 2-isobutyl-3-methoxypyrazine, the odorant used in the vegetable spiked wine, has a characteristic bell pepper odor. In most parts of the United States bell peppers in supermarkets are green and often referred to as green peppers. Interestingly, the wine spiked with bell pepper odor was not more associated with green. However, it has been noted that it is difficult for people to communicate smell experiences through words (Engen, 1982), and when they cannot recognize an odor, consumers will likely focus on odor pleasantness instead (Néhmé et al., 2016) and as such, it has been suggested that hedonics play a role in crossmodal correspondences (Deroy et al., 2013). Crossmodal correspondences, not being a strict origin phenomenon, has been noted previously with basic tastes (Spence, Wan, Woods, Velasco, Deng, Youssef, & Deroy, 2015), indicating that there are more to these crossmodal correspondences than the relationships between odors and their associated colors alone. Furthermore, several instances were found of colors being significantly associated with wine odors that have no discernable origin associations. For example, the citrus-forward wine was associated with brown and the smoke-forward wine was associated with yellow. Olfactory capability may benefit greatly from the visual cues that are presented, specifically color, implying the importance of crossmodal effects that occur between vision and smell (Spence, 2011; Zellner, 2013).

In regard to shape, chardonnays with buttery, citrus, floral and smoky odor profiles were similarly grouped with the round shapes, and vegetable with the sharp shapes. Odors that were rated more pleasant were grouped with the round shapes, and odors that were rated less pleasant

were grouped with the sharp shapes. This finding is consistent with previous studies and highlights a correlation between aroma liking and shape matching, with a tendency for the more pleasant aromas to be associated with rounder shapes and less pleasant aromas to be associated with angular shapes (Crisinel, Jacquier, Deroy, & Spence, 2013; Velasco, Woods, Deroy, & Spence, 2015). Our findings corroborate those of others and add to the conclusion that shape and color odor pairings might also be mediated by hedonics (Kaeppler, 2018). In the case of a hedonic origin of correspondences, people associate stimuli that they tend to like to the same degree (Schifferstein & Howell, 2015).

Additionally, curvature is claimed to be a basic, primitive concept, and is linked to emotional processing (Leder, Tinio, & Bar, 2011). Angular stimuli are found to be associated with threat (Arnoff, Barclay, & Stevenson, 1988), and emotion often dictates how people react to stimuli, after determining if it will increase or decrease their ability to satisfy one of their personal concerns (Schifferstein et al., 2003), and might explain the more negative scores given to the angular objects. The findings in the present study confirm that some odor-color-shape crossmodal interactions exist in complex odor matrices. Additionally, we found little evidence that the reasoning for arranging the wine and object stimuli were consistent through the participants. The correspondence analysis of the open-ended explanations for associating the stimuli together did not show overarching themes in associative reasoning. Similarly, the low variance components in the MFA analyses are evidence of a lack of consensus by the participants.

Experiment 2.

Materials and Methods

Participants

Fifty-two participants (27 females; 25 males) with a mean age of 31 years (range of 20-63) took part in the experiment. All participants completed a screening questionnaire preceding their experimental session. Only participants who had consumed white wine in the past 6 months were included in the study. Participants over age 65 were excluded due to documented reductions in olfactory ability and sinus issues. All participants had normal olfactory ability and no colorblindness as determined by the “Sniffin’ Sticks” test (Hummel, Sekinger, Wolf, Pauli, &

Kobal, 1997) and Ishihara test for color deficiency (Ishihara, 1917), respectively. The experimental procedure was conducted according to the Declaration of Helsinki—Ethical Principles for Medical Research Involving Human Subjects and was approved by the University of Tennessee Institutional Review Board (IRB # UTK IRB-17-03940-XP).

Stimuli

The same odor-spiked wine samples from Experiment 1 were prepared the same day of evaluations and served at room temperature. Each sample was presented in a covered wine glass and labeled with random 3-digit codes. The visual stimuli consisted of 8 wine labels (10 cm x 8 cm) affixed to wine bottles (375 mL). Two levels of angularity were presented as a label background image: rounded and sharp, as well as four colors: red, brown, yellow, and green (L*C*H values- yellow: 95 95 102, Red: 49 89 37, Green: 68 84 137, and Brown: 33 31 68). Hues were matched in terms of brightness, apart from the brown color which had a much lower brightness in order to distinguish it from orange (HSL lightness values of ~125). A small online study was performed to verify that the wine labels were indeed perceived to be different in their levels of angularity. Participants ($n = 14$) were asked to rate the labels on the "angularity of the label design" using a 10-point scale: 1= round, 10= angled. The label designed to be angular was rated 8.1 ± 1.0, while the label designed to be round was rated 4.1 ± 2.1 ($p < 0.0001$). Each wine bottle was referred to by a 4-digit code. The visual stimuli are shown in Figure 7.

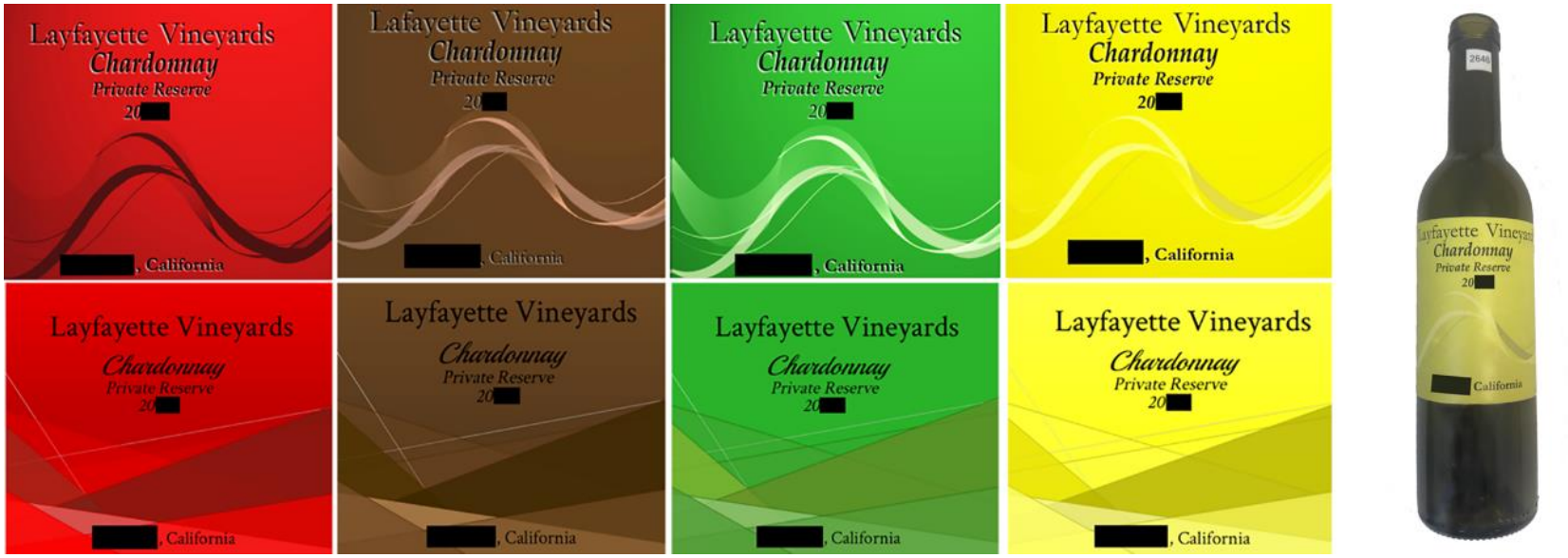


Figure 7. Wine labels affixed to wine bottles. Two levels of angularity were presented on label backgrounds: rounded and sharp, as well as four colors: red, brown, yellow, and green.

Procedure

During evaluations, a set of four colored labels with either rounded or sharp background images was presented to the subject; they then received one sample of odorant spiked wine. Using Red Jade software (Redwood City, California), participants were asked to rate how pleasant they found the odor (10-point scale: 1= not at all pleasant, 10=extremely pleasant), and were then asked to rate how well the odor matched each of the four labels (10-point scale: 1= not at all, 10= perfect match). After participants had responded, coffee beans were provided to aid in olfactory dishabituation and the next wine sample was presented. The same evaluation then occurred with the next set of wine labels. Additionally, the participants were asked to rate the label for liking, using a 9-point hedonic scale (1= dislike extremely, 9= like extremely).

Statistical Analysis

To compare matching scores, a repeated 3-way ANOVA, using odor, label color, and label angularity as fixed factors was ran considering interactions up to the second degree. Within each aroma, color matching scores were compared using simple LS means contrasts. The hedonic scores of the labels were assessed for an effect of angularity and color through a repeated 2-way ANOVA, using label color and label angularity as fixed factors. The hedonic scores of the odors were assessed through a repeated ANOVA, using the odor character as a factor. If a significant difference in means was determined by ANOVAs, post hoc comparisons between independent variables were conducted using a Tukey HSD adjustment. A statistically significant difference was defined as $p < 0.05$. Correlations between hedonic scores and matching scores were also evaluated. All analyses were run in JMP 13.0.0 (SAS, Cary, NC).

Results

Effect of color and angularity on odor matching

Crossmodal correspondence results for odors and angularity of background can be found in Table 5 and Figure 8. There was no significant interaction detected between wine odor and angularity or between angularity and color on label matching ($F_{4, 1593} = 0.09$, $p = 0.9861$, $\omega p^2 = 0$; $F_{4, 1593} = 1.14$, $p = 0.3342$, $\omega p^2 = 0.008$, respectively).

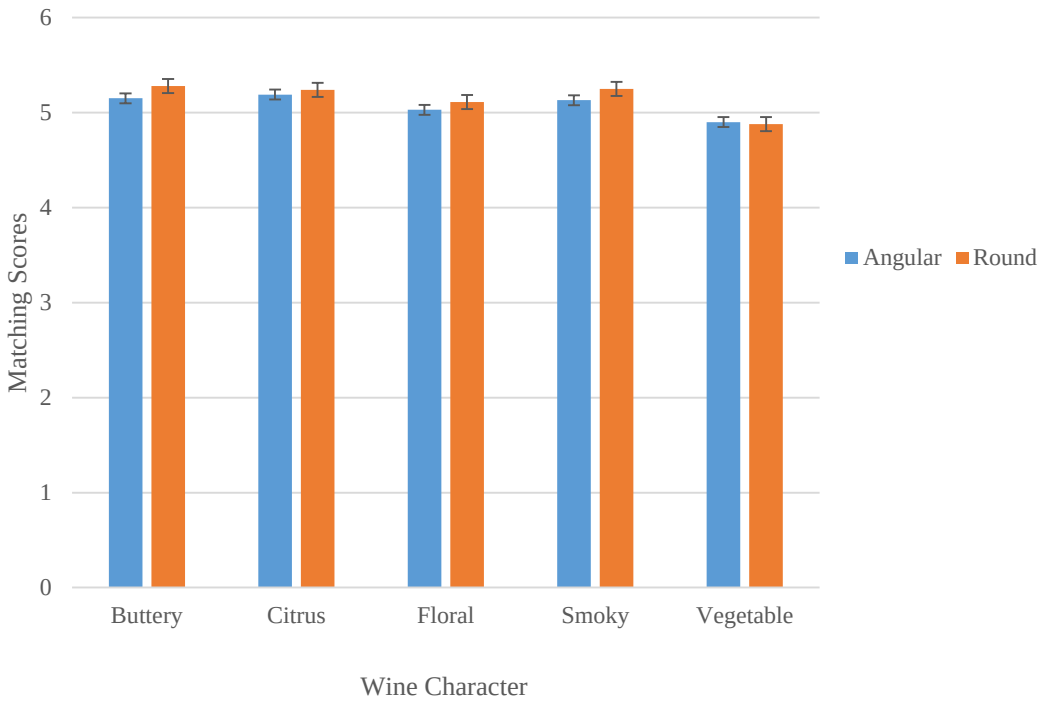


Figure 8. The effect of wine odor character on label angularity matching.

Table 5. LSMeans differences with Tukey HSD adjustment and std. error for aromas and angularity matching scores ($p < 0.0001$) for label study.

Odor	Angled	Round
Buttery	5.2 ± 0.2 A	5.3 ± 0.2 A
Citrus	5.2 ± 0.2 A	5.2 ± 0.2 A
Floral	5.0 ± 0.2 A	5.1 ± 0.2 A
Smoky	5.1 ± 0.2 A	5.3 ± 0.2 A
Vegetable	4.9 ± 0.2 A	4.9 ± 0.2 A

Means in a column or row followed by like letters do not differ (α=0.05). 1=not at all match; 10= perfect match

There was, however, a significant interaction between color and odor character on label matching ($F_{12, 1593}$ =3.76, $p < 0.0001$, $\omega p^2 = 0.389$). Angularity was a non-significant factor in the matching scores ($F_{1, 51} = 0.888$, $p = 0.3504$, $\omega p^2 = 0$). Results for odors and colors of background on matching scores can be found in Table 6 and Figure 9.

Table 6. LSMeans differences with Tukey HSD adjustment and std. error for aromas and color matching scores ($p < 0.0001$) for label study.

	Buttery	Citrus	Floral	Smoky	Vegetable
Yellow	6.7 ± 0.3 A	6.3 ± 0.3 A	5.9 ± 0.3 A	6.3 ± 0.3 A	5.1 ± 0.3 A
Green	5.6 ± 0.2 B	5.6 ± 0.3 AB	5.6 ± 0.3 AB	5.7 ± 0.3 AB	5.3 ± 0.2 A
Red	4.8 ± 0.3 BC	5.1 ± 0.3 B	4.7 ± 0.3 BC	4.7 ± 0.3 BC	4.4 ± 0.3 A
Brown	3.8 ± 0.3 C	3.8 ± 0.3 C	4.2 ± 0.3	4.1 ± 0.3 C	4.8 ± 0.3 A

Means within each column followed by like letters do not differ (α=0.05). 1= not at all match; 10= perfect match.

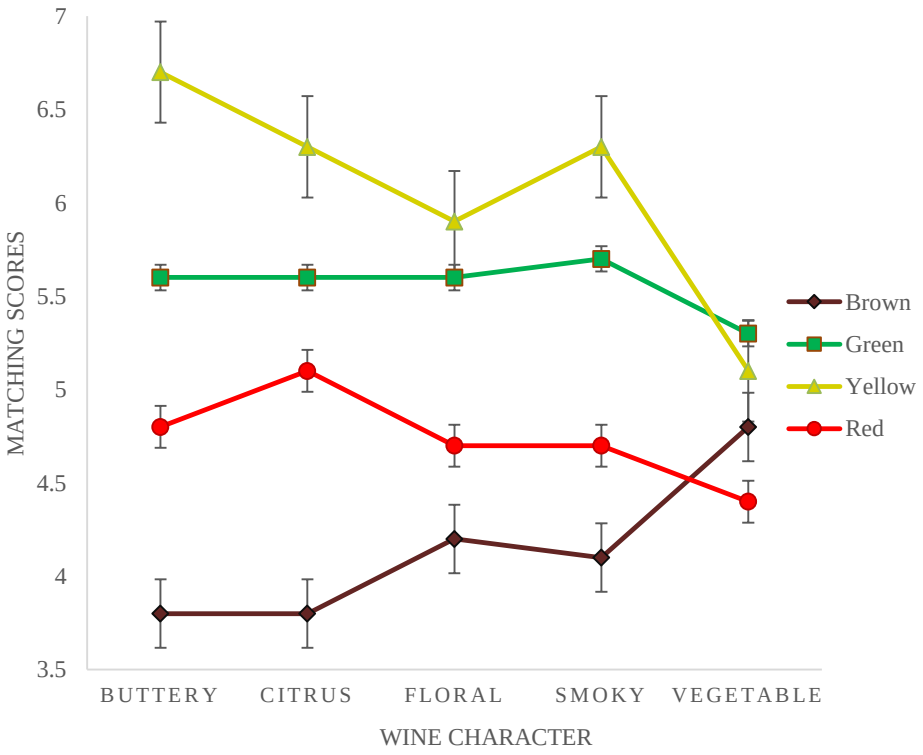


Figure 9. The effect of wine odor character on label color matching

Odor/Color Matching

Comparing how well each color was matched with buttery chardonnay, yellow was rated as a better match than red or brown ($p < 0.0001$). Similar results were found for citrus chardonnay with yellow, again, being a better match than red or brown ($p < 0.0001$). When comparing which colors were most associated with floral chardonnay, yellow was a better match than brown ($p = 0.0147$). Lastly when looking at the colors most associated with smoky chardonnay, it was again revealed that yellow was better matched than brown or red ($p = 0.0004$). No significant differences were detected between the colors associated with the vegetable chardonnay.

Hedonic Ratings

The liking scores of labels were affected by the label color ($F_{3, 153} = 22.3936$, $p < 0.0001$, $\omega p^2 = 0.552$), but not background angularity ($F_{1, 51} = 0.028$, $p = 0.9577$, $\omega p^2 = -0.020$). The wine odor liking scores were influenced by odor character ($F_{1, 51} = 10.1948$, $p < 0.0001$, $\omega p^2 = 0.414$). Buttery, citrus, and smoky were all rated as more pleasant than vegetable ($p = 0.0108$). Yellow and green labels were found to be more pleasant than red or brown ($p < 0.0001$). Mean separations can be found in Table 7. There was a significant positive correlation between stimuli liking and matching scores ($r = 0.2953$, $p < 0.0001$).

Table 7. LSMeans differences with Tukey HSD adjustment and std. error for hedonic pleasantness scores of wine aromas, colors, and angularities for label study.

		Mean ± Std. Error	p-value
Wine Aroma	Buttery	7.5 ± 0.1 A	< 0.0001
	Smoky	7.2 ± 0.1 AB	
	Citrus	7.1 ± 0.1 B	
	Floral	6.7 ± 0.1 C	
	Vegetable	5.9 ± 0.1 D	
Color	Yellow	6.0 ± 0.1 A	< 0.0001
	Green	6.0 ± 0.1 A	
	Red	5.3 ± 0.1 B	
	Brown	3.9 ± 0.1 C	
Angularity	Round	5.3 ± 0.1 A	0.8129
	Sharp	5.3 ± 0.1 A	

Means in a column followed by like letters do not differ (α=0.05). 1= not at all pleasant; 9=extremely pleasant

Discussion

Expanding upon results of Experiment 1, Experiment 2 sought to test odor-color-shape crossmodal interactions with more real-world stimuli. This test is especially important since, in reality, objects are almost always perceived in some setting or context that can play a substantial role in how the food attributes are perceived (Piqueras-Fiszman & Spence, 2015). It is interesting to note that manipulation of a tasting room environment (audiovisual display and background soundtrack) has been shown to elicit changes in the perception of flavor notes found in whiskey (Velasco, Jones, King, & Spence, 2013). This work shows that changes in atmospheres, or environmental cues, can emphasize different attributes within the same product, and in turn, highlight particular flavor or aroma characteristics. Studies have indeed shown that meaningful context does affect perception (Biederman, 1972) and labeling is especially important as a means to relay information to the consumer and is one of the most important criteria relied upon to differentiate products (Giraud, & Trigui, 2005). This is an important distinction as most packaging studies tend to focus on receptacles that are in direct contact with the product, but indicates that manipulating the context in which the product is presented may still elicit perceptual changes.

Contrary to image studies that have shown crossmodal associations between image angularity and taste/flavor perception (Spence et al., 2011; Ngo et al., 2012), no association was found between angularities of the background image (round and sharp) on odor matching scores. It is possible that subtle stimuli might not garner enough attention from the subject to actually elicit a significant correspondence. It has been suggested that manipulation of label image alone might be too weak in itself, and manipulation of the actual package shape might be necessary to elicit the interaction as found in previous studies (Becker et al, 2011; Velasco et al, 2015). Within this study the lack of an influence of angularity on label liking points towards the possibility that participants did not notice the angularity stimuli of the label. However, wine labels have limitations on the range of angularity that can be presented. Selective attention is the mechanism by which our brain prioritizes its constrained neural resources toward the processing of certain ‘more relevant’ information over other less important information (Spence, 2014). Consumers employ various strategies when evaluating complex products, and differ the extent to which they pay attention to different product aspects (Carbon & Leder, 2005; Sujan, 1985). One particular study found that when manipulating the colors on a fragrance package, the appropriateness of color was determined mainly by the major color used, whereas the additional

colors had smaller or no effects (Schifferstein et al., 2017). It has been noted that not all of packaging attributes necessarily affect consumers' sensory evaluation of the contents in the same way, nor for all consumers equally. For example, researchers found effects only amongst those participants with a sensitivity to design (Becker et al, 2011), which could help explain why the background image did not elicit a stronger crossmodal association. There is a surprising lack of information as to how label shape (e.g. rectangular or oval) might influence perception, and would be an area of future research.

As with Experiment 1, these results highlight a statistically significant correlation between hedonic liking scores of odors and labels with matching scores, again indicating that hedonics play a key role in modulating crossmodal interactions, but does not account for the entirety of the effect. In agreement with (Ngo et al., 2011) hedonics mediated how odors were matched with shapes, but played a larger role with more overt stimuli (e.g. experiment 1- angular shapes associated with bitter & sharp aromas), however, once subtlety became a factor panelists did not associate any of the chardonnay aromas with the angular background image.

Recently a crossmodal study with label color and flavor found that a beer label with increased levels of green led to significantly higher ratings in terms of fruity/citrus notes present in the beer, as opposed to a brown label (Barnett et al., 2016). In agreement with Schifferstein et al. (2004), we found that people did in fact associate chardonnay aroma with the color yellow, indicating that perceptual learning maybe an underlying factor. But, in agreement with Demattè (2006), while the yellow label was generally better matched to the wines, regardless of subtle differences in odor, there were varying color associations with chardonnay odors of different character. This evidence could be interpreted against the construct that crossmodal correspondences are simply based on odor origin, as all odors in this study were representative of chardonnay which is yellow in color. These findings, taken together, provide evidence that crossmodal correspondences are not formed by a single mechanism. In another packaging study, it was found that the color of a candy wrapper had less impact on flavor expectations than the color of the candy itself and suggests that judgments of a food product are strongly influenced by attributes integral to the food and not the packaging alone (Zellner, Greene, Jimenez, Calderon, Diaz, & Sheraton, 2018). However, it would be interesting future research to assess whether a yellow label would increase the perception of citrus, or buttery as opposed to the other colored labels.

The vegetable-forward sample was the lone exception to the higher matching scores with the yellow label. This finding is one of several in which the vegetable-forward wine shows notable differentiation to the other wine samples. We believe there may be potentially three explanations for such a consistent deviation. First of all, the vegetable-forward chardonnay was regularly rated to be the least pleasant and, in parallel, the brown label was determined unpleasant by the participants. Maric et al. (2013) found similar findings, and determined that darker colors tend to be rated less pleasant, and as such, are correlated to odors that are rated to be less pleasant.

Secondly, vegetable-forward chardonnay may not be commonly experienced and therefore seen as unusual compared to the other, more familiar chardonnay odor variants. Within white wines, vegetal notes are more associated with wines such as Sauvignon Blanc due to their higher methoxypyrazine content (Alberts, Stander, Paul, de Villiers, 2009). Less familiar odors have been shown to be more difficult to retrieve from memory, and thus participants could have had a greater difficulty to associate it with an appropriate color (Jacquot et al., 2016).

Thirdly, the odor could be perceived as more pungent, creating a slight chemesthetic sensation perceived to be unique. The brown label tended to be matched least with every wine regardless of its odor profile, except, again, for the vegetable spiked wine. This finding indicates that more nuanced odor-color crossmodal correspondences are still relevant, even with complex aromas, and in a more authentic context. Additional experiments would need to be conducted to better understand the phenomena observed and support these hypotheses.

This series of two experiments has several experimental limitations that should be taken in to account when discussing the findings. First, the odorants were not matched for intensity in a traditional manner. The odorant levels were determined in relationship to the base wine, not in regard to each other. The possibility exists for some variance in perceived odor intensity across the participants, and subsequent effects of odor strength on the results. Additionally, when heightening the levels of odors already found in the wine, controlling for pleasantness is not always possible, as some components of chardonnay odor are generally more pleasant. Lastly, regarding the salience of the visual stimuli, it is entirely possible that participants were unaware of the variations in label angularity. In this case, the authors find that as an interesting difference between a functional visual stimulus and one designed solely for a study on crossmodal correspondences.

Conclusion

Our results provide support for the existence of crossmodal associations between odors, colors, and shapes. However, the level of interaction was not found to be as strong as in more controlled environments. In Experiment 1, we demonstrated there were indeed associations between odors in a complex odor matrix with certain colors and shapes. In Experiment 2, we sought to test these associations with more real-life stimuli and found significant interactions between odors and colors, but none between odors and angularity.

Future research is needed to determine the amount of influence these correspondences exert over our perception, as this study sought only to match odors to colors and shapes. The factors that mediate crossmodal correspondences also need further exploration, more specifically, with emotion in regard to odor-color-shape matching. It has been proposed that simple stimuli, such as colors, shapes, and musical fragments could be matched directly to emotions and may also be a mechanism for crossmodal correspondences (Collier, 1996). There is some evidence for emotion as a moderating factor in crossmodal correspondence, as research has shown that smooth textures are associated with pleasantness, comfort, and relief (Etzi, Spence, Zampini, & Gallace, 2016). Furthermore, pleasure has been proposed as the emotional dimension that is most likely responsible for the odor-color relationship, and it has been shown an odors most salient attribute is pleasantness (Schifferstein et al, 2003).

The findings of the present study help to bring a better understanding of crossmodal correspondences by providing evidence of odor associations with both colors and shapes. Moreover, the current work brings the perspective of complex and real-life stimuli to the study on correspondences of odor-color-shape interactions. The present findings have potential applications in the food industry, helping to bridge the gap between theoretical measurements of crossmodal correspondences with real world application. Specifically, valuable data that some packaging characteristics match specific complex odor profiles better than others might be provided.

CHAPTER II
SENSITIVITY TO SUBTLE CHANGES IN WINE ODOR

Abstract

The goal of this study was to determine whether odor mixtures were easier to discriminate when an odorant was added, or when an odor was removed. We further wished to evaluate whether expertise had any bearing on discrimination abilities. To do this, wine experts and novices were used to assess whether discrimination was altered with the addition/subtraction tasks. After producing a model wine odor in which odorant could easily be manipulated, a homologous series of esters, varying in chain length, were chosen as odor modifiers. A-not-A tests were then used to gauge the discriminatory ability of experts and novices. Panelists as a whole were not able to discriminate between either the addition or subtraction samples compared to their base counterparts. Furthermore, expertise did not seem to play a role in discriminatory abilities either, with experts and novices producing similar d' scores. Overall, the d' values were consistently low and demonstrated that the stimuli were challenging to discriminate between.

Introduction

Single odorants are seemingly straightforward in their perception. It has been determined that the quality of an odor is largely attributed to the chemical structure of the odorant (Thomas-Danguin et al., 2014; Chastrette, 1997; Gaudin, 2007; Sanz, 2008; Kaeppler & Mueller, 2013; Snitz et al., 2013). The intensity is credited to the concentration of the odorant (Thomas-Danguin et al., 2014; Stevens, 1960; Berglund, Berglund, & Lindvall, 1976; Chastrette, Thomas-Danguin, & Rallet, 1998; Devos, Rouault, & Laffort, 2002). Many studies have addressed olfactory perception from different angles such as discrimination, identification, and sensitivity; however, most studies have used these simple monomolecular odorants as stimuli (Thomas-Danguin et al., 2014).

Our knowledge of odor mixture perception is not nearly as clear as our understanding of singular odorant perception. There are several phenomena that can complicate attempts to understand odor mixture perception. For example, individual components can still be perceived within the mixture, where blending has not occurred and implies some type of analytical olfactory processing (Berglund & Olsson, 1993). Sometimes a new odor quality is produced altogether. The idea that odor mixtures are not merely a sum of their parts, but can actually have distinct odor qualities apart from their constituents is not a new one (Foster, Scofield, & Dallenbach, 1950). This new distinct odor mixture is called a blending mixture (Thomas-Danguin, Le Berre, Barkat, Coureaud, & Sicard, 2007). These unique blended odor qualities have been termed “odor objects” (Weiss & Vickers, 2016; Derby, Hutson, Livermore, & Lynn, 1995; Thomas- Danguin et al., 2014), and are arguably the way we encounter most every day odors. So, it becomes the challenge of our sense of smell, to actually extract relevant information from these highly complicated odor mixtures (Thomas-Danguin et al., 2014).

One proposed method for how we can still recognize and use olfactory information from these complex odor mixtures is that the olfactory cortex still allows for recognition, despite unavoidable changes in the same odor each time we encounter it (Weiss et al., 2016). The cortex does this through what has become known as pattern completion. Pattern completion, is when incoming odor stimuli creates a pattern, which activates a match in our stored memory, allowing the brain to fill in the gaps and complete the pattern, making perception and recognition possible (Weiss et al., 2016; Wilson & Sullivan, 2011). Theoretically, pattern matching might suggest that

humans would have a difficult time discriminating between odor mixtures and the same mixture with one missing component, since the brain would fill in the missing piece (Wilson et al., 2001).

The concept of discriminating between an odor mixture and the same mixture with an odorant removed is known as omission testing. This type if testing is often used to determine which odorants are of importance in an odor object. If people can tell if an odor has been removed, then it is of important value to the odor object. In omission testing, a model target odor is created through a series of instrumental and sensory testing in concentrations based on the naturally occurring stimuli (Weiss et al., 2016). Once the model has been constructed, individual or groups of odorants can then be removed, or omitted, to create partial models (Weiss et al., 2016; Gao, Fan, & Xu, 2014; Guth & Grosch, 1994; Kiatbenjakul, Intarapichet, & Cadwallader, 2015; Mayer, Czerny, & Grosch, 2000; Pavez et al., 2015). On the other hand, studies focusing on odor discrimination have shown that people are very sensitive to small concentrations of added odorants, or contaminants that are not usually found within a complex odor mixture (Laing &Wilcox, 1983).

It has been shown empirically that a high familiarity with the majority component also aids in the detection, of both minor and major components (Rabin, 1988). Indeed, wine experts have shown higher accuracy at matching wines than novices, suggesting better memory recall (Hughson, 2002; Melcher et al., 1996). It has also been shown that the ability to label odors, regardless of expertise, is moderately correlated to discrimination (Rabin, 1988). In a study recently released by Poupon (2018), training sessions improved the performance of identification by wine novices to that of sommeliers, but only with single odorants, not with two or more. They stated that expertise allows for identification abilities of up to 4 odorants within a mixture (Poupon, Fernandez, Boisvert, Migneault-Bouchard, & Frasnelli, 2018).

Similarly, it has been shown that detection is more difficult if the minor component is unfamiliar. Pleasantness of constituents is also a factor with stimuli gauged as unpleasant being easier to detect than ones that are gauged as pleasant, however this effect is not as large as with familiarity (Rabin, 1988).

However, familiarity and experience with odorants does not always lead to better olfactory performance. While olfactory recognition by wine experts has been shown to be superior, they show similar sensitivities and bias measures to novices (Parr, Heatherbell, & White, 2002). Hughson (2002) suggests that expertise relies heavily on knowledge about wine,

and part of the reason novices cannot perform to the ability of experts is because they lack the vocabulary and knowledge that experts use in such tasks. (Hughson, & Boakes, 2002).

The objectives of the present research are three-fold. First, since it has been shown that experts have more familiarity with wine odors and olfactory recognition, we wish to determine if experts are better at discriminating between complex wine odor mixtures than novices. Thus, the first hypothesis is that experts are better at discriminating between wine odor mixtures than novices. Studies using rodent models have indicated that odor mixtures with one odor removed (n-1) can be difficult to discriminate, but show it is easier to discriminate between a full odor mixture and one where the missing odorant was replaced by a completely different odorant (n + 1) (Barnes et al., 2008; Lovitz, Sloan, Rennaker, & Wilson, 2012). Secondly, we wish to investigate whether humans, in general, are better at detecting whether an odor has been added or has been removed from a complex odor mixture. Thus, we wanted to assess whether humans are better at detecting when an odor has been added to a complex odor matrix than when an odor has been removed from a complex odor matrix. Finally, it has also been shown that humans show a relatively high miss rate when presented with identical samples, in fact 28% of people reported identical perfumes as different, and 17% rated distilled water samples as different (Eisenson et al., 1954) and when Laska (1992) presented identical samples of odor mixtures, panelists judged them to be different from each other 50% or more. Implying that we, as humans, want to detect a difference, even when one does not necessarily exist. Lastly, we wish to evaluate whether subjects indicate they detect a difference in same samples at the same rate in which they indicate they detect no difference in different samples. Hence, the third hypothesis: humans indicate samples are different at a higher rate than they indicate them as similar.

Materials and Methods

Participants

Two groups of participants were used in the study, novice wine drinkers and wine judging experts. All novice participants were recruited by the University of Tennessee's sensory database, comprised of individuals who have expressed an interest in participating in sensory tests and research projects. The novice group was comprised of 36 individuals, (19 females; 17 males) with a mean age of 32.2 (range of 20-59).

Twenty wine experts were included in the study and were comprised of 8 females and 12 males. Experts were classified in a similar way to previous wine expert studies and fell into one of the following categories: established wine makers, wine researchers or teaching staff who are regularly involved in wine-making and/or wine evaluation, wine professionals (e.g. Masters of wine, wine judges, wine writers, and wine retailers) (Melcher & Schooler, 1996; Bende & Nordin, 1997; Parr, W. V., Heatherbell, D., & White, K. G., 2002). More specifically, however, all wine experts were AWS (American Wine Society) or CWS certified (Certified Wine Specialist). Experts were recruited from The University of Tennessee's annual wine competition, Wines of the South. All participants signed an informed consent and were compensated for their time. This experiment was conducted according to the Declaration of Helsinki for studies on human subjects and approved by the University of Tennessee IRB review for research involving human subjects (IRB #18- 04485-XP).

Stimuli

Materials

Joh. Jos. Prüm**,** a 2009 Riesling Kabinett produced in Wehlen, Germany, was purchased from a local distributor. The wine was selected as a target for the development of an odor model reminiscent of general white wine character.

Reference odorants.

The odorants used to assist in compound verification and to create the stimuli, namely ethyl hexanoate, ethyl octanoate, (*E*)-*β*-damascenone ((E)-1-(2,6,6-trimethylcyclohexa-1,3-dien-1-yl)but-2-en-1-one), linalool (3,7-dimethylocta-1,6-dien-3-ol), cis-rose oxide ((2*S*,4*R*)-4-methyl-2-(2-methylprop-1-enyl)oxane), ethyl propanoate, ethyl 2-methylpropanoate, ethyl butyrate (ethyl butanoate), ethyl 2-methylbutanoate and ethyl 3-methylbutanoate, were purchased from Sigma Aldrich (St. Louis, Missouri). Additionally, wine lactone (3,6-dimethyl-3,3a,4,5-tetrahydrobenzofuran-2(7aH)-one) was purchased from eNovation Chemicals LLC (Bridgewater, New Jersey).

Isotopically labeled compounds.

The following labeled isotopes ($^2H_{15}$)ethyl octanoate, ($^2H_{11}$)ethyl hexanoate and ($^2H_3$)linalool were acquired from C/D/N Isotopes Inc. (Quebec, Canada), and ($^2H_4$)*β*-damascenone was acquired from aromaLAB (Planegg, Germany).

Additional chemicals.

Un-stabilized diethyl ether (ethoxyethane) (Honeywell Burdick & Jackson) and anhydrous sodium sulfate were purchased from Fisher Scientific (Waltham, Massachusetts). Sodium chloride and 200 proof ethyl alcohol were acquired from Sigma Aldrich (St. Louis, Missouri).

Volatile Compound Isolation.

To isolate the volatile compounds present in the wine, the wine was subjected to organic extraction followed by solvent assisted flavor evaporation (SAFE). Sodium chloride (10 g) was combined with a portion of the wine (100 mL) and agitated to dissolve at room temperature. In a separatory funnel, the wine solution was combined with freshly distilled diethyl ether (100 mL) and manually extracted by vigorous shaking (5 minutes). The aqueous and organic phases were separated, and the aqueous phase was extracted with additional diethyl ether (50 mL) in the same manor. The aqueous phase was discarded, and the organic phases were combined with a saturated salt solution (50 mL) and extracted for an additional five minutes. The ether extract was dried over anhydrous sodium sulfate and subjected to SAFE. The SAFE apparatus was maintained at 41 °C with a 10^{-4} mbar vacuum throughout the isolation process. The volatile isolate was condensed to 2 mL on a Vigreux column and then to 200 μL under a gentle stream of nitrogen.

Aroma Extract Dilution Analysis (AEDA).

Serial dilutions of the SAFE isolate containing the wine volatiles were prepared and evaluated by aroma extract dilution analysis (AEDA). Each of the eleven flavor dilutions (FDs), ranging from the pure SAFE isolate (FD 1) to the most dilute isolate (FD 1024), were individually analyzed by gas chromatography-olfactometry (GC-O). The odor quality and the lowest dilution at which each aroma was perceivable was documented in order to determine the odorants that have the greatest potential to contribute to the characteristic odor of the wine.

Gas Chromatography- Olfactometry (GC-O).

An Agilent Technologies 7820A GC system (Santa Clara, CA) with a Zebron™ ZB-FFAP GC capillary column (30 m x 0.32 mm OD x 0.25 µm film thickness) from Phenomenex (Torrance, CA) was employed. Helium was used as the carrier gas (1.5 mL/minute) and each isolate (1 µL) was injected on column. After injection, the oven temperature was held at 35° C for one minute, followed by a ramp in temperature to 60 °C at a rate of 60 °C/minute. The temperature was then increased to 240° C at a rate of 6° C/minute with a final hold time of ten minutes at 240° C. At the end of the capillary column the effluent was divided and channeled to sniffing port (250° C) or a flame ionization detector (250 °C) with air flow of 450 mL/minute, hydrogen flow of 40 mL/minute and makeup flow of 45 mL/minute.

Stable Isotope Dilution Assays (SIDAs).

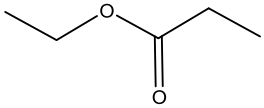
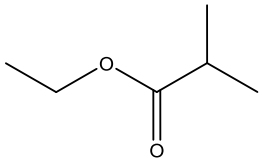
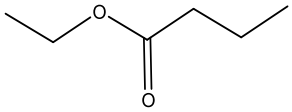
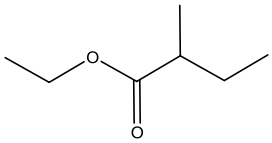
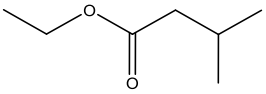
Select compounds with high FD factors, as determined by AEDA, were quantified by stabile isotope dilution assays (SIDAs). The sample preparation detailed previously was employed with the addition of deuterium labelled isotope solutions (20 µL) to the wine prior to extraction. After extraction, SAFE isolation and condensation, the volatile isolates were analyzed by gas chromatography-mass spectrometry (GCMS). The concentration of each odorant of interest was quantified in the wine using the ratio of concentration and peak area of the labelled isotope and analogous compound. For each of the analytes the following response factors (RFs) was calculated: ethyl hexanoate, m/z 99/110, RF 0.90; ethyl octanoate, m/z 127/142, RF 0.93; (*E*)-*β*-damascenone, m/z 69/73, RF 0.85; linalool, m/z 93/96, RF 0.85.

An isotopically labelled analog to cis-rose oxide and wine lactone were not available so cis-rose oxide was quantified by external calibration and a previously published concentration was used for wine lactone (Guth, 1997). Based on this quantification and empirical modifications an odor model base was designed (Table 8) which exhibited an odor characteristic of white wine. Additionally, a series five homologous esters, which varied in chain length, were selected as odor modifiers and individually added to the wine base odor at detection thresholds which were derived from relevant literature (Table 9).

Table 8. Odorants that were included in the odor model base developed with instrumental methods to produce odor reminiscent of the target white wine

wine base odorants	**concentration (ppb)**
ethyl octanoate	655.8
ethyl hexanoate	454.9
(*E*)-*β*-damascenone	2.514
linalool	7.359
wine lactone	0.1000
cis-rose oxide	0.1750

Table 9. Odorants that were individually added to the wine base at detection thresholds ([2]Kahn, 1968; [3]Czerny, 2008, [4]Munafo, 2016).

Odor modifiers	**Chemical Structure**	**Threshold Concentration (ppb)**	**Serving Concentration (ppb)** [a]
ethyl propanoate		3452[2]	3650
ethyl 2-methylpropanoate		0.089[3]	0.089
ethyl butyrate		0.76[3]	0.77
ethyl 2-methylbutanoate		0.008[4]	0.008
ethyl 3-methylbutanoate		0.023[3]	0.024

[a] Concentrations reported as the average over all testing sessions.

Gas Chromatography-Mass Spectrometry (GC-MS).

A Zebron™ ZB-FFAP GC capillary column (30 m x 0.25 mm OD x 0.25 µm film thickness) from Phenomenex (Torrance, CA) connected to an Agilent Technologies 78204 GC system (Santa Clara, CA) was used for analysis of volatile isolates. The prepared isolate (1µL) was injected on column with helium as the carrier gas (1 mL/ minute). Upon injection the oven temperature was maintained a 35° C for one minute before increasing at a rate of 60° C/min to reach 60° C. Then the temperature was increase at 6° C/min until it reached 250° C and was held at this temperature for 5 minutes. At the end of the capillary column the effluent was transferred via a heated transfer line to an Agilent Technologies 5977B mass spectrometry detector (Santa Clara, CA). The detector functioned in electron ionization mode at a voltage of 70 eV and the MS source and MS quadrupole were heated to 230° C and 150° C, respectively.

Wine Matrix Construction

To create the white wine base, a matrix of 9% ethanol, and 3.2% sugar was created with distilled water. The solution was colored for context, using food dye (155, AmeriColor Corp, Placentia, CA). For the wine base, only the odor model base was added to the ethanol matrix. For all other modified wines, the odor model base as well as an individual modifier was added. All wine odor mixtures were prepared the day of evaluations and kept at room temperature. Thirty-five mL of each sample was served in clear 150 mL glasses and covered with a 70 mm watch glass and a 3-digit random code label.

Procedure

Wine experts and novice's ability to differentiate between wine odor mixtures were assessed through a series of A-not-A tests. In an A-not-A test, two samples are provided to the subject. One sample is a reference (A) followed by a second sample (random 3-digit number) in which the subject has to determine whether or not the numbered sample is identical to (A). Testing took place over two days, except in the case of experts in which sessions occurred during the same day with at least a 10-minute break in between sessions.

To test whether a subject had the ability to detect differences between a mixture and the same mixture that had an odorant added (n + 1), the base stimuli was presented to the subject as the reference (A) followed by either an identical sample, or the base stimuli containing an added modifier (not A). The subject was then asked to determine whether or not it was identical to the

reference sample. Samples were served in a randomized order, with the reference sample always being the base stimuli.

A similar test protocol was used to assess whether subjects had the ability to detect differences in mixtures in which an odorant had been removed. This was accomplished by presenting one of the modified stimuli as the reference, A, followed by either an identical sample or the base stimuli (same mixture as reference but with the absent modifier), not A, and the subject was to determine whether or not it was identical to the reference sample. Samples were served in a randomized order, with the reference sample always being one of the 5 modified odor mixtures.

To ensure panelists were consistent in how they evaluated all samples, a protocol was explained fully to each panelist before each session. This consisted of proper handling instructions, in which panelists were instructed to pick up the glass, remove the watch glass, swirl the contents in glass for 5 sec. Panelists were also given further instructions, such as: place your nose in the glass and inhale deeply through nose for 3-5 sec, you can smell again if desired but cannot go back once you move on to the second sample. Lastly, panelists were given resting instructions, such that a 60 sec timer will begin between samples and this time can be used to breathe normally or take a sip of water.

Pleasantness, Familiarity, and Intensity of Stimuli

The intensity of the odor modifiers was a critical factor in the design. It has been shown that when an odor mixture has one component with a strong intensity, and thus completely covers the other, complete overshadowing or masking can occur (Cain & Drexler, 1974). Furthermore, it only requires very small changes in the ratio of individual components to shift the perception of mixtures largely in the direction of the more intense component (Laing & Wilcox, 1983). In order to check that the intensities of the modifiers, as well as the resulting odor mixtures were of fairly equivalent intensities, each panelist rated the intensities (100-point visual analog scale) of all modifiers and odor mixtures after they had completed each session of A-Not-A tests. Odor mixtures were presented in their testing concentrations in glasses covered with 3-digit labeled watch glasses. Modifiers were presented on cotton balls in 20 mL scintillation vials, and concentrations of modifiers were equivalent to 10x threshold values.

Pleasantness of the odorants was the next important factor to control. As discussed by Rabin (1988), it was desirable to select modifiers that were not distinctive in terms of their

pleasantness. This was accomplished by choosing a series of five homologous esters, which differed in chain length, but all possessed generally pleasing perceived odors. We did not wish to facilitate discrimination by creating stimuli with a large hedonic range, so pleasantness scores were collected (9-point scale) for all modifiers as well as resultant odor mixtures, and compared.

Since it has been shown that people are good at discriminating once the odors have become familiar, and expertise was built into the hypothesis, familiarity of the modifiers and resultant odor mixtures was important. Familiarity scores were taken (9-point scale) for each modifier and odor mixture (with an assumption that experts will have higher familiarity with the wine relevant odors and will thus have higher discrimination capabilities).

Statistical Analysis

Discrimination

In order to measure if subjects were more sensitive to changes in an odor mixture in which an odorant had been added (n + 1) or removed (n – 1) and if specific modifiers changed the difficulty of the discrimination task, d' values were calculated in R 3.5.1 with the SensR sensory package version 1.5-1 (Christensen, R. H. B., Brockhoff, P. B., Kuznetsova, A., Birot, S., & Stachlewska, K. A., 2018). The variance of d' scores, as well as 95% confidence intervals, z-scores, and differences in d' values were all calculated in Microsoft Excel (2013). All d' values were compared using the method of Bi & Ennis (1997), in which the calculated z-scores are compared to normal distribution values ($\alpha = 0.05$). Data can be accessed at: https://osf.io/nwv5a/

Rate of "A" and "Not A" responses

The rate of A and Not A responses was assessed to determine if people, specifically within expert and novice groupings, are inclined to find differences when none actually exist. This was accomplished through a chi-squared test, with Answer (A or Not A) as the response variable, and Knowledge (Expert or Novice) as the grouping category.

Stimuli Intensity, Pleasantness, and Familiarity Check

Intensity (100-point scale), pleasantness (9-point scale), and familiarity (9-point scale) scores were collected for all wine odor mixtures, as well as the individual odor modifiers. One-way analysis of variance (ANOVA) models were run for each intensity, familiarity, and

pleasantness score by the wines and modifiers with Tukey HSD adjustment using JMP 13.0.0 (SAS, Cary, NC).

Results

Discrimination

It was hypothesized that participants, as a whole, would be better at the addition task than the subtraction task, this did not seem to be the case. The overall d' score for the addition (n + 1) task was low with a value of 0.0037, and the overall d' for the subtraction (n – 1) task was also low with a value of 0.0650, values that were not significantly different ($z = 0.29$, $p = 0.7741$). When looking at the experts, it was revealed that discriminatory abilities within the addition (d' = -0.1510) and subtraction (d' = -0.1177) tasks were not different ($z = 0.09$, $p = 0.9267$). Similarly, with the novices, it was also revealed that discriminatory abilities within the addition (d' = 0.1157) and subtraction (d' = 0.1601) tasks were not different ($z = 0.87$, $p = 0.8669$), results of discrimination by expertise level can be found in Figure 8.

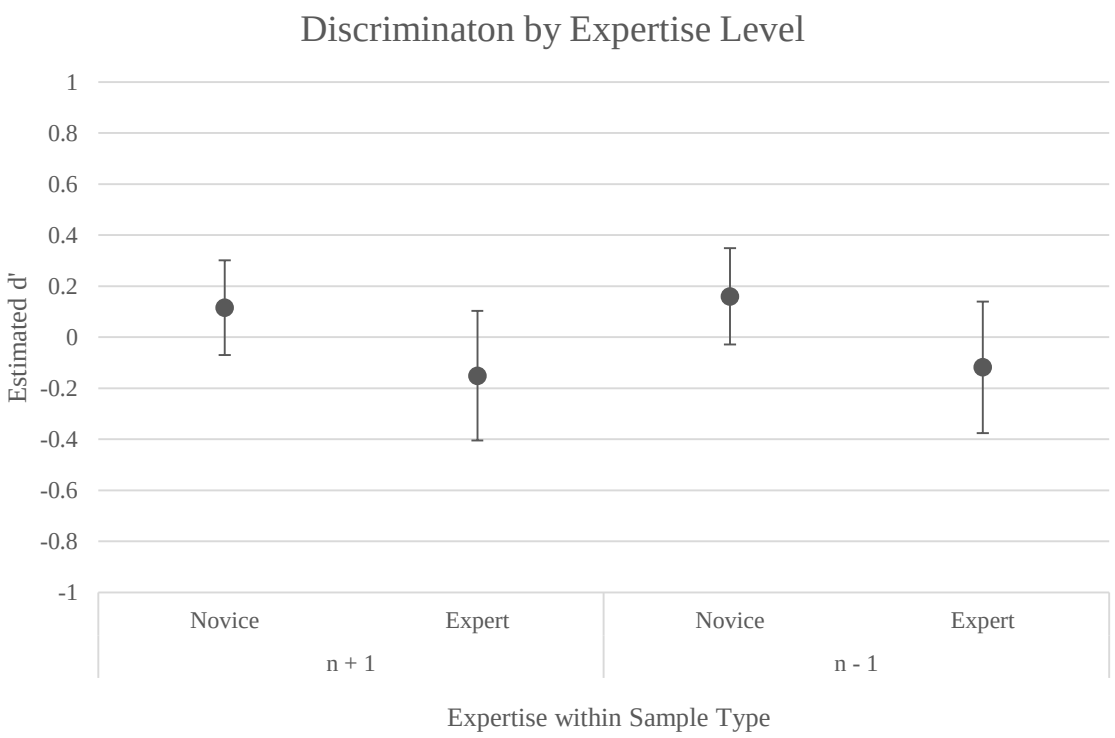


Figure 10. The d' values for n + 1 & n – 1 samples for each expertise level. Error bars correspond to the standard error

Additionally, we hypothesized that experts would generally be better at the discrimination tests than novices. The results indicate that there was no overall difference (z = 1.62, p = 0.3705) in the abilities of experts (d' = 0.0012) and novices (d' = 0.1456) to discriminate between odor mixtures. Additionally, there was no difference in gender (z=1.78, p = 0.0756).

Each of the modifiers were compared within their corresponding addition or subtraction paradigm to determine if any modifiers were more easily distinguished than others. The addition (n + 1) results can be found in Figure 11. The five modifying odorants were not different in difficulty, as evidenced by no differences in their d' values (all p-values > 0.05).

The subtraction (n -1) results can be found in Figure 12. The difficulty of the subtraction task was not found to be dependent on the odorant that was subtracted (all p-values > 0.05).

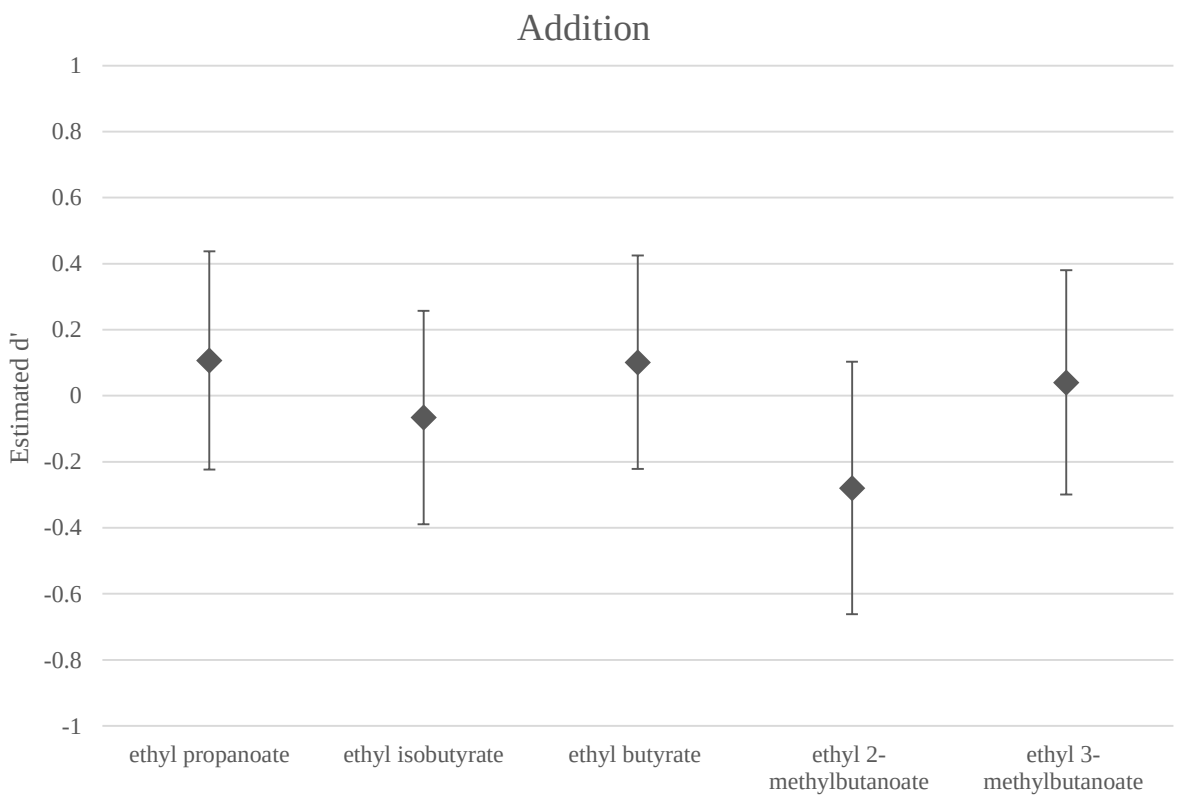


Figure 11. The d' values for n + 1 addition samples for each added modifier. Error bars correspond to the standard error.

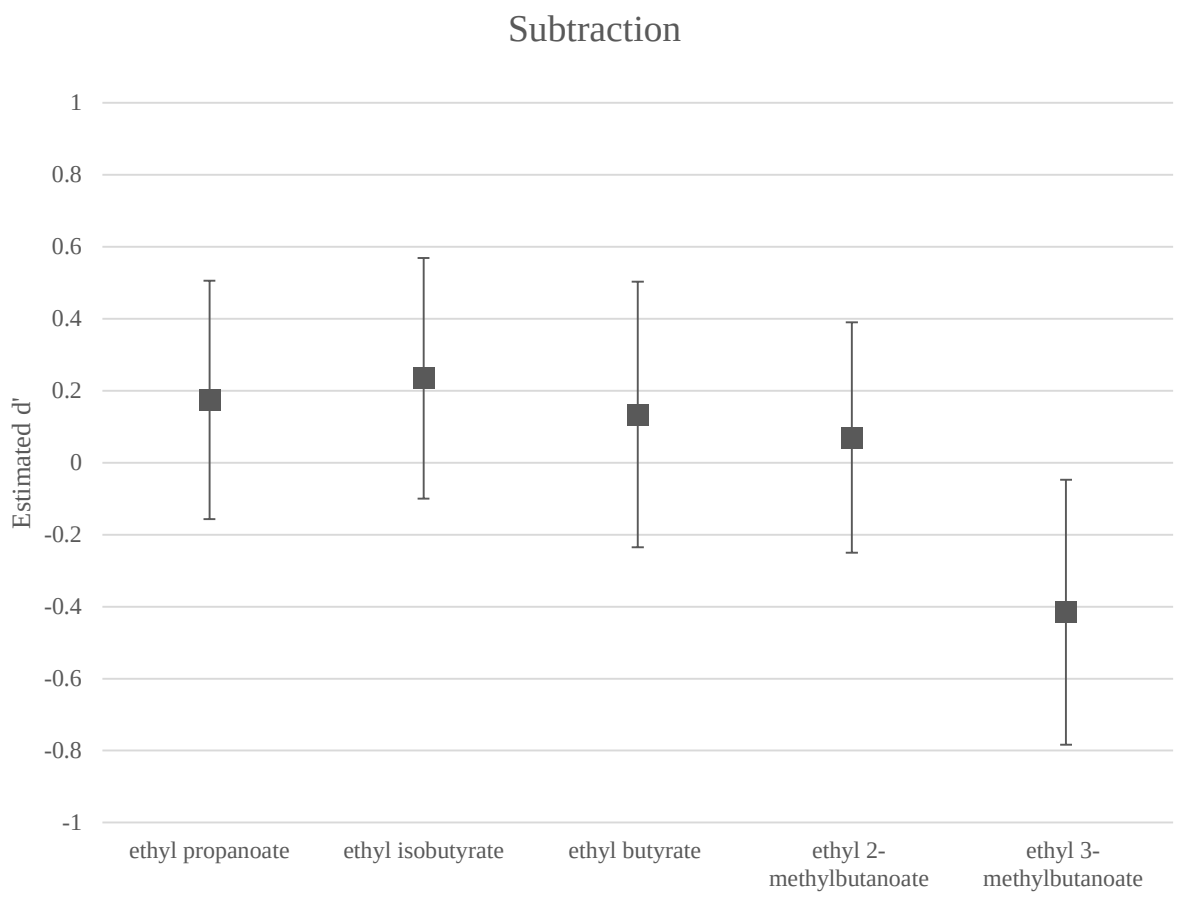


Figure 12. d' values for n - 1 subtraction samples for each modifier that was removed. Error bars correspond to the standard error.

Rate of "A" and "Not A" responses

Experts indicated the samples were different at a rate of 56.4%, while novices only responded that the samples were the same 54.4%. Neither of these rates were found to be significantly different from chance. A chi-square test was performed, and no relationship was found between expertise and the rate at which samples were identified as "A" or "Not A", χ^2 (1, 554 = 0.1976, p = 0.6566.)

Intensity, Pleasantness, and Familiarity

There were no differences found among the intensity scores collected for the modifiers ($F_{4,273}$ = 1.69, p = 0.1528) or their resultant wine odor mixtures ($F_{5,326}$ = 0.5656, p = 0.7263). Intensity results confirmed that wine odor mixtures were not perceived to be too weak or too strong (M = 42.5, SE = 1.3). Mean pleasantness scores for modifiers initially showed differences between the means ($F_{4,273}$ = 2.55, p = 0.0394). However, a post-hoc Tukey test showed no differences amongst the modifying odors. The wine odor mixtures were also found to be similar in terms of pleasantness ($F_{5,326}$ = 0.6533, p = 0.6592). Lastly, familiarity scores were found to be rated similarly within the modifiers ($F_{4,273,}$ = 0.93, p = 0.444) and the resultant wine odor mixtures ($F_{5,326}$ = 1.15, p = 0.3351). All means ± standard errors can be found in Table 10.

Table 10. LSMeans differences with Tukey HSD adjustment and standard error for intensity, pleasantness, and familiarity scores of wines and modifiers used in addition and subtraction A-Not-A tests.

	Intensity	**Pleasantness**	**Familiarity**
Wines	**Mean ± Std. Error**	**Mean ± Std. Error**	**Mean ± Std. Error**
Base Wine (BW)	45.2 ± 3.2A	6.5 ± 0.2A	7.1 ± 0.2A
BW + ethyl propanoate	40.6 ± 3.2A	6.2 ± 0.2A	6.7 ± 0.2A
BW + ethyl isobutyrate	45.7 ± 3.2A	6.5 ± 0.2A	7.0 ± 0.2A
BW + ethyl butyrate	41.4 ± 3.2A	6.6 ± 0.2A	6.7 ± 0.2A
BW + ethyl 2-methylbutanoate	40.0 ± 3.2A	6.5 ± 0.2A	6.7 ± 0.2A
BW + ethyl 3-methylbutanoate	42.2 ± 3.2A	6.2 ± 0.2A	6.7 ± 0.2A
Modifiers			
ethyl propanoate	44.2 ± 3.9A	5.0 ± 0.2A	6.0 ± 0.2A
ethyl isobutyrate	31.9 ± 3.9A	5.7 ± 0.2A	5.8 ± 0.2A
ethyl butyrate	34.9 ± 3.8A	5.1 ± 0.2A	5.7 ± 0.2A
ethyl 2-methylbutanoate	32.2 ± 3.9A	5.5 ± 0.2A	5.4 ± 0.2A
ethyl 3-methylbutanoate	37.0 ± 3.9A	4.8 ± 0.2A	5.9 ± 0.2A

Discussion

There are a few reasons we wish to consider why the discriminatory abilities seemed to be consistent across expertise and among the n+1 and n-1 samples. First, odor discrimination is not an easy task. Our results are in line with many other studies that show the human ability to discriminate between odor stimuli might be poorer than commonly assumed (Laska, 1992; Engen, 1970, Laing & Francis, 1989). Jones (1968) demonstrates that even highly specialized perfumers and chemists have trouble discriminating between mixtures (Jones, 1968). To discriminate between mixtures and similar olfactory "patterns," specific training might be necessary (Stevenson & Mahmut, 2013; Stevenson & Wilson, 2007) such as the study by Poupon, who demonstrated that training improved novice identification performance, but only with 1 odorant (Poupon, 2018). However, a recent study from Weiss & Vickers (2016) showed similar findings to the present study, in that initially before training, their participants were not able to discriminate between n and n-1 mixtures (d' = 0.1), and only 60% of panelists were able to discriminate between n and n-1 samples after 200 trials (Weiss et al., 2016). Also, outlined by Weiss (2016), other n-1 studies have shown that this discrimination task is quite difficult. Sinding (2013) used a sorting task for a complete odor mixture and 6 corresponding n-1 samples, and the 3D representation showed overlap for most of the n-1 omission samples, indicating similarity (Sinding, Thomas-Danguin, Chambault, Béno, Dosne, Chabanet, & Coureaud, 2013). Another n-1 study by Hongsoongern (2003) with a training component found that the initial session gave discrimination results at chance level- indicating participants were unable to discriminate between full mixtures and those with one missing component (Hongsoongern, 2003). However, the study performed by Laska found that n-1 samples were discerned significantly more often than the base mixture, however the difference was small, an increase from 0-20% of ratings shifting from "no difference" to "a difference" between the two samples. But intensities of odorants weren't controlled within the mixtures and may have facilitated discrimination (Laska, 1992).

Although the concentrations and intensities appeared to have been consistent in the present study, it is possible that using a single concentration for the group might have caused some overshadowing or suppression in individuals (Frank, Goyert, & Hettinger, 2010; Kay, Crk, & Thorngate, 2005). Especially on the assumption that thresholds vary from person to person,

the single concentrations used for each modifier may have been above or below threshold on an individual basis, and could only be corrected with individualized threshold testing for each odor modifier. However, Laska (1992) indicates that individual substances being controlled within mixtures, is appropriate for methodology within a lab, but rarely occurs- if ever, in natural odor mixtures (Laska, 1992), and might limit discrimination by creating unrealistic stimuli. Moreover, it has been proposed that the pleasantness of stimuli exerts a direct bearing on similarity judgments (Schiffman, Robinson, & Erickson, 1977), which could have added to the difficulty of discrimination since all the stimuli were of relative pleasantness.

As far as the wine judges not performing better than novices, we hypothesize two possible reasons. First, the concentrations of odorants at their threshold levels were too low for a complex odor matrix of 7 odorants. The results indicate that panelists were performing more or less at chance, and could be attributed to weak stimuli. Secondly, the sessions occurred concurrently with the Wines of the South competition, and fatigue was something that was not extensively controlled for, aside from the minute timer between samples.

Future research should continue in multiple directions. First, the concentrations of all modifiers could be amplified to ensure the task is not too difficult. This would address the concern that concentrations were too low for perception. Second, Weiss & Vickers (2016) found that discrimination for n-2 samples were greater than n-1 samples. It might be prudent to re-assess the study design and change from n ± 1 samples to n ± 2 samples to see if this might improve d' scores and facilitate the direct comparison between novices and experts as well as addition and subtraction. It would also be interesting to see if a training component would produce differences between groups, since it is well established that training can improve discrimination ability, especially with olfactory stimuli (Poupon, 2018; Engen, 1960; Moskowitz & Gerbers, 1974; Rabin, 1988; Rabin & Cain, 1989).

Odor identification research has shown that humans cannot identify individual odorants in mixtures containing more than 3 odorants (Jinks & Laing, 1999, 2001; Laing & Francis, 1989; Laing & Glenmarec, 1992; Laing & Jinks, 2001). This is an interesting concept. If our odor matrix was considered as an odor object, with its own distinct odor profile, it should theoretically be perceived as one entity. So, it would follow that discrimination with n ± 1 odorant would be possible. However, maybe due to complexities in perception of complex odors, a wine odor base with fewer than 6 odorants would be required for n ± 1 study. A follow up study could include a

portion on the wine odor base perception, to determine if every odorant within the mixture is necessary, and if a simpler model could be produced in order to facilitate discrimination. It would also be interesting to see if an odor object simply requires more than 1 odorant to be manipulated, and n ± 2 or 3 odorants is required.

Conclusion

Experts and novices had equivalent discriminatory abilities when assessing odor mixtures with one odorant added or removed. Additionally, participants performed equally well in cases where odorants were being added to the mixture or omitted. Future experimentation is needed to determine if stronger stimuli, or additional odorants within the mixture need to be manipulated in order to compare groups and tasks.

CONCLUSION

Based on the findings from these studies, wine odor perception is complex. Results from Chapter 1 highlight certain wine odors do correspond with specific visual stimuli, but is dependent on the strength of the visual stimuli. These findings have potential applications in the food industry, helping to bridge the gap between theoretical findings, and real-world settings. Specifically, that some packaging characteristics match better with certain odor profiles than others.

Findings of Chapter 2 indicate that human sensitivity to subtle changes in odor mixtures is not extremely high, even in wine experts. While experts and novices had equivalent discriminatory abilities when assessing n ± 1 odor mixtures, all discrimination scores were low. It will require future experimentation to determine if stronger stimuli, or additional odorants within the mixture need to be manipulated in order to compare groups and tasks.

REFERENCES

Abramov, I. & Gordon, J. (1994). Color appearance: On seeing red, or yellow, or green, or blue. *Annual Review of Psychology, 45,* 451-485.

Adams, C. & Doucé, L. (2017). What's in a scent? Meaning, shape, and sensorial concepts elicited by scents. *Journal of Sensory Studies, 32 (2),* 1-20.

Alberts, P., Stander, M. A., Paul, S. O., & de Villiers, A. (2009). Survey of 3-Alkyl-2-methoxypyrazine content of South African Sauvignon blanc wines using a novel LC− APCI-MS/MS method. *Journal of Agricultural and Food Chemistry, 57(20),* 9347-9355.

Arnoff, J., Barclay, A.M., & Stevenson, L. A. (1988). The recognition of threatening facial stimuli. *Journal of Personality and Social Psychology, 54(4),* 647-655.

Ayabe-Kanamura, S., Schicker, I., Laska, M., Hudson, R., Distel, H., Kobayakawa, T., & Saito, S. (1998). Differences in perception of everyday odors: a Japanese-German cross-cultural study. *Chemical Senses, 23,* 31-38.

Barnes, D.C., Hofacer, R.D., Zaman, A.R., Rennaker, R.L., & Wilson, D.A. (2008). Olfactory perceptual stability and discrimination. *Nature Neuroscience, 11(12),* 1378-1380.

Barnett, A. & Spence, C. (2016). Assessing the effect of changing a bottled beer label on taste ratings. *Nutr Food Technol Open Access. 2*(4).

Becker, L., Van Rompay, T. J. L., Schifferstein, H. N. J, & Galetzka, M. (2011). Tough package, strong taste: The influence of packaging design on taste impressions and product evaluations. *Food Quality and Preference, 22,* 17-23.

Bende, M. & Nordin, S. (1997). Perceptual learning in olfaction: professional wine tasters versus controls. *Physiol. Behav. 62,* 1065-1070.

Berglund, B., Berglund, U., & Lindvall, T. (1976). Psychological processing of odor mixtures. *Psychol. Rev., 83,* 432-441.

Berglund, B., & Olsson, M. J. (1993). Odor-intensity interaction in binary mixtures. *J. Exp. Psychol. Hum. Percept. Perform, 19,* 302-314.

BI, J., ENNIS, D.M., & O'MAHONY, M.I.C.H.A.E.L. (1997). How to estimate and use the variance of d' from difference tests. *Journal of Sensory Studies, 12(2),* 87-104.

Biederman, I. (1972). Perceiving Real-World Scenes. *Science, 177(4043),* 77-80.

Blazhenkova, O. & Kumar, M. M. (2018). Angular versus curved shapes: Correspondences and emotional processing. *Perception, 47,* 67-89.

Buettner, A. (2004). Investigation of potent odorants and afterodor development in two Chardonnay wines using the buccal odor screening system (BOSS). *Journal of agricultural and food chemistry, 52(8),* 2339-2346.

Cain, W.S., & Drexler, M. (1974). Scope and evaluation of odor counteraction and masking. *Ann. N. Y. Acad. Sci, 237,* 427-439.

Carbon, C. C., & Leder, H. (2005). The repeated evaluation technique (RET). A method to capture dynamic effects of innovativeness and attractiveness. *Applied Cognitive Psychology, 19,* 587-601.

Cavazana, A., Larsson, M., Hoffmann, E., Hummel, T., & Haehner, A. (2017). The vessel's shape influences the smell and taste of cola. *Food Quality and Preference, 59,* 8-13.

Chastrette, M. (1997). Trends in structure-odor relationships. *SAR QSAR Environ. Res. 6,* 215-254.

Chastrette, M., Thomas-Danguin, T., & Rallet, E. (1998). Modelling the human olfactory stimulus-response function. *Chem. Senses, 23,* 181-196.

Chen, Y.-C., Woods, A., & Spence, C. (2018) Sensation transference from plateware to food: The sounds and tastes of plates. *Int. J. Food Des, 3,* 41-62

Cheskin, L. (1957). How to predict what people will buy. Liveright, New York, USA.

Christensen, R. H. B., Brockhoff, P. B., Kuznetsova, A., Birot, S., & Stachlewska, K. A. (2018). Thurstonian models for sensory discrimination. R package version 1.5-1. https://cran.r-project.org/web/packages/sensR/sensR.pdf

Collier, G. L. (1996). Affective synesthesia: extracting emotion space from simple perceptual stimuli. *Motivation and Emotion, 20,* 1-32.

Crisinel A.S., Jacquier, C., Deroy, O., & Spence, C. (2013). Composing with cross-modal correspondences: music and odors in concert. *Chemosensory Perception, 6,* 45-52.

Croy, I., Nordin, S., & Hummel, T. (2014). Olfactory disorders and quality of life- An updated review. *Chemical Senses,* 39, 185-194.

Czerny, M., Christlbauer, M., Christlbauer, M., Fischer, A., Granvogl, M., Hammer, M., Hartl, C., Hernandez, N.M., & Schieberle, P. (2008). Re-investigation on odour thresholds of key aroma compounds and development of an aroma language based on odour qualities of defined aqueous odorant solutions. *European Food Research and Technology, 228(2),* 265-273.

Damm, M., Vent, J., Schmidt, M., Theissen, P., Eckel, H. E., Lötsch, J., & Hummel, T. (2002). Intranasal volume and olfactory function. *Chemical Senses, 27(9),* 831-839.

Derby, C., Hutson, M., Livermore, A., & Lynn, W. (1995). Generalization among related complex mixtures and their components: Analysis of mixture perception in the spiny lobster. *Chem Senses, 20(6),* 61.

Deroy, O., Crisinel A. S., & Spence, C. (2013). Crossmodal correspondences between odors and contingent features: odors, musical notes, and geometrical shapes. *Psychon Bull. Rev, 20,* 878-896.

Deroy, O. & Spence, C. (2013). Why we are not all synesthetes (not even weakly so). *Psychonomic Bulletin & Review, 20(4),* 643-64.

Deliza, R. (1996). The effects of expectation on sensory perception and acceptance. Ph.D. Thesis, UK: The University of Reading.

Delwiche, J. F., & Pelchat, M. L. (2002). Influence of glass shape on the perception of wine aroma. *Journal of Sensory Studies, 17,* 19-28.

Demattè, M. L., Sanabria, D., & Spence, C. (2006). Cross-modal associations between odors and colors. *Chem Senses, 31,* 531-538.

Devos, M., Rouault, J., & Laffort, P. (2002). *Standardized olfactory power law exponents.* Dijon: Editions Universitaires de Dijon.

Dodd, G. H. (1988). The molecular dimensions of perfumery. *Perfumery*, 19-46.

Eisenson, J., Fisichelli, V. R., & Welch, L. (1954). Imagined differencs in the perception of identical olfactory stimuli. *J. Genel. Psychol, 84,* 77-83.

Engen, T. (1970). Man's ability to perceive odors. In Johnston, J.W., Moulton, D.G., & Turk, A. (eds) *Communication by Chemical Signals,* Vol. 1. Appleton- Century- Crofts, New York, pp. 361-383.

Engen, T. (1982). *The Perception of Odors*. New York: Academic Press

Esterl, M. (2011). "A frosty reception for Coca-Cola's white Christmas cans." *The Wall Street Journal*, December 1.

Etzi, R., Spence, C., Zampini, M., & Gallace, A. (2016). When sandpaper is "Kiki" and satin is "Bouba": an exploration of the associations between words, emotional states, and the tactile attributes of everyday materials. *Multisensory Research, 29,* 133-155.

Ferdenzi, C., Schirmer, A., Roberts, S. C., Delplanque, S., Porcherot, C., Cayeux, I., Velazco, M. I., Sander, D., Scherer, K. R., & Grandjean, D. (2011). Affective dimensions of odor perception: a comparison between Swiss, British, and Singaporean populations. *Emotion, 11,* 1168-1181.

Ferris, A. M. & Duffy, V. B. (1989). Effect of olfactory deficits on nutritional status. Does age predict persons at risk? a. *Annals of the New York Academy of Sciences, 561(1),* 113-123.

Fiore, A. M. (1993). Multisensory integration of visual, tactile, and olfactory aesthetic cues of appearance. *Clothing and Textiles Research Journal, 11,* 45-52.

Foster, D., Scofield, E. H., & Dallenbach, K. M. (1950). An olfactorium. *The American journal of psychology, 63(3),* 431-440.

Frank, M.E., Goyert, H.F., & Hettinger, T.P. (2010). Time and intensity factors in identification of components of odor mixtures. *Chemical Senses, 35(9),* 777-787.

Gao, W., Fan, w., & Xu, Y. (2014). Characterization of the key odorants in light aroma type Chinese liquor by gas chromatography-olfactometry, quantitative measures, aroma recombination, and omission studies. *Journal of Agricultural and Food Chemistry, 62(25),* 5796-5804.

Gaudin, J.M., Nikolaenko, O., de Saint Laumer, J. Y., Winter, B., & Blanc, P. A. (2007). Structure-activity relationship in the domain of odorants having marine notes. *Helv. Chim. Acta, 90,* 1245-1265.

Gilbert, A. N., Martin, R., & Kemp, S. E. (1996). Cross-modal correspondence between vision and olfaction: the colour of smells. *Am J Psychol, 109,* 335-351.

Giraud, G. & Trigui, T. I. (2005). Effet de l'expérience émotionnelle sur les préférences du consommateur, une étude exploratoire appliquée aux produits alimentaires labellisés. *Tendances du Marketing en Europe*. ESCP-EAP, Université Ca Foscari, 24.

Goldstein, E.B. *Sensation and Perception 9th Edition.* Belmont, CA: Cengage Learning, 2014.

Guth, H. (1997). Quantitation and sensory studies of character impact odorants of different white wine varieties. *J. Agric. Food Chem, 45,* 3027-32.

Guth H. & Grosch, W. (1994). Identification of the character impact odorants of stewed beef juice by instrumental analyses and sensory studies. *Journal of Agricultural and Food Chemistry, 42(2),* 2862-2866.

Hanson-Vaux, G., Crisinel, A. S., & Spence, C. (2013). Smelling shapes: Crossmodal correspondences between odors and shapes. *Chem Senses, 38,* 161-166.

Harrell, F.E. Jr. with contributions from Dupont, C. and others, (2018). Hmisc: Harrell Miscellaneous. R package version 4.1-1. https://cran.r-project.org/web/packages/Hmisc/Hmisc.pdf

Hongsoongern, P. (2003). *Learning to discriminate a five-odorant mixture from mixtures containing four of the five odorants.* MS Thesis University of Minnesota, St. Paul, MN.

Hughson, A. L. & Boakes, R. A. (2002). The knowing nose: the role of knowledge in wine expertise. *Food Quality and Preference, 13(7-8),* 463-472.

Hummel, T. & Nordin, S. (2005). Olfactory disorders and their consequences for quality of life. *Acta otolarynologica, 125(2),* 116-121.

Hummel, T., Sekinger, B., Wolf, S.R., Pauli, E., & Kobal, G. (1997). 'Sniffin' Sticks': Olfactory performance assessed by the combined testing of odor identification, odor discrimination and olfactory threshold. *Chem Senses, 22(1),* 39-52.

Hummel, T., Delwiche, J. F., Schmidt, C., & Hüttenbrink, K. B. (2003). Effects of the form of glasses on the perception of wine flavors: a study in untrained subjects. *Appetite, 41,* 197-202.

Hurvich, L. (1981). *Color vision.* Sunderland, MA: Sinauer Associates.

Husson, F., Le, S., & Cadoret, M. (2017). Statistical Methods to Analyze Sensory Data. SensoMineR: A package for sensory data analysis. R package version 1.23. https://cran.r-project.org/web/packages/SensoMineR/SensoMineR.pdf

Hüttenbrink, K. B., Schmidt, C., Delwiche, J. F., & Hummel, T. (2001). The enjoyment of red wine is influenced by the shape of the wine glass. *Laryngo-Rhino-Otologie, 80(2),* 96-100.

Ishihara, S. (1917). Tests for color-blindness. Handaya, Tokyo.

Jacquot, M., Noel, F., Velasco, C., & Spence, C. (2016). On the colours of odors. *Chemosensory Perception, 9,* 79-93.

Jinks, A. & Laing, D.G. (1999). A limit in the processing of components in odor mixtures. *Perception, 28(3),* 395-404.

Jinks, A. & Laing, D.G. (2001). The analysis of odor mixtures by humans: Evidence for a configurational process. *Physiology and Behavior, 72(1-2),* 51-63.

Johnson, E.N., Hawken, M.J., & Shapley, R. (2008). The orientation selectivity of color-responsive neurons in Macaque V1. *Journal of Neuroscience, 28,* 8096-8106.

Jones, F.N. (1968). Information content of odor quality. In Tanyolac, N. (ed.) *Theories of Odors and Odor Measurement.* Robert College Research Center, Istanbul, pp. 133-141.

Jones, P. R., Gawel, R., Francis, I. L., & Waters, E. J. (2008). The influence of interactions between major white wine components on the aroma, flavour and texture of model white wine. *Food Quality and Preference, 19,* 596-607.

Kaeppler, K. (2018). Crossmodal associations between olfaction and vision: Color and shape visualizations of odors. *Chemosensory Perception.* 1-17.

Kaeppler, K. & Mueller, F. (2013). Odor classification: a review of factors influencing perception-based odor arrangements. *Chem Senses, 38,* 189-209.

Kahn, J. H., LaROE, E.G., & Conner, H.A. (1968). Whiskey composition: Identification of components by single-pass gas chromatography-mass spectrometry. *Journal of Food Science, 33(4),* 395-399.

Kay, L.M., Crk, T., & Thorngate, J. (2005). A redefinition of odor mixture quality. *Behavioral Neuroscience, 119(3),* 726-733.

Kemp, S. E & Gilbert, A. N. (1997). Odor intensity and color lightness are correlated sensory dimensions. *The American Journal of Psychology, 11*, 35-46.

Kiatbenjakul, P., Intarapichet, K.O., & Cadwallader, K.R. (2015). Characterization of potent odorants in male giant water bug (Lethocerus indicul Lep. And Serv.) an important edible insect of Southeast Asia. *Food Chemistry, 168*, 639-647.

Kim, Y.J. (2013). Can eyes smell? Cross-modal correspondences between color hue-tone and fragrance family. *Color Research and Application, 38(2),* 139-156.

Köhler, W. (1929). *Gestalt psychology*. New York, NY: Liveright.

Laing, D. G. & Francis, G. W. (1989). The capacity of humans to identify odors in mixtures. *Physiol. Behav, 46,* 809-814.

Laing, D. & Jinks, A. (2001). Psychophysical analysis of complex odor mixtures. *CHIMIA International Journal for Chemistry, 55(5),* 413-420.

Laing, D.G. & Glenmarec, A. (1992). Selective attention and the perceptual analysis of odor mixtures. *Physiology and Behavior, 52(6),* 1047-1053.

Laing, D. G. & Willcox, M. E. (1983). Perception of components in binary odor mixtures. *Chemical Senses, 7,* 249-264.

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

Leder, H., Tinio, P.P., & Bar, M. (2011). Emotional valence modulates the preference for curved objects. *Perception, 40*, 649-655.

Lee, Seung-Joo & Noble, A. C. (2003). Characterization of odor-active compounds in Californian Chardonnay wines using GC-olfactometry and GC-mass spectrometry. *Journal of agricultural and food chemistry, 51(27),* 8036-8044.

Leopold, D.A. (1988). The relationship between nasal anatomy and human olfaction. *The Laryngoscope, 98(11),* 1232-1238.

Levitan, C., Ren, J., Woods, A. T., Boesveldt, S., Chan, J. S., McKenzie, K. J., Dodson, M., Levin, J. A., Leong, C. X. R., & van den Bosch, J. F. (2014). Cross-cultural color associations. *PLoS ONE, 9(7):* e101651.

Liland, K., Naes, T., & Indhal, U. (2017). Matrix Correlation Coefficients. R package version 0.9.2. https://cran.r-project.org/web/packages/MatrixCorrelation/

Lovitz, A.M., Sloan, A.M., Rennaker, R.L., & Wilson, D.A. (2012). Complex mixture discrimination and the role of contaminants. *Chemical Senses, 37(6),* 533-540.

Maarse, H. & Vischer, C. A. (1989). Volatile compounds in food. Alcoholic beverages. *Qualitative and Quantitative data.* TNO-CIVO Food Analysis Institute, Zeist.

Marais, J. (1983). Terpenes in the aroma of grapes and wines: A review. *South African Journal of Enology and Viticulture, 4(2),* 49-58.

Mayer, F., Czerny, M., & Grosch, W. (2000). Sensory study of the character impact aroma compounds of a coffee beverage. *European Food Research and Technology, 211(4),* 272-276.

Maric, Y. & Jacquot, M. (2013). Contribution to understanding odour-color associations. *Food Quality and Preference, 27(2),* 191-195.

Marks, L. E. (1978). The unity of the senses: interrelations among the modalities. Academic, New York.

Mirabito, A., Oliphant, M., Van Doorn, G., Watson, S., & Spence, C. (2017). Glass shape affects the perceived taste of beer. *Food Quality and Preference, 62,* 257-261.

Mizutani, N., Okamoto, M., Yamaguchi, Y., Kusakabe, Y., Dan, I., & Yamanaka, T. (2010). Package images modulate flavor perception for orange juice. *Food Quality and Preference, 21(7),* 867-872.

Miwa, T., Furukawa, M., Tsukatani, T., Costanzo, R. M., DiNardo, L. J., & Reiter, E. R. (2001). Impact of olfactory impairment on quality of life and disability. *Arch Otolaryngology-Head Neck Surgery, 127(5),* 497-503.

Melcher, J. & Schooler, J. (1996). The misrembrance of wines past: verbal and perceptual expertise differentially mediate verbal over-shadowing of taste memory. *J. Mem. Lang. 35,* 231-245.

Mollon, J.D. (1989). Tho' she kneel'd in that place where they grew… *Journal of Experimental Biology, 146,* 21-38.

Mollon, J.D. (1997). Tho' she kneel'd in that place where they grew…: The uses and origins of primate colour visual information. In A. Byrne & D.R. Hilbert (eds.) *Readings on color: Vol. 2.*

Moskowitz, H.R. & Gerbers, C.L. (1974). Dimensional salience of odors. *Ann. N.Y. Acad. Sci., 237,* 1-16.

Mozell, M. M. (1970). Evidence for a chromatographic model of olfaction. *Journal of General Physiology, 56(1),* 46-63.

Munafo, J. P., Didzbalis, J., Schnell, R. J., & Steinhaus, M. (2016). Insights into the key aroma compounds in mango (Mangifera Indica L. 'Haden') fruits by stable isotope dilution quantitation and aroma simulation experiments. *J. Agric. Food Chem, 64 (21),* 4312–4318.

Murphy, C., Cain, W. S., & Bartoshuk, L. M. (1977). Mutual action of taste and olfaction. *Sensory processes.*

Murphy, C. & Cain, W.S. (1980). Taste and olfaction: independence vs interaction. *Physiology & Behavior, 24(3),* 601-605.

Nathans, J., Thomas, D., & Hogness, D.S. (1986). Molecular genetics of human color vision: The genes encoding blue, green, and red pigments. *Science, 232,* 193-202.

Negoias, S., Visschers, R., Boelrijk, & Hummel, T. (2008). New ways to understand aroma perception. *Food Chemistry, 108,* 1274-1254.

Néhmé, L., Barbar, R., Maric, Y., & Jacquot, M. (2016) Influence of odor function and color symbolism in odor-color associations: a French-Lebanese-Taiwanese cross-cultural study. *Food Quality and Preference,* 33-41.

Ngo, M. K., Misra, R., & Spence, C. (2011) Assessing the shapes and speech sounds that people associate with chocolate samples varying in cocoa content. *Food Quality and Preference, 22(6),* 567-272.

Ngo, M. K., Piqueras-Fiszman, B., & Spence, C. (2012). On the color and shape of still and sparkling water: Insights from online and laboratory-based testing. *Food Quality and Preference, 24(2),* 260-268.

Nordin, S. (2009). Sensory perception of food and aging. In *Food for the Aging Population,* 57-82.

Parr, W. V., Heatherbell, D., & White, K. G. (2002). Demystifying wine expertise: Olfactory threshold, perceptual skill and semantic memory in expert and novice wine judges. *Chemical Senses, 2002,* 747-755.

Pavez, C., Steinhaus, M., Casaubon, G., Schieberle, P., & Agosin, E. (2015). Identification, quantification and sensory evaluation of methyl 2- and methyl 3-methylbutanoate in varietal red wines. *Australian Journal of Grape and Wine Research, 21(2),* 189-193.

Persaud, K. & Dodd, G. (1982). Analysis of discrimination mechanisms in the mammalian olfactory system using a model nose. *Nature, 229,* 352-355.

Piqueras-Fiszman, B. & Spence, C. (2011). Crossmodal correspondences in product packaging: Assessing color-flavor correspondences for potato chips (crisps). *Appetite, 57,* 753-757.

Piqueras-Fiszman, B. & Spence, C. (2015). Sensory expectations based on product-extrinsic food cues: An interdisciplinary review of the empirical evidence and theoretical accounts. *Food Quality and Preference, 40(A),* 165-179.

Postel, W. & Güvenc, U. (1976). Gaschromatographische Bestimmung von Diacetyl, Acetoin und 2, 3-Pentandion in WeinGaschromatographical determination of diacetyl, acetoin, and 2.3-pentanedione in wine. *Zeitschrift für Lebensmittel-Untersuchung und Forschung, 161(1),* 35-44.

Poupon, D., Fernandez, P., Boisvert, S.A., Migneault-Bouchard, C., & Frasnelli, J. (2018). Can the identification of odorants within a mixture be trained? *Chemical Senses, 20,* 1-6.

R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rabin, M. D. (1988) Experience facilitates olfactory quality discrimination. *Percept. Psychophys, 44,* 532-540.

Rabin, M.D. & Cain, W.S. (1989). Attention and learning in the perception of odor mixtures. In Laing, D.G., Cain, W.S., McBride, R.L., & Ache B.W. (eds) *Perception of Complex Smells and Tastes.* Academic Press, Sydney, pp. 173-188.

Ramachandran, V.S. & Hubbard, E. M. (2001). Synaesthesia- a window into perception, thought and language. *Journal of Consciousness Studies, 8(12),* 3-34.

Rapp, A. & Mandery, H. (1989). Wine aroma. *Experientia, 42,* 873-884.

Raudenbush, B. & Meyer, B. (2001). Effect of nasal dilators on pleasantness, intensity and sampling behaviors of foods in the oral cavity. *Rhinology, 39(2),* 80-83.

Reineccius, G. A. & Anandaraman, S. (1984). Analysis of volatile flavors. *Food Constituents and Food Residues- Their Chromatographic Determinants,* 195-293.

Robinson, A. L., Ebeler, S. E., Heymann, H., Boss, Pl K., Solomon, P. S., & Trengover, D. (2009). Interactions between wine volatile compounds and grape and wine matrix components influence aroma compound headspace portioning. *J. Agric. Food Chem, 57,* 10313-10322.

Rozin, P. (1982). "Taste-smell confusions" and the duality of the olfactory sense. *Attention, Perception, & Psychophysics, 31(4),* 397-401.

Ryan, D., Watkins, P., Smith, J., Allen, M., & Marriott, P. (2005). Analysis of methoxypyrazines in wine using headspace solid phase microextraction with isotope dilution and comprehensive two-dimensional gas chromatography. *Journal of separation science, 28(9-10),* 1075-1082.

Sanz, G., Thomas-Danguin, T., Hamdani, E.H., Le Poupon, C., Briand, L., Pernollet, J.C., et al. (2008). Relationships between molecular structure and perceived odor quality of ligands for a human olfactory receptor. *Chem Senses, 33,* 639-653.

Schifferstein, H. N. J., & Tanudjaja, I. (2004). Visualising fragrances through colours: The mediating role of emotions. *Perception, 33,* 1249-1266.

Schifferstein, H. N. & Howell, B. F. (2015). Using color-odor correspondences for fragrance packaging design. *Food Quality and Preference, 46,* 17-25.

Schiffman, S.S., Robinson, D.E., & Erickson, R.P. (1977). Multidimensional scaling of odorants: Examination of psychological and physiochemical dimensions. *Chemical Senses & Flavor, 2,* 375-390.

Seo, H.S., Arshamian, A., Schemmer, K., Scheer, I., Sander, T., Ritter, G., & Hummel, T. (2010). Cross-modal integration between odors and abstract symbols. *Neuroscience letters, 478(3),* 175-178.

Sinding, C., Thomas-Danguin, T., Chambault, A., Béno, N., Dosne, T., Chabanet, C. … & Coureaud, G. (2013). Rabbit neonates and human adults perceive a blending 6-component odor mixture in a comparable manner. *PLoS One, 8(1),* e53534.

Snitz, K., Yablonka, A., Weiss, T., Frumin, I., Khan, R.M., Sobel, N. (2013). Predicting odor perceptual similarity from odor structure. *PLoS Comput Biol, e1003184.*

Sobel, N., Khan, R. M., Saltman, A., Sullivan, E. V., & Gabrieli, J. D. (1999). Olfaction: the world smells different to each nostril. *Nature, 402(6757),* 35.

Spence, C. (2011). Cross-modal correspondences: a tutorial review. *Atten Percept Psychophys, 73,* 971-995.

Spence, C. (2012). Managing sensory expectations concerning products and brands: Capitalizing on the potential of sound and shape symbolism. *J Consum. Psychol, 22,* 37-54.

Spence, C. (2014). Orienting attention: A crossmodal perspective. In A. C. Nobre & S. Kastner (Eds.) *The Oxford handbook of attention* (pp. 446-471). Oxford: Oxford University Press.

Spence, C. & Gallace, A. (2011). Tasting shapes and words. *Food Quality and Preference, 22,* 290-295.

Spence, C. & Deroy, O. (2013). On why music changes what (we think) we taste. *I-Perception, 4(2),* 137-140.

Spence, C., Wan, X., Woods, A., Velasco, C., Deng, J., Youssef, J., & Deroy O. (2015). On tasty colours and colorful tastes? Assessing, explaining, and utilizing crossmodal correspondences between colours and basic tastes. *Flavour, 4(1),* 23.

Spence, C. & van Doorn, G. (2017). Does the shape of the drinking receptacle influence taste/flavour perception? A review. *Beverages, 3,* 33.

Spors, H. & Grinvald, A. (2002). Spatio-temporal dynamics of odor representations in the mammalian olfactory bulb. *Neuron, 34(2),* 301-315.

Stevens, S.S. (1960). The psychophysics of sensory function. *Am Sci, 48,* 226-253.

Stevenson, R.J. & Mahmut, M.K. (2013). Familiarity influences odor memory stability. *Psychonomic Bulletin & Review, 20(4),* 754-759.

Stevenson, R.J. & Wilson, D.A. (2007). Odor perception: An object-recognition approach. *Perception, 36(12),* 1821-1833.

Stewart, P. C. & Goss, E. (2013). Plate shape and colour interact to influence taste and quality judgments. *Flavour, 2,* 27.

Sujan, M. (1985). Consumer knowledge: Effects on evaluation strategies mediating consumer judgments. *Journal of Consumer Research, 12,* 31-46.

Sumner, P. & Mollon, J.D. (2000). Catarrhine photopigments are optimized for detecting targets against a foliage background. *Journal of Experimental Biology, 23,* 1963-1986.

Tanaka, J.W. & Presnell, L.M. (1999). Color diagnosticity in object recognition. *Perception & Psychophysics, 61,* 1140-1153.

Temmel, A. F., Quint, C., Schickinger-Fischer, B., Klimek, L., Stoller, E., & Hummel, T. (2002). Characteristics of olfactory disorders in relation to major causes of olfactory loss. *Arch Otolaryngology- Head Neck Surgery, 128(6),* 635-641.

Tennen, H., Affleck, G., & Mendola, R. (1991). Coping with smell and taste disorders. *Smell and taste in health and disease*, 787-802.

Thomas-Danguin, T., Le Berre, E., Barkat, S., Coureaud, G., & Sicard, G. (2007) Evidence for odor blending in odorant mixtures. *Chem. Annu. Meet., 32,* A64.

Thomas-Danguin, T., Sinding, C., Romagny, S., El Mountassir, F., Atanasova, B., Le Berre, E., Le Bon, A-M., & Coureaud, G. (2014). The perception of odor objects in everyday life: a review on the processing of odor mixtures. *Frontiers in psychology, 5,* 504.

Tootelain, D. H. & Ross, K. (2000). Products labels: What information do consumers want and will they believe it? *Journal of Food Products Marketing, 61,* 25-38.

Van Rompay, T. J. L., Finger, F., Saakes, D., & Fenko, A. (2016). “See me, feel me”: Effects of 3D-printed surface patterns on beverage evaluation. *Food Quality and Preference, 62,* 332-339.

Van Toller, S. (1999). Assessing the impact of anosmia: review of a questionnaire’s findings. *Chemical Senses, 24,* 705-712.

Velasco, C., Jones, R., King, S., & Spence, C. (2013). Assessing the influence of the multisensory environment on the whisky drinking experience. *Flavour, 2(1),* 23.

Velasco, C., Woods, A. T., Deroy, O., & Spence, C. (2015). Hedonic mediation of the crossmodal correspondence between taste and shape. *Food Quality and Preference, 41,* 151-158.

Walls, G.L. (1942). *The vertebrate eye.* New York: Hafner (Reprinted in 1967).

Weiss, K. & Vickers, Z. (2016). Evaluation of omission testing as a method for identifying important odorants in a mixture. *Journal of Sensory Studies,* e12460.

Wilson, D.A. & Sullivan, R.M. (2011). Cortical processing of odor objects. *Neuron, 72(4),* 506-519.

Zellner, D. (2013). Color-odour interactions: a review and model. *Chemosensory Perception, 6,* 155-169.

Zellner, D., Greene, N., Jimenez, M., Calderon, A., Diaz, Y., & Sheraton, M. (2018). The effect of wrapper color on candy flavor expectations and perceptions. *Food Quality and Preference, 68,* 98-10.

Zhao, K., Scherer, P. W., Hajiloo, S. A., Dalton, P. (2004). Effect of anatomy on human nasal air flow and odorant transport patterns: implications for olfaction. *Chemical senses, 29(5),* 365-379.

VITA

Michelle Lynn Heatherly was born in Knoxville, TN in 1990 to James and Camille Heatherly. Michelle has one younger brother, Jimmy. The family remained in Knoxville where Michelle grew up and attended school. She graduated from Powell High School in 2008. Michelle graduated with a Bachelor's degree from the University of Tennessee Knoxville in May of 2015, and joined the Peace Corps. She served as an education volunteer in Mozambique before returning to the United States to pursue a Master of Science degree. In the spring of 2017, she began work as a Sensory intern at Diageo while studying toward a Master of Science degree in Food Science with a minor in Statistics.