Exploring the sensory characteristics of Virginia ciders through descriptive analysis and external preference mapping

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Abstract

The cider industry has experienced recent growth within the USA and Virginia in particular. However, the sensory characteristics and drivers of consumer acceptance of ciders are largely uncharacterized. Therefore, this work describes the sensory profiles of commercial Virginia ciders and links these to consumer acceptance. In study 1, a descriptive analysis (DA) of 24 representative ciders from 16 producers in Virginia was conducted: 6 panelists defined 48 descriptive terms for ciders. In study 2, a consumer acceptance study was conducted on 8 ciders from the DA with 67 subjects. For the DA study, 22 descriptors were found to be significant, and multivariate analyses identified 6 groups. In the consumer study, external preference mapping was conducted to identify 3 clusters of consumers with distinctive patterns of sensor preference. The largest cluster favored sweet ciders without off-flavors; a second, smaller cluster favored sweetness even in the presence of off-flavors; and the smallest cluster disliked sweetness in ciders and was intolerant of off-flavors. We describe these groups' demographic and consumption profiles. All ciders' basic chemistry was within previously reported ranges, and expected relationships between flavor and chemistry were observed. We were able to establish sensory profiles for Virginia ciders, and tentatively link sensory profiles and consumer acceptance. Overall, this work adds to a small-but-growing body of knowledge about ciders' sensory properties. Producers can use the sensory profiles in comparison to other regions' ciders to establish regional sensory profiles, and the consumer preference map to understand how to capitalize on their ciders' distinct profiles.

Keywords: cider; descriptive analysis; sensory evaluation; consumer acceptance; preference mapping

Word Count: 6835

1. Introduction

Cider was once the most popular alcoholic beverage in North America in the18th and 19th centuries (34). In the modern US, “cider” typically refers to the unfiltered sweet juice made from apples, whereas “hard cider” refers to the fermented, alcoholic product made from apples, but in the rest of the world “cider” refers to the alcoholic beverage (12,32). In deference to the majority usage, in this manuscript we adopt the latter terminology: “cider” will refer to the alcoholic beverage. Over the intervening two and a half centuries, due to factors including urbanization due to industrialization, Prohibition, and the increased mass-production of competitive products such as beer, cider fell out of popularity, until it experienced a popular resurgence in the last two decades (32,34). Cider is a growing industry, and is a preferred beverage among younger consumers (16). The cider industry in the United States generated an annual revenue of $517.26 million USD between 2016 and 2021, with much consumer interest focusing on “craft” or locally produced ciders (6).

Virginia is the sixth largest producer of apples within the United States, and Virginia lists apples as its sixteenth top agricultural commodity (31). There are more than 200 apple varieties grown in the state of Virginia, including both cider and dessert apples (2,3). In the state of Virginia, there are currently 32 cider producers. Six of these producers also act as wineries, breweries, or distilleries. This information was collected by preforming a web search for Virginia cider producers with the key words: “Virginia”, “cider”, “hard cider”, “cider producer”, and “craft cider”. Results were crosschecked with information from the Virginia Association of Cidermakers (30).

Despite the growing popularity of cider in Virginia and the US as a whole, there is very little published knowledge on the nature, origins, or importance of sensory profiles of cider. Early work by Williams (36) produced a sensory lexicon for British cider; while this work showed the diverse possible sensory profiles in ciders, it is more than half a century old and applies largely to cider produced with different apple cultivars and with different processing methods and traditions than are currently used in Virginia and the US as a whole.

Currently, there is a knowledge gap in terms of defining descriptive language for not only Virginia ciders, but all ciders. Williams (1975) created a flavor wheel, but little work on descriptive language for cider has been completed since. Further research on European cider varieties demonstrated that there is a broad range of cider flavors, and that ciders differ in flavors based on production method (11) and place of origin (22); these conclusions highlight the need for more research into American ciders. In the US, Tozer et al. (27) demonstrated that consumers were not able to describe their sensory experience of ciders consistently, which led to a mismatch between their expectations and experiences. Fabien-Ouellet and Conner (4), in qualitative research with cider producers, identify this mismatch as a key barrier to continued growth of the US cider market sector.

The American Cider Association called for work to be conducted to develop a sensory lexicon for American ciders in 2019, but this has not yet been accomplished (15). However, several pilot studies exploring the diversity of flavors in American ciders illustrate the need for this work. For example, Jamir et al. (9) used rapid sensory methods to produce flavor profiles for a set of ciders from two different cultural groups (American and Chinese college students). The researchers found strong diversity in flavors both within and between groups, and highlighted the need for a standardized lexicon (9). Phetxumphou et al. (19) created a functional preliminary lexicon for Virginia ciders using open comments and Check-All-That-Apply (CATA) and suggested a descriptive analysis could help produce a broader and more detailed lexicon for all cider. Kessinger et al. (10) used sorting methods to show that Virginia ciders are diverse in flavors, and that without a standardized lexicon consumers and producers use different terms to describe the same ciders. Littleson et al. (14) used descriptive analysis (DA) to define a lexicon and quantify the sensory profiles of 4 experimental ciders produced with different varieties and fermentation protocols. To our knowledge, these authors were the first to report a DA approach with American ciders, and they were able to demonstrate quantitative, significant differences among their experimental ciders. Thus, it is clear that Virginian (and American) ciders have diverse sensory profiles, that DA is an effective tool to define these sensory profiles, and that these sensory profiles are key to allowing producers and consumers to effectively communicate and match expectations to experiences.

To address this knowledge gap, we report two main and one supplementary study on Virginia ciders. In the first study, a descriptive analysis (DA) was completed using n = 6 panelists who defined and evaluated a total of 48 attributes for k = 24 Virginia ciders. Next, a consumer study was completed to understand the relationships between these sensory attributes and overall liking, willingness to pay and purchasing intent for Virginia ciders: a subset of k = 8 representative ciders from those used in the DA were evaluated by k = 67 cider consumers, and external preference mapping was conducted. Finally, to supplement the sensory analyses, a standard panel of cider chemistry was measured on all k = 24 ciders used in the DA.

2. Materials and Methods

2.1. Study 1: Descriptive analysis of Virginia hard ciders

2.1.1. Samples

For the DA study, samples were chosen by contacting the 32 known Virginia cider producers identified in a web search (30). Each cidery was requested to suggest their "flagship" cider that was "most typical" and "best represented" their cidery. Out of the 32 producers, 16 producers responded with 1-2 suggested ciders to include in the study. In the end, a total of 24 Virginia ciders were identified and purchased from retailers in the Blacksburg, VA area or shipped from producers' online shops. Samples are described in Table 1; we have anonymized producers and ciders. Based on information from packaging or website descriptions, 17 of these ciders were blends, 5 of them were single cultivars, and 2 could not be determined. Additionally, 13 were packed in 750mL bottles, 2 in 500mL bottles, 4 in 16oz cans, 3 in 12 oz cans, 2 in 12 oz bottles.

2.1.2. Subjects

Panelists were recruited from Virginia Tech and the Blacksburg, VA, USA communities. Panelists were screened to ensure that they were over the age of 21, not currently pregnant, had previously consumed alcoholic beverages, no known allergies to alcohol, apple cider, or any other fermented beverage, and were fully vaccinated against COVID-19. Because of restrictions on gatherings imposed by the COVID-19 pandemic, a total of 6 panelists participated in this study (4 male, 2 female). All panelists were between the ages of 21-30. Panelists did not receive compensation for participating in the study but were able to take snacks at the end of every training and evaluation session. Subjects gave informed signed consent for their participation. This study was approved by the Virginia Tech Institutional Review Board (IRB 19-1067).

2.1.3. Experimental Design

For all sessions, ciders were placed in a commercial refrigerator a day before the sessions to ensure each of the ciders were chilled to approximately 2 ºC. For each session, 1.5 oz of each cider sample used in that session was poured 10 minutes before the session started into black wine glasses labeled with blinding codes and covered with a watch glass. Panelists were instructed to smell and taste the ciders and expectorate the sample after tasting. Panelists were also instructed to clean their palates between samples by taking a sip of water and a bite of an unsalted saltine cracker.

Training and data collection followed the guidelines for DA laid out by Heymann et al. (7). Briefly, panelists participated in 8, 1-hour training sessions. In training sessions, panelists were served with 3-4 cider samples from the sample set in Table 1 per session, and were exposed to all samples at least once. Panelists generated descriptors for the ciders and suggested and approved reference standards (see Table 2).

After training was completed, data collection was accomplished in individual booths with neutral lighting, using Compusense Cloud (Guelph, ON, Canada). A design was adapted from a previous study on sparkling wines by Hood White & Heymann (8) to minimize both product waste and sensory changes from carbonation loss. All panelists evaluated all samples in duplicate, in a randomized, Williams Block Design. However, each panelist received the same samples on the same day of testing, so presentation order randomization was between replicates, rather than between each panelist. This was done in an effort to present samples on the day the bottle or can was opened, while also limiting the cost of samples, due to some of the more expensive samples evaluated being available in larger format bottles.

Ciders were poured 10 minutes prior to a panelist's arrival, and then the remainder of the bottle or can was transferred to an air-tight, 1000 mL glass flask equipped with a nalgene cap. All panelist sessions on a given day were in a 3-hour block. Six (6) cider samples were presented to panelists per session, and the sample set was evaluated in duplicate over the course of the individual sessions. Panelists rated the intensity of each descriptor in each cider on a 15-point line scale ranging from “None” to “Very High”. Panelists were presented with all references standards and were asked to review them once a week during evaluation sessions.

2.1.4. Data Analysis

All statistical analyses were completed in R (23) according to the standard methods laid out by Heymann et al. (7). The data from the descriptive analysis was first analyzed by a three-way multivariate analysis of variance (MANOVA) (*sample* x *panelists* x *replication*) with two-way interactions. A three-way univariate analysis of variance (ANOVA) (*sample* x *panelists* x *replication*) was completed for each of the individual descriptive terms, with two-way interactions. For each descriptor, if *sample* x *subject* or *sample* x rep *interactions* were significant, a pseudomixed test was conducted using the larger interaction effect as the error term (7). Following these omnibus tests, Tukey’s Honestly Significant Differences (HSD) test was used to identify significant pairwise differences for each descriptor among samples. For all tests, significance was defined as $p < 0.05$. Principal Component Analysis (PCA) was used to visualize relationships among both the cider samples and sensory attributes. Groups of ciders were identified using Hierarchical Cluster Analysis (HCA) with Ward’s method on the PCA space.

2.2. Study 2: Consumer acceptance and preference mapping

2.2.1. Samples

In order to select a representative sample of ciders from the DA study for further evaluation, the PCA plot was used to choose eight samples: two from every quadrant of the first two dimensions of the PCA (see Figure 1 and Table 1). Within each quadrant, samples that were not close to each other were selected to maximize sample variation among those select for this subset. Samples were purchased from retailers in the Blacksburg, VA, USA area or shipped from producers’ online shops

2.2.2. Subjects

Subjects (N = 67) were recruited from the Blacksburg, VA, USA and Virginia Tech community. Subjects were screened to ensure that they were over the age of 21, not currently pregnant, had previously consumed alcoholic beverages, had no known allergies to alcohol, apples, apple cider, or any other fermented beverage, and were fully vaccinated against COVID-19. This study was approved by the Virginia Tech Institutional Review Board (IRB 21-1045).

2.2.3. Experimental Design

Subjects were presented a total of 8 cider samples in randomized, sequential, monadic order as 1.5 oz pours in black wine glasses which completely obscured the appearance of the ciders. The cider was chilled at in the refrigerator at 1 ºC, and serving commenced only as panelists entered the booths. On each study day, as the first panelists came in, cider was transferred from original packaging into air-tight, 1000 mL glass flasks equipped with airtight screw caps. The flasks were subsequently stored in the refrigerator for 3 hours after first filling. After that time period (or if the volume was exhausted), the flasks were emptied and refilled to maintain approximately consistent carbonation (8).

Subjects were first asked a series of demographic and consumption questions: age range, gender identity, income range, education level, and cider consumption frequency. For each of the 8 cider samples, subjects rated liking on a standard 9-point hedonic scale. Then, subjects were asked to rate their purchasing intent on a 5-point scale, ranging from "definitely will not buy" to "definitely will buy". Finally, subjects used a marked line scale to indicate how much they would be willing to pay for a 6-pack of 12oz cans of that particular cider, with prices ranging from $11-$15 USD in $0.50 increments. This packaging size was chosen because 12 oz 6-packs accounted for the plurality (47%) of all off-premise cider sale shares in 2021 (17). The price range was based on the median of the price range for this volume of cider for all 24 ciders in the study. All data was collected using Compusense Cloud (Guelph, Ontario, Canada).

2.2.4. Data Analysis

All statistical analyses were completed in R (23). Consumer data was treated in several ways. First, external preference mapping and clustering was accomplished using the Clustering around Latent Variables (CLV) approach (29). Briefly, CLV simultaneously identifies clusters of consumers with similar patterns of liking for a particular set of products and sets of products with a similar set of attributes that fit those consumer liking patterns in an iterative, optimization framework (28). Following CLV, Partial Least Squares Regression (PLS-R) was used to visualize the relationships among the identified consumer clusters, the products, and the sensory attributes.

For each cluster, demographic and purchasing data were tabulated as proportions. Fisher's Exact Test was used to test for significant differences in patterns between clusters. Purchasing intent was treated as numerical, and is reported as mean and standard deviation for each cider for each cluster. For each subject and cider, willingness-to-pay (WTP) was only considered for ciders rated 3-5 on the 5-pt purchase scale; after that filtering, WTP was calculated as mean and standard deviation for each cider for each cluster.

2.3. Study 3: Supplemental chemical analysis of Virginia ciders

2.3.1. Samples

All 24 ciders from the DA (Table 1) were analyzed for basic cider chemistry parameters (see below).

2.3.2. Experimental Design

The following analyses were completed on each of the cider samples, pH (Ion probe, AOAC Official Method 960.19); Titratable Acidity (Titration, AOAC Method 960.12); Volatile Acidity (Cash Still and Titration, AOAC Method 964.08,TTB Method SSD:TM:502 modifications); Total SO_2 (Aeration & Oxidation, modifications for Free Sulfite Quantification SSD:TM:500); Free SO_2 (Aeration & Oxidation, modifications for Free Sulfite Quantification SSD:TM:500); Residual Sugars (Megazyme Sucrose/D-Fructose/D-Glucose Assay Kit Assay Kit, Megazyme International, Wicklow, Ireland); Total Polyphenols (Folin-Ciocalteu (F-C)); Malic Acid (Megazyme Malic Acid Enzymatic Kit, Megazyme International, Wicklow, Ireland); CO_2 (Anton Paar: PBA (Package Beverage Analyzer)); ABV (Anton Paar: PBA (Package Beverage Analyzer)).

2.3.3. Data Analysis

All statistical analyses were completed in R (23). For each measurement, a one-way univariate analysis of variance (ANOVA) was performed with sample as the independent variable to identify any significant differences. For each measurement, Tukey's Honestly Significant Differences (HSD) test was used to identify any pairwise differences among samples. Significance was identified at $p < 0.05$. The chemical analysis data was expressed in mean ± standard deviation. Alcohol and CO_2 were not measured in duplicate because of limited sample quantity, and so were not included in ANOVA and posthoc testing.

3. Results and Discussion

3.1. Descriptive analysis

A descriptive analysis (DA) was conducted with 6 trained panelists to determine the sensory attributes of 24 Virginia ciders. The panel defined and approved a total of 48 attributes for the Virginia ciders: 13 flavor (retronasal) attributes, 20 aroma (orthonasal) attributes, 3 taste attributes, and 12 mouthfeel attributes (see Table 2). Each of the attributes was anchored by a reference that was approved and defined by the 6 panelists in consensus (Table 1).

A three-way MANOVA showed there was not a significant interaction between samples and replicates (approx. $F_{1104,1567} = 0.99, NS$) but that there was a significant interaction between samples and subjects (approx. $F_{5520,3798} = 1.38, p < 0.05$), which is common in DA studies. To account for this, 3-way pseudomixed univariate ANOVA was conducted for each of the 48 attributes, resulting in a finding of significant differences among samples for 22 of these attributes (see Table 2).

Principal Component Analysis (PCA) was used to visualize the overall pattern of variation among samples in mean attribute intensity for the significant attributes. Figure 1 shows the PCA score (product) and loading (attribute) plots for the first two dimensions of the PCA analysis, accounting for a total of 59.96% of variance. The expected variance explained by any principal component in the absence of variable correlation would be $100/22 = 4.09\%$, making these two dimensions highly effective in explaining a much greater than expected amount of variation. Non-significant attributes were projected into the PCA space as supplementary variables in order to help explain the space (1). The first dimension was most positively correlated with attributes *sour, tingly, sharp, sour candy*, and *bubbly*, and most negatively correlated with attributes *smooth, flat, watery, sweet,* and *earthy*. The second dimension was most positively correlated with terms like *smokey, bitter, pungent, urine*, and *sulfur*, and most negatively correlated with *apple juice, green apple, sweet, smooth*, and *bubbly*. The second dimension particularly was positively correlated with a number of potential off-flavors in cider, although it is interesting to note that the presence of the potentially desirable *bitter* taste is correlated with these same terms. The cider samples themselves can also be understood in terms of their association with the flavor terms: C9, C16 and C15 were given high intensity ratings for *smokey, bitter pungent, grapefruit, alcohol*, and *citrus*; C6, C5, C4, C13, C2, C19, C21, C11 and C3 were characterized by descriptors such as *apple juice, green apple, bubbly, sour candy, sharp, sour*, and *tingly*; C8, C7, C18, C1, C20, C22, and C24 were described as *sweet, smooth,* and *watery*; and lastly C14, C23, C10, C17 and C12 were characterized as *rot, sulfur, urine, earthy, flat,* and *green vegetable*.

The cider samples were clustered into six groups using Hierarchical Cluster Analysis (HCA) based on the distances among the samples in the space defined by the PCA. Six clusters were selected manually because of the presence of two clear isolates in the main descriptive space of the PCA: C15 and C12. As is evident from the PCA scores and loadings plots (Figures 1), specifying 6 clusters produces compact clusters with reasonably well-defined sensory characteristics. The two outliers (C15 and C12) are already well separated in the first two dimensions, but can be even more clearly distinguished in Dimension 3 (results not shown).

The clusters represent groups of ciders with similar sensory attributes—these are possible prototypes for cider characters in Virginia (see Figure 1 for reference to the following). The ciders in Cluster 1 were mostly associated with *sweet, smooth, watery, flat,* and *apple juice*. Cluster 2 was associated with *sweet, smooth, rot, earthy, green vegetable, flat,* and to a lesser degree *urine* and *sulfur*. Cluster 3 was associated with *citrus* and *alcohol* attributes, as well as to a lesser degree the cluster of attributes *sharp, tingly, sour, bubbly*, etc. Cluster 4 is the singular C12, which is associated with a number of potential off-flavors associated with fermentation problems and/or and microbiological instability, such as *sweet, urine*, and *sulfur*. Cluster 5 is associated with *sour, tingly, sharp, sour candy, green apple*, and *bubbly*. Lastly, cluster 6 contains the other singular sample, C15, which is associated with *smokey, bitter*, *grapefruit, alcohol,* and *pungent*.

Interestingly, 5 of the ciders contained the apple variety Virginia Hewes Crab, which is a crab apple grown in Virginia. While the current study was not designed to assess cultivar characteristics, it is worth considering whether ciders made with the same apple have similar flavors. Samples C2, C4, C5, and C17 were described as single cultivar ciders containing Virginia Hewes Crab, while C16 was blended with a total of seven other apple varieties in addition to the Virginia Hewes Crab. In the PCA plot it is apparent that 4 of these ciders have relatively similar characteristics: C2, C4, C5, and C16. However, one of the single-cultivar ciders containing this apple (C17) is quite distinct from the other 4. Therefore, it is fair to conclude that even though all these ciders contain the same cider apple, their flavor profiles are not predictably similar. This could be due to a variety of reasons, such as but not limited to fermentation method, adjuncts, cider style, apple maturity, filtration, chemical and microbiological stabilization, or packaging method and materia (35).

3.2. Consumer studies

In Study 2, 67 cider consumers rated their overall liking for 8 representative ciders from the DA sample set (Table 1), and answered questions about demographics and purchasing and consumption habits (Table 3). This was a relatively small sample size for a consumer study, as recruitment and sampling efforts were hindered by the continued impact of the COVID-19 pandemic. However, results can still provide some insight into possible preference and consumption patterns for cider consumers.

3.2.1 Preference mapping and clustering

Using the Clustering around Latent Variables (CLV; 29) technique, consumers were clustered into groups based on their patterns of liking for ciders with distinct sensory profiles. Here, we report the patterns of liking for the ciders in general and in the identified clusters; below (section 3.2.2 and 3.2.3) we discuss the demographic and purchasing patterns in the identified clusters.

The CLV analysis identified 3 clusters of consumers based on patterns of liking (Figure 2). In cluster 1 (n = 32), the samples that were most liked overall were C1, C3, C7, and C21. The attributes that were most positively loaded for consumers in cluster 1 were *apple juice, smooth, sweet,* and *green apple*. The second largest cluster, cluster 2 (n = 21) most preferred ciders C7 and C12, with a mild liking for C23, and consumers in this cluster showed strong preferences for the attributes *sweet* and *smooth*, and in contrast to the other two clusters also showed (smaller) positive loadings for flaws such as *urine*, *sulfur*, and *earthy*. The third and smallest group of consumers, cluster 3 (n = 14) preferred a distinct set of samples: C3, C9, C16, and C21. The attributes that were most positively loaded for cluster 3 were *sour, sour candy, sharp, green apple, tingly, bubbly,* and *grapefruit.* Because CLV provides both patterns of liking (the ciders liked by each cluster) *and* explanations based on the attributes describing those patterns, we are able to draw some conclusions about the type of consumers in each cluster. Cluster 1 might be termed "modern cider" drinkers who prefer sweeter ciders, but had low tolerance for potential flaws and off flavors. Meanwhile, cluster 2 also preferred sweeter ciders, but did not mind the presence of potential off-flavors—we could call these cider drinkers "casual" or "novice" cider drinkers. Finally, cluster 3 actively disliked sweetness in ciders, but was also generally intolerant of potential flaws and off-flavors: we call these cider drinkers "craft cider" drinkers since their liking was driven by tart and complex ciders.

In order to visualize the relationship between consumers, attributes, and products, Partial Least Squares Regression (PLS-R) was used to explain the pattern of consumer preferences simultaneously with the sensory attributes identified through the DA (Figure 3). Consumers were colored according to their cluster from CLV. This figure is particularly helpful for elucidating the preferences of the two smaller clusters (clusters 2 and 3). While no consumers actively prefer potential flaws like *rot* or *sulfur* (in the negative direction on dimension 2 of Figure 3), consumers from cluster 2 are much likelier to rate ciders with these attributes more favorably than other groups. Conversely, *only* consumers from cluster 3 are likely to rate ciders with low *sweetness* and other related attributes highly (in the positive direction of dimension 2 of Figure 3). Interestingly, as can be seen by looking at Figures 2 and 3, only *smokey* was disliked by all clusters.

Mean liking scores overall and by cluster are given in Table 4. While overall sample C7 was the most liked sample, which was closely associated with attributes of *sweetness* and *smooth*, cluster 3 did not prefer this sample. Instead, Cluster 3 overall preferred C16, which is associated attributes with *sharp*, *citrus*, and *tingly*. Meanwhile, C12, which was highly disliked overall and by both cluster 1 and 3, and which was most associated with the cluster of potential off-flavors, is the second most liked cider in cluster 2 (Figure 2).

3.2.2 Consumer cluster demographics and purchasing behavior

For each demographic and consumption question, proportions are reported overall and by cluster from CLV in Table 3. Clusters did not differ by age range or gender identity (Fisher's Exact Test, $p > 0.05$). Given the small sample size and because a general population sample was recruited, this was not surprising. Overall, subjects were mostly female (62.1%) young (73.1% age 21-30), highly educated (more than 52% holding at least a US bachelor's degree), and with relatively low household income (the plurality of 38.8% reported income of less than $25,000 USD). This sample makes sense given the university population in Blacksburg, VA, USA where the study was conducted. The sample size was too small to detect significant patterns between the clusters, which are reported in Table 3 for completeness.

3.2.3. Purchasing intent and willingness-to-pay

Overall and within-cluster purchasing intent (on a scale of 1 to 5) for each cider is reported in Table 4. Overall, cider C7 was rated on average highest on the scale, with a mean rating of 3.75—this was the sweetest cider according to both DA and cider chemistry (measured residual sugar, Table 5). This result is not surprising, since overall, it had the highest mean overall liking score among all consumers. The within-cluster results closely followed the patterns of liking—this is also unsurprising, as liking and purchasing intent are nearly perfectly correlated (r = 0.91). However, it is important to note that a reported purchase intent of 3 is “neutral”, so despite the strong correlation it is not entirely clear that any cluster was strongly enthusiastic about any particular cider besides C7 in cluster 1 (Table 4).

Overall and within-cluster willingness-to-pay (WTP) for each cider sample is reported in Table 4. WTP was only collected from consumers who indicated a neutral to positive purchasing intent (3, 4, or 5 on the given scale) for each cider. The results indicate that on average no consumer was willing to pay above $13.00 for a 6-pack of 12-ounce cans of any of these ciders. For all 67 subjects, all the ciders were within the $12.00 range, with sample C7 receiving the highest WTP at $12.80, and C9 the lowest at $12.00. There was variation within clusters for these results, which reflects a lower correlation between overall liking and WTP (r = 0.69) and purchase intent and WTP (r = 0.75). For example, in cluster 1, C7 received the highest purchasing intent rating, but C7 was rated the second highest price at $12.80, while C1 was rated at $12.90. This is interesting as C1 has both a lower mean purchasing intent rating and overall liking within this cluster. In cluster 2, consumers were likewise most willing to spend the most on sample C7, but they were also willing to spend more on purchasing C12, which received the lowest WTP from cluster 1 and which no-one from cluster 3 was willing to purchase. Following their inferred preferences from CLV, subjects from cluster 3 differed in their patterns, being willing to spend the most on sample C3, which was neither the most liked sample nor had a high purchasing intent rating overall. As noted above, in cluster 3 no consumer indicated that they would even consider purchasing sample C12 on the purchasing intent scale, so WTP could not be calculated. The low cost for each of the samples could be since these ciders were not overall well liked among the consumers. The most liked cider was rated a 7 on average on the 9-point hedonic scale among all consumers, which was sample C7. Additionally, since WTP was calculated only for subjects who rated their purchasing intent for a sample above 2, these prices may only reflect a small number of consumers overall and in each cluster.

3.3. Cider chemistry

3.3.1. Basic cider chemistry

A comprehensive cider chemistry panel was conducted on all 24 ciders from the DA study to enable comparison of basic quality metrics between Virginia ciders in this study and those reported in the literature for ciders produced elsewhere worldwide. In addition, these results could be used qualitatively to provide context for the DA results, and to compare those results to generally understood relationships between sensory and chemical data for cider. Results for analyses are given in Table 8. All analyses were conducted in duplicate except for alcohol and CO_2. One-way ANOVA for all analyses with replication indicated that samples varied significantly in the measured chemistry (Table 8). This is to be expected for the diverse range of ciders included in the study.

The alcohol content for these ciders ranged from 4.81% to 9.86% ABV. These ranges were high compared to previous reports in the literature (e.g., 26). Symoneaux et al. (26) did not report any cider with ABV over 6.3%, while 18 of the ciders used in this study had an ABV% over 7.0%. This could be due to apples in Virginia being grown in warmer climates than those used to make the ciders studied by Symoneaux et al (26), which would cause a higher sugar content in the apples (and associated higher potential alcohol content). There could also be stylistic and production process differences between the ciders in our study compared to the French ciders studied by Symoneaux et al (26). Malic acid range was also found to higher compared to results reported from the study by Qin et al. (22). Qin et al. reported malic acid concentration from 0.02 to 3.56 g/L, while in this study malic acid ranged from < 0.020 g/L to 8.44 g/L. This can be attributed to variation across apple cultivars, as well as the fact that several ciders from the former study underwent malolactic fermentation. It is also possible that exogenous malic acid additions were made in the production of some of the Virginia ciders, which would elevate the malic acid concentration. As malic acid is the main fruit acid present in apples and ciders, we focus on this chemical, but it is worth noting that the titratable acidity ranges of ciders in this study follow the same pattern. In these ciders, TA ranged from 2.60 to 8.28 g/L malic acid equivalents, whereas in the Qin et al (22) study the range was smaller and lower, from 2.41 to 6.39 g/L malic acid equivalents. Meanwhile, pHs ranged from 3.61 to 4.09, which is consistent with the commercial ciders reported in previous studies (9,22,26).

Residual Sugar (RS) levels, measured in g/L, were quite different than those reported in previous studies (22,26). These previous studies reported much higher RS than the range reported in Table 8, indicating that the ciders used in those studies were likely to be perceived as more sweet, and possibly more full-bodied and less sour or bitter. In this study, RS ranged from below the level of detection to 38 g/L, whereas Symoneaux et al (26) reported RS from 12.7 to 52.1 g/L, and Qin et al (22) reported RS from 8.87 to 75.44 g/L. Given that these previous studies included or even focused on European styles that are not generally fermented to dryness (22,26), this is unsurprising, and indicates the need for much more work to characterize cider styles so that sensible comparisons can be made.

Measured polyphenol concentration ranged from 144 to 778 mg/L gallic acid equivalents (GAE), which was consistent with range determined by the Folin-Ciocalteu method on a sample set of 17 commercial ciders from the Eastern USA from Ma et al. (2019). Volatile acidity (VA) ranged from 0.21 to 2.15 g/L acetic acid equivalents in this study. The range of VA for these ciders were consistent with a previous study on Asturian ciders (20). All ciders this study were carbonated, and the CO_2 readings ranged from 1.48 g/L to 7.89 g/L, showing a broad range of carbonation among the ciders in this study. Both free and total SO_2 were measured in all cider samples. Analysis of total SO_2 confirmed that all samples were well below the regulatory limit. Likewise, free SO2 levels were within a normal-to-low range, and therefore unlikely to cause deleterious sensory effects in any sample. However, other studies did not report this potentially informative measurement, so we did not compare the measured range in these ciders (Table 8).

The results from the chemical analysis indicate that Virginia ciders are generally within the expected range of cider chemistry reported in other studies, with some specific and potentially important differences. Specifically, the ciders in this study were higher in alcohol and lower in residual sugar than ciders in other, similar studies, which may indicate a tendency towards higher sugar content in Virginia-grown apples and/or more complete fermentations (conversion of sugar in juice to alcohol) in Virginia ciders that is distinct from cider fermentations in other regions.

3.3.2. Connecting cider chemistry to sensory outcomes

It is possible to find associations among the measured cider chemistry and the quantitative results of the DA, which provides support for the quality and utility of the DA results. For example, in the DA analysis Samples C9, C15, and C16 were closely related to the alcohol attribute (Figure 1). All three of these ciders had an ABV above 7%, with C15 and C16 having the highest ABV among all the samples at 9.68% and 8.99%. Further, C16 had the highest mean reading of VA among all samples, at 2.15 g/L. Since high levels of VA can be perceived as nail polish or vinegar, this could explain why panelists associated it with descriptors like pungent, sharp, and sour (33).

Titratable acidity (TA) can be an indicator of sensory sourness or tartness within samples (33). The terms *sour*, *sour candy*, *sharp* and *green apple* are all closely related attributes according to the PCA (Figure 1), and samples, C5, C2, and C11 among others were found to be associated with these descriptors. C2 had the highest mean intensity rating of *sharp* and *sour* among panelists, and was also found to have a mean TA reading of 6.16 g/L malic acid equivalents (Table 5). Similarly, sample C5 was found to have the highest mean TA among all other samples (Table 5) and was closely associated with the *sharp* and *sour* descriptors.

Sweetness perception in DA is also associated with cider chemistry, in this case measured residual sugar (RS). Ciders C7, C8, and C24 had measured RS over 25.0 g/L (Table 5), and were also most closely associated with the *sweet* and *smooth* attributes in the DA (Figure 1). However, it is interesting to note that RS does not *solely* explain sensory sweetness: C22, C20, and C18 were associated with *sweet* (Figure 1), but had undetectable levels of RS (Table 5). This is very likely due to interactions between taste and aroma (21).

CO_2 is known to impact the sensory profiles of beverages (8), with high concentrations of CO_2 correlated to perceived sourness (37). All ciders described as *bubbly* were also described as *sour*, and *sour candy*. Among these, C11 and C9 had the highest concentrations of CO_2 (Table 5), and were also described using the *sour* and *sour candy* attributes (Figure 1). Conversely, sweetness perception can reduce the overall carbonation mouthfeel in beverages (37). This effect can be observed in this study: most ciders with a high intensity rating in *sweet* did not have high rating of *bubbly* or *sour* (Figure 1).

It has long been thought that polyphenol content in fermented beverages is related to total polyphenols (13,34). Samples C9, C15, and C16 were closely associated with the *bitter* attribute, with high mean intensity ratings (Figure 1). However, the polyphenol content for these samples were solidly in the middle of the range of the samples in the current study (Table 5). This shows that within these samples, bitterness perception may not be only impacted by polyphenol concentration—there are presumably both interactions with other sensory attributes (such as *sweet*) and other causes that can be traced to cider chemistry (5).

Overall, the observation of the expected associations between cider chemistry and the measured sensory attributes from the DA provide a measure of assurance that the panel was well-trained, and that DA results can reliably inform and contribute to the advancement of research on cider production factors.

3.4. Limitations and Future Work

A major limitation of the current work is the sample size used in the consumer study. A sample of $n = 67$ consumers is obviously not a fully representative sample. In part this sample size is due to the difficulty of conducting consumer research during the COVID-19 pandemic. Thus, this part of the research should be treated as exploratory, rather than confirmatory: the patterns of consumer liking observed can be used as hypotheses to test in future research. However, the clear and provocative patterns of reported liking, which to some degree align with those hinted at in previous research (4,27) indicate that these will be productive avenues for further, better-powered consumer research. In particular, research to explore the “modern” vs “craft” segments that emerged in this small sample should be encouraged.

A second limitation of the current study is the selection of cider chemistry to associate with sensory outcomes. In this study, the cider chemistry measured was based in large part on producer-relevant analyses, but these are unlikely to be able to explain the full range of flavors and aromas in cider identified by DA, which are likely to originate from volatile aroma compounds that require different analytical strategies (33). Future studies that aim to better characterize and identify the highest impact odorants in Virginia ciders should consider employing flavor-chemistry approaches like gas chromatograpy-olfactometry (GC-O).

Further research should also be undertaken to survey the flavor profiles of American ciders beyond Virginia. While Virginia is a major producer of cider with a broad range of producers and products, the current study cannot compare these products to other ciders produced in the United States simply because there is no published research on those products. Therefore, it would be of interest to determine the sensory profiles of ciders in the United States and, from the perspective of Virginia producers, what makes Virginia ciders distinctive.

Finally, it would benefit both researchers and producers to compile sensory research from this and other studies into a usable, comprehensive sensory lexicon for ciders in the style of the widely adopted wine wheel (18). The wine wheel, as noted by Sela Bowen et al. (24) and Shapin (25) is a powerful tool for producers and consumers to communicate the often ineffable flavor of wines. As the US cider industry grows, a similar tool for these products would help consumers, who clearly can have distinct sensory preferences and expectations, understand how to select ciders; it would also help producers target their products appropriately. The current research is a key contribution towards such a tool, which is critical future work.

4. Conclusions

In this research, a trained panel employed descriptive analysis to quantify the sensory profile of 24 Virginia ciders using 48 attributes, 22 of which were found to differ significantly among the samples. A representative subset of 8 of these ciders were evaluated for liking and willingness-to-purchase by a panel of 67 consumers. Using external preference mapping, 3 distinct clusters of consumers were identified with quite distinct liking profiles. Finally, producer-relevant cider chemistry was found to be associated with sensory profiles, which supports the quality of the sensory profiling work through the DA.

This research contributes to the larger project of understanding the origin and significance of flavors in ciders produced in Virginia and the United States as a whole. The terms that were used in the descriptive analysis are consistent with but expand on previous studies on Virginia ciders (10,10,14). This indicates that there is an underlying, common set of attributes which can ultimately be catalogued to create a sensory lexicon for American ciders, analogous to the famous wine wheel (18). Uniquely, this research investigated the connections among sensory profile and consumer preference: the finding that distinct consumer segments exist for different cider sensory profiles further supports the need to investigate and develop a consistent sensory lexicon for cider.

Acknowledgements

This work was funded by the Virginia Department of Agriculture and Consumer Services (VDACS) and the United States Department of Agriculture (USDA) through Specialty Crop Block Grant #301-20-026. The authors would also like to thank Ann Sandbrook and Ken Hurley of the VA Tech Enology Services lab for their assistance with chemical analyses of cider.

Interest Statement

No potential conflict of interest was reported by the authors.

Data Availability Statement

Data and code are available from the corresponding author upon reasonable request.

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Tables

Table 1. Cider sample descriptions; please note that the ciders and producers have been anonymized.

Sample	Packaging Format	Blend or Single Cultivar	Apple Varieties	Location in Virginia
C1*	*750 mL Bottle*	*Blend*	*Albemarle Pippin, Gold Rush, Pink Lady, Virginia Gold, undesignated*	*North Garden*
C2	*750 mL Bottle*	*Single*	*Virginia Hewes Crab*	*North Garden*
C3*	*750 mL Bottle*	*Blend*	*N/A*	*Monterey*
C4	*750 mL Bottle*	*Single*	*Virginia Hewes Crab*	*Monterey*
C5	*750 mL Bottle*	*Single*	*Virginia Hewes Crab*	*Richmond*
C6	*750 mL Bottle*	*Single*	*Harrison*	*Richmond*
C7*	*12 oz Bottle*	*Blend*	*N/A*	*Nellysford*
C8	*12 oz Bottle*	*Blend*	*N/A*	*Nellysford*
C9*	*16 oz Can*	*N/A*	*N/A*	*Roseland*
C10	*12 oz Can*	*Blend*	*N/A*	*Richmond*
C11	*750 mL Bottle*	*Blend*	*Albemarle Pippin, Gold Rush*	*Keswick*
C12*	*16 oz Can*	*Blend*	*Granny Smith, undesignated*	*Mineral*
C13	*12 oz Can*	*Blend*	*N/A*	*Alexandria*
C14	*750 mL Bottle*	*Blend*	*N/A*	*Middleburg*
C15	*500 mL Bottle*	*Blend*	*N/A*	*Middleburg*
C16*	*750 mL Bottle*	*Blend*	*Harrison, Ashmead's Kernel, Winesap, Golden Russet, Arkansas Black, Black Twig, Albemarle Pippin, Virginia Hewes Crab*	*Warm Springs*
C17	*750 mL Bottle*	*Single*	*Virginia Hewes Crab*	*Warm Springs*
C18	*750 mL Bottle*	*N/A*	*N/A*	*Abingdon*
C19	*750 mL Bottle*	*Blend*	*N/A*	*Abingdon*
C20	*12 oz Can*	*Blend*	*N/A*	*Leesburg*
C21*	*16 oz Can*	*Blend*	*N/A*	*Winchester*
C22	*500 mL Bottle*	*Blend*	*N/A*	*Winchester*
C23*	*750 mL Bottle*	*Blend*	*Gold Rush, Albemarle Pippin, Winesap*	*Charlottesville*
C24	*16 oz Can*	*Blend*	*Golden Delicious, Red Delicious and Granny Smith*	*Roseland*

*Cider was selected for use in study 2 (consumer preference mapping study).

Table 2. Sensory attributes and reference standards as defined by the DA panel.

Aroma (orthonasal aroma)	
Alcohol*	*15% ABV EtOH*
Cinnamon Spice Apple	*Canned apple pie filling (Kroger)*
Citrus*	*1” lemon peel, 1” lime peel in 0.5 oz 5% ABV EtOH*
Earthy*	*Handful of grass plucked from outside*
Fermented	*1 tbsp 2% Greek yogurt (Fage), 1/8 tsp apple cider vinegar, 1/8 tsp white vinegar*
Fermented/Yeast	*1 packet of dry active yeast in 500mL water*
Floral	*¼ tsp of rose water (Heritage Store)*
Grassy	*Clumps of cut grass with dirt from outside*
Grapefruit*	*1” grapefruit peel in 0.5 oz 5% ABV*
Green Apple Jolly Rancher	*1 Green Apple Jolly Rancher. 0.5 oz 5% EtOH*
Green Vegetable*	*Frozen broccoli (Kroger), microwaved 6 mins*
Lemon	*1” lemon slice, 0.5 oz 5% EtOH*
Metallic	*2 pennies, panelists instructed to rub pennies on hands, and smell their hands*
Peach	*2 fresh peach slices*
Petroleum	*Verbal anchor*
Pear	*2 fresh pear slices*
Rot*	*2 slices of red apples (microwaved 2 mins), 1/8 tsp apple cider vinegar*
Smokey*	*1/8 tsp “liquid smoke” (Colgan), 500mL water*
Sulfur*	*Hard-boiled egg (Simple Truth), microwaved for 2 mins*
Urine*	*Verbal anchor*
Flavor (retronasal aroma)	
Acidic	*1 tbsp apple cider vinegar, 8 oz water juice*
Apple Juice*	*2 oz apple juice (Simple Truth)*
Beer	*2 oz Coors Light*
Champagne	*2 oz prosecco (Lamarca)*
Fruity	*2 oz fruit smoothie (Bolthouse Farms Berry Boost)*
Grape	*2 green grapes, sliced in half*
Green Apple*	*2 1” slices granny smith apple (Simple Truth)*
Maple Syrup	*1 tbsp Vermont maple syrup (Kroger)*
Red Wine	*2 oz cabernet sauvignon wine (Bay Bridge)*
Red Apple	*2 1” slices honey crisp apple*
Sour Candy*	*1 piece sour candy (WarHead Black Cherry)*
Watery*	*1 oz apple juice (Simple Truth Organic), 1 oz water*
White Wine	*2 oz pinot grigio wine (Dark House)*
Taste	
Bitter*	*2 oz caffeine solution (1.6 mg/mL)*
Sour*	*2 oz citric acid solution (0.005 mg/mL)*
Sweet*	*2 oz sucrose solution (30 mg/mL)*
Mouthfeel	
Bubbly*	*2 oz citrus soda (Sprite)*
Dry	*1 oz 100% cranberry juice (Ocean Spray), 1 oz 100% pomegranate juice (POM Wonderful)*
Flat*	*2 oz seltzer water (San Pellegrino), poured an hour before panelist arrival*
Full-Bodied	*2 oz merlot wine (Dark Horse)*
Heavy	*2 oz of apple juice (100 mL Simple Truth Organic) thickened with ¼ tsp of cornstarch*
Pungent*	*1 tsp wasabi sauce (Snow Fox)*
Mouth-Watering	*2 oz 100% cranberry juice (Ocean Spray)*
Sharp*	*2 oz of apple juice (400 mL Simple Truth Organic) with added 1.4 tsp brewer’s grade Malic Acid*
Linger	*2 oz black tea (1 bag Lipton black tea, brewed 5 minutes in 16 oz water)*
Smooth*	*2 oz chardonnay wine (Flip Flop)*
Sticky	*2 oz of drink mix (200 mL Grape Kool-Aid) thickened with ¼ tsp of cornstarch*
Tingly*	*¼ tsp popping candy (Strawberry Pop Rocks)*

*This descriptor was found to be significantly different among samples in pseudomixed, 3-way ANOVA (p < 0.05).

Table 3. Demographic and consumption behavior questions, given as proportions of all subjects and of the clusters found from external preference mapping via CLV.

Question	Response	Overall (n = 67)	Cluster 1 (n = 32)	Cluster 2 (n = 21)	Cluster 3 (n = 14)
Gender	*Male*	*35.8*	*28.1*	*47.6*	*35.7*
	Female	*61.2*	*68.8*	*52.4*	*57.1*
	Non-Binary	*2.99*	*3.12*	*0*	*7.14*
	Prefer to Self-Describe	*0*	*0*	*0*	*0*
Age	*21-30*	*73.1*	*78.1*	*71.4*	*64.3*
	31-40	*8.96*	*6.25*	*4.76*	*21.4*
	41-50	*0*	*0*	*0*	*0*
	51-60	*11.9*	*9.38*	*14.3*	*14.3*
	60+	*5.97*	*6.25*	*9.25*	*0*
Education	*Some High School*	*0*	*0*	*0*	*0*
	High School Graduate	*1.49*	*0*	*0*	*7.14*
	Some College	*7.46*	*15.6*	*0*	*0*
	Associate Degree	*2.99*	*3.12*	*4.76*	*0*
	Bachelor's Degree	*52.2*	*56.2*	*42.9*	*57.1*
	Master's Degree	*26.9*	*18.8*	*42.9*	*21.4*
	Doctorate	*8.96*	*6.25*	*9.52*	*14.3*
Cider Consumption Frequency	*Everyday*	*0*	*0*	*0*	*0*
	A Few Times a Week	*4.48*	*6.25*	*4.76*	*0*
	Once a Week	*8.96*	*15.6*	*4.76*	*0*
	Once or Twice a Month	*34.3*	*18.8*	*38.1*	*64.3*
	Occasionally	*52.2*	*59.4*	*52.4*	*35.7*
Income*	*Less than $25,000*	*38.8*	*40.6*	*42.9*	*28.6*
	$25,000 - $49,000	*20.9*	*25*	*19.0*	*14.3*
	$50,000 - $75,000	*14.9*	*9.38*	*9.52*	*35.7*
	$76,000 - $99,999	*2.99*	*3.12*	*0*	*7.14*
	$100,000 - 150,000	*4.48*	*6.25*	*4.76*	*0*
	Greater than $150,000	*10.4*	*9.38*	*9.52*	*14.3*
	Prefer not to answer	*7.46*	*6.25*	*14.3*	*0*

*All values are in $USD.

Table 4. Mean and standard deviation for liking (1-9 scale), purchase intent (1-5 scale), and willingness to pay (WTP in $USD; $11-$15 scale) for ciders overall and in each cluster identified in external preference mapping with CLV.

	Overall			Cluster 1 (*n* = 32)			Cluster 2 (*n* = 21)			Cluster 3 (*n* = 14)		
Sample	**Liking**	**Purchase intent**	**WTP**	**Liking**	**Purchase intent**	**WTP**	**Liking**	**Purchase intent**	**WTP**	**Liking**	**Purchase intent**	**WTP**
C1	*3.87 ± 2.06*	*2.01 ± 1.01*	*12.50 ± 1.04*	*3.66 ± 2.22*	*2.06 ± 1.16*	*12.90 ± 1.33*	*3.95 ± 1.99*	*2.00 ± 0.89*	*12.30 ± 0.65*	*4.21 ± 1.85*	*1.93 ± 0.83*	*12.00 ± 0.67*
C3	*5.55 ± 2.14*	*2.94 ± 1.18*	*12.70 ± 1.17*	*5.47 ± 1.97*	*3.00 ± 1.22*	*12.70 ± 1.26*	*5.24 ± 2.51*	*2.67 ± 1.15*	*12.80 ± 0.98*	*6.21 ± 1.93*	*3.21 ± 1.12*	*12.60 ± 1.29*
C7	*7.00 ± 1.72*	*3.75 ± 1.15*	*12.80 ± 1.07*	*7.53 ± 1.24*	*4.00 ± 1.05*	*12.80 ± 1.01*	*7.14 ± 1.56*	*3.86 ± 1.01*	*12.90 ± 1.26*	*5.57 ± 2.17*	*3.00 ± 1.3*	*12.30 ± 0.73*
C9	*4.61 ± 1.87*	*2.34 ± 0.95*	*12.00 ± 0.66*	*4.41 ± 1.66*	*2.31 ± 0.82*	*11.80 + 0.72*	*4.48 ± 1.94*	*2.14 ± 0.91*	*12.20 ± 0.77*	*5.29 ± 2.20*	*2.71 ± 1.2*	*12.00 ± 0.45*
C12	*3.88 ± 2.32*	*2.04 ± 1.15*	*12.30 ± 0.99*	*2.78 ± 1.62*	*1.59 ± 0.91*	*11.80 ± 0.82*	*6.38 ± 1.77*	*3.19 ± 0.93*	*12.50 ± 1.01*	*2.64 ± 1.22*	*1.36 ± 0.5*	*N/A**
C16	*4.18 ± 2.43*	*2.21 ± 1.21*	*12.20 ± 0.95*	*2.94 ± 1.90*	*1.59 ± 0.67*	*11.60 ± 0.48*	*4.19 ± 2.29*	*2.24 ± 1.37*	*12.10 ± 0.67*	*7.00 ± 0.96*	*3.57 ± 0.76*	*12.30 ± 1.14*
C21	*5.79 ± 1.85*	*2.99 ± 1.12*	*12.50 ± 0.98*	*6.12 ± 1.93*	*3.19 ± 1.00*	*12.50 ± 0.96*	*5.00 ± 1.05*	*2.57 ± 1.16*	*12.80 ± 1.11*	*6.21 ± 1.63*	*3.14 ± 1.23*	*12.10 ± 0.92*
C23	*5.55 ± 1.77*	*2.96 ± 1.02*	*12.50 ± 1.06*	*5.44 ± 1.83*	*3.03 ± 0.97*	*12.60 ± 1.25*	*5.62 ± 1.77*	*2.81 ± 1.08*	*12.50 ± 0.85*	*5.71 ± 1.73*	*3.00 ± 1.11*	*12.20 ± 0.77*

*N/A indicates that no subject in this cluster indicated intent to purchase this sample.

Table 5. Mean and standard deviation for cider chemistry parameters.

Sample	ABV (% v/v)	CO_2 (g/L)	Malic Acid (g/L)	pH	FSO_2 (mg/L)	TSO_2 (mg/L)	TA (g/L)*	VA (g/L)†	RS (g/L)	Glucose (g/L)	Fructose (g/L)	Sucrose (g/L)	TPH (mg/L)§
C1	7.58	4.97	4.72 ± 0^{g}	3.82 ± 0.01^{ef}	0.5 ± 0.71^{f}	32 ± 0^{lm}	4.41 ± 0.03^{i}	0.21 ± 0.02^{g}	8.8 ± 0^{f}	4.1 ± 0^{f}	4.7 ± 0^{fg}	ND^{e}	298 ± 1.41^{fg}
C2	8.1	5.01	6.16 ± 0^{c}	3.66 ± 0.01^{ijk}	2 ± 0^{f}	29 ± 1.41^{mn}	6.5 ± 0.01^{d}	0.3 ± 0.02^{fg}	6.6 ± 0^{g}	3 ± 0^{g}	3.6 ± 0^{h}	ND^{e}	778 ± 12.73^{a}
C3	7.52	4.35	5.52 ± 0^{d}	3.67 ± 0.04^{hij}	2 ± 0^{f}	40.5 ± 0.71^{k}	5.98 ± 0.1^{f}	0.03 ± 0^{h}	9.3 ± 0.14^{f}	3.5 ± 0^{fg}	3.7 ± 0.14^{h}	2.1 ± 0^{b}	632.5 ± 21.92^{c}
C4	7.56	4.08	4.33 ± 0^{i}	3.9 ± 0.01^{d}	2 ± 0^{f}	29 ± 1.41^{mn}	5.3 ± 0.02^{g}	0.28 ± 0.01^{fg}	9.6 ± 0.14^{f}	3.1 ± 0^{fg}	5.3 ± 0.14^{f}	1.2 ± 0^{cd}	351 ± 7.07^{e}
C5	7.95	4.65	8.44 ± 0^{a}	3.73 ± 0^{gh}	1 ± 0^{f}	20 ± 1.41^{op}	7.84 ± 0.04^{b}	0.23 ± 0^{g}	ND^{h}	ND^{h}	ND^{i}	ND^{e}	427.5 ± 3.54^{d}
C6	7.82	4.99	5.09 ± 0^{f}	3.69 ± 0.03^{hij}	2 ± 0^{f}	38.5 ± 4.95^{kl}	5.48 ± 0.13^{g}	0.28 ± 0^{fg}	ND^{h}	ND^{h}	ND^{i}	ND^{e}	349 ± 5.66^{e}
C7	4.93	3.86	2.46 ± 0^{m}	3.71 ± 0.01^{ghi}	19 ± 1.41^{b}	94.5 ± 0.71^{f}	3.86 ± 0.02^{lmn}	0.31 ± 0^{efg}	38 ± 0^{a}	16 ± 0^{a}	22 ± 0^{b}	ND^{e}	163.5 ± 2.12^{klm}
C8	4.88	3.79	2.55 ± 0^{l}	3.8 ± 0^{ef}	18 ± 1.41^{b}	131.5 ± 2.12^{d}	3.79 ± 0.07^{mno}	0.32 ± 0.03^{efg}	36.5 ± 0.71^{a}	13.5 ± 0.71^{b}	23 ± 0^{a}	ND^{e}	233.5 ± 3.54^{i}
C9	7.21	4.99	0.02 ± 0^{v}	3.91 ± 0.03^{d}	2 ± 0^{f}	37.5 ± 2.12^{kl}	3.42 ± 0.01^{q}	0.45 ± 0.02^{d}	ND^{h}	ND^{h}	ND^{i}	ND^{e}	151 ± 1.41^{lm}
C10	5.46	4.22	0.42 ± 0^{r}	3.98 ± 0^{c}	15.5 ± 2.12^{bc}	62 ± 0^{i}	2.6 ± 0.03^{r}	0.38 ± 0.01^{def}	20 ± 1.41^{d}	6.5 ± 0.71^{e}	13.5 ± 0.71^{d}	ND^{e}	161 ± 2.83^{klm}
C11	7.5	7.87	6.42 ± 0^{b}	3.83 ± 0.01^{e}	2 ± 0^{f}	144 ± 0^{c}	6.24 ± 0.04^{e}	0.3 ± 0.01^{efg}	10 ± 0^{f}	1 ± 0^{h}	8 ± 0^{e}	1 ± 0^{cd}	242 ± 9.9^{hi}
C12	6.06	3.94	1.54 ± 0^{p}	3.99 ± 0.01^{c}	13 ± 2.83^{c}	109.5 ± 3.54^{e}	3.38 ± 0.04^{q}	0.68 ± 0.04^{c}	29 ± 0^{b}	11.5 ± 0.71^{c}	16.5 ± 0.71^{c}	1 ± 0^{cd}	142.5 ± 7.78^{m}
C13	8.5	5.54	0.15 ± 0^{s}	4.02 ± 0.03^{bc}	3 ± 0^{ef}	11 ± 0^{q}	3.52 ± 0.03^{pq}	0.86 ± 0.01^{b}	1 ± 0^{h}	ND^{h}	ND^{i}	1 ± 0^{cd}	281 ± 4.24^{fg}
C14	8.09	5.11	0.05 ± 0^{t}	4.09 ± 0.01^{a}	7 ± 0de	70.5 ± 4.95^{h}	2.58 ± 0.01^{r}	0.42 ± 0.01^{de}	1 ± 0^{h}	ND^{h}	ND^{i}	1 ± 0^{cd}	144 ± 7.07^{m}

C15	9.68	4.23	5.18 ± 0^{e}	3.65 ± 0.01^{jk}	4.5 ± 2.12^{def}	53 ± 2.83^{j}	6.78 ± 0.02^{c}	0.29 ± 0.01^{fg}	1.5 ± 0.71^{h}	ND^{h}	ND^{i}	1.5 ± 0.71^{bc}	397.5 ± 3.54^{d}
C16	8.99	4.85	$<0.020^{w}$	3.76 ± 0.02^{fg}	$< 1^{f}$	2.5 ± 0.7^{1}	8.28 ± 0.04^{a}	2.15 ± 0.11^{a}	ND^{h}	ND^{h}	ND^{i}	ND^{e}	283 ± 8.49^{fg}
C17	8.63	1.48	$<0.020^{w}$	4.06 ± 0.01^{ab}	2 ± 0^{f}	9 ± 1.41^{qr}	4.12 ± 0.01^{jk}	0.96 ± 0.01^{b}	ND^{h}	ND^{h}	ND^{i}	ND^{e}	702.5 ± 20.51^{b}
C18	7.19	4.26	1.13 ± 0^{q}	3.82 ± 0.01^{d}	2 ± 0^{f}	22 ± 0^{no}	4.04 ± 0.09^{kl}	0.28 ± 0.03^{fg}	14.85 ± 0.07^{e}	4 ± 0.14^{fg}	4 ± 0^{gh}	6.85 ± 0.2^{a}	269.5 ± 2.12^{gh}
C19	7.22	4.86	2.81 ± 0^{k}	3.91 ± 0.01^{d}	2 ± 0^{f}	156.5 ± 0.71^{b}	4.32 ± 0.13^{ij}	0.3 ± 0.03^{fg}	ND^{h}	0 ± 0^{h}	ND^{i}	ND^{e}	222.5 ± 0.71^{ij}
C20	8.5	3.77	3.64 ± 0^{j}	3.9 ± 0.01^{d}	8 ± 0^{d}	82 ± 0^{g}	4 ± 0.01^{klm}	0.38 ± 0.02^{def}	ND^{h}	0 ± 0^{h}	ND^{i}	ND^{e}	307.5 ± 2.12^{f}
C21	7.07	7.31	4.56 ± 0^{h}	3.7 ± 0.02^{ghij}	$< 1^{f}$	44 ± 0^{k}	5.78 ± 0^{f}	0.31 ± 0^{efg}	ND^{h}	0 ± 0^{h}	ND^{i}	ND^{e}	179 ± 7.07^{kl}
C22	5.45	2.94	0.04 ± 0^{u}	3.8 ± 0.01^{ef}	$< 1^{f}$	12 ± 0^{pq}	3.56 ± 0.02^{opq}	0.45 ± 0.01^{d}	ND^{h}	0 ± 0^{h}	ND^{i}	ND^{e}	190 ± 2.83^{jk}
C23	7.36	4.85	1.91 ± 0^{o}	3.8 ± 0.01^{ef}	3 ± 0^{ef}	27 ± 1.41^{mno}	3.72 ± 0.04^{nop}	0.32 ± 0.01^{efg}	ND^{h}	0 ± 0^{h}	ND^{i}	ND^{e}	175 ± 5.66^{klm}
C24	4.81	4.19	2.11 ± 0^{n}	3.61 ± 0^{k}	82 ± 2.83^{a}	190.5 ± 2.12^{a}	4.73 ± 0.08^{h}	0.28 ± 0.01^{fg}	26.5 ± 0.71^{c}	10 ± 0^{e}	16 ± 0^{c}	0.5 ± 0.71^{de}	170.5 ± 9.19^{klm}

*Titratable Acidity (TA) is given as malic acid equivalents.
†Volatile Acidity (VA) is given as acetic acid equivalents.
§Total Polyphenol Content (TPH) is given as gallic acid equivalents.
$^{a\text{-}z}$Superscript letters indicate group separation according to Tukey's HSD; means with different superscripts are significantly different at a $p < 0.05$ level.
ND indicates "not detected", and was treated as "0" in calculation of ANOVA and Tukey's HSD.

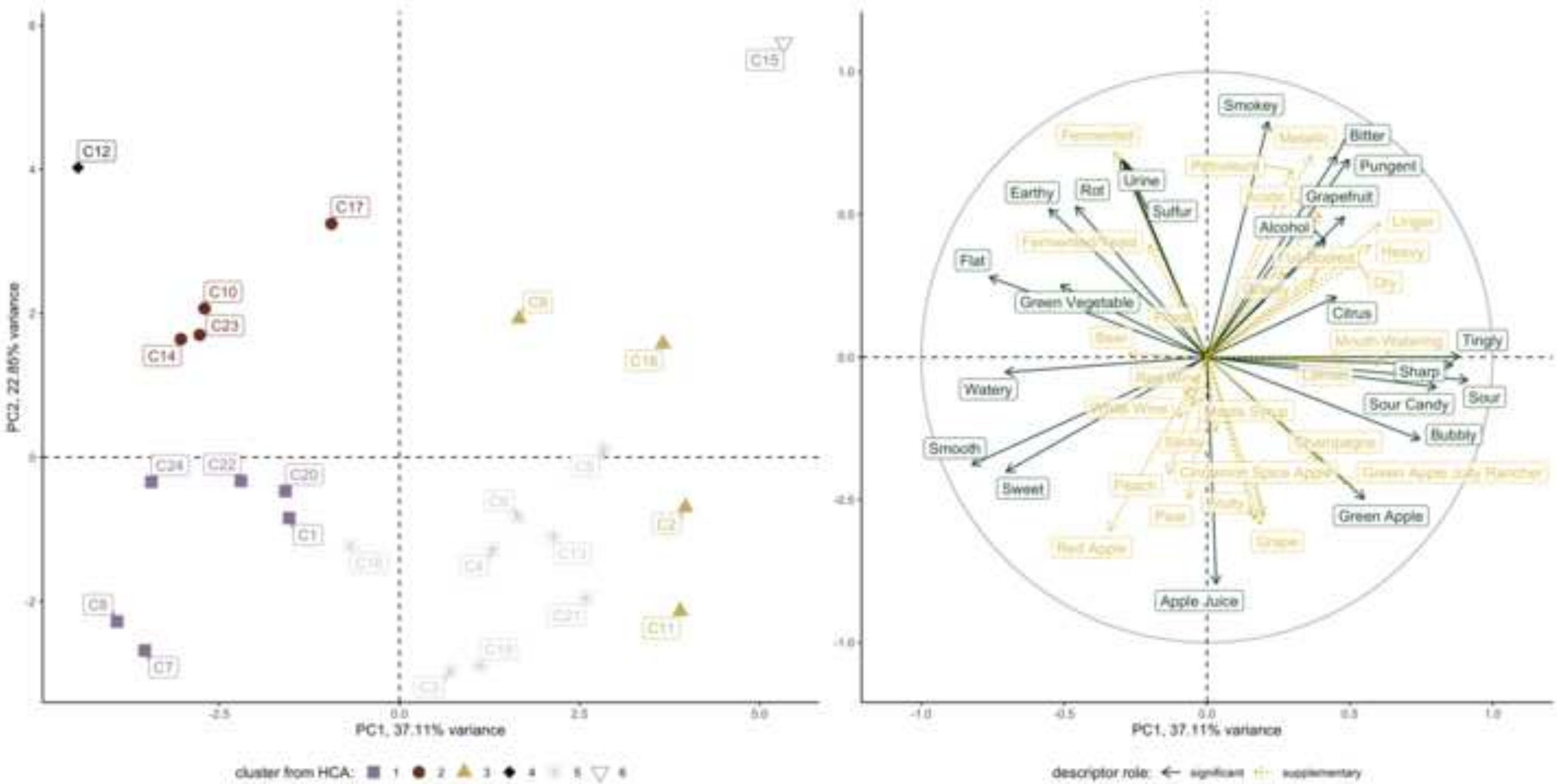
Figures

Figure 1. Principal Components Analysis (PCA) plots of Principal Components 1 and 2 for results from the DA study. On the left, samples are plotted with colors and shapes representing membership of clusters from HCA on the same space. On the right, descriptors are plotted as correlations with the space, colored by whether they are significant (contributing to the PCA) or supplementary (projected into the PCA).

Figure 2. Clustering around Latent Variables (CLV) plot showing the resulting 3 clusters of (Caption) PCA Plot of Significant and Non-Significant Descriptors, Dimension 1, and Dimension 2. Significant descriptors are represented in purple, and non-significant attributes are represented in green.

Figure 3. Partial Least Squares Regression (PLS-R) showing the relationships among descriptors from the DA, consumer liking from the consumer study, and products from the consumer study.

Figure 1



C12
C17
C10
C23
C14
C15
C24
C22
C20
C1
C8
C7
C11
PC1, 37.11% variance
PC2, 22.85% variance
cluster from HCA: 1 2 3 4 5 6
Smokey
Bitter
Pungent
Grapefruit
Alcohol
Urine
Sulfur
Earthy
Rot
Flat
Green Vegetable
Citrus
Tingly
Sharp
Sour
Sour Candy
Bubbly
Watery
Smooth
Sweet
Green Apple
Apple Juice
PC1, 37.11% variance
descriptor role: significant supplementary

Figure 2

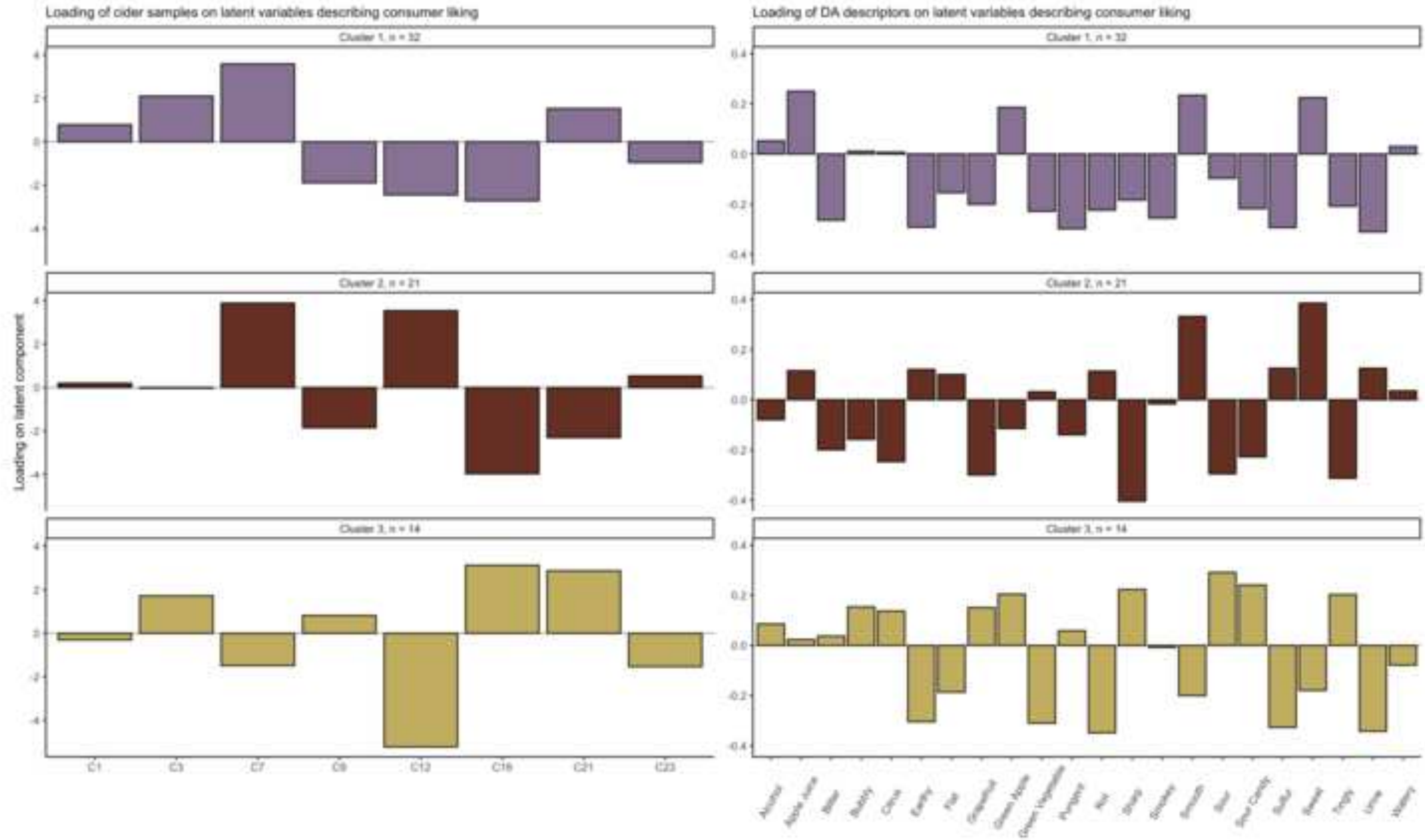
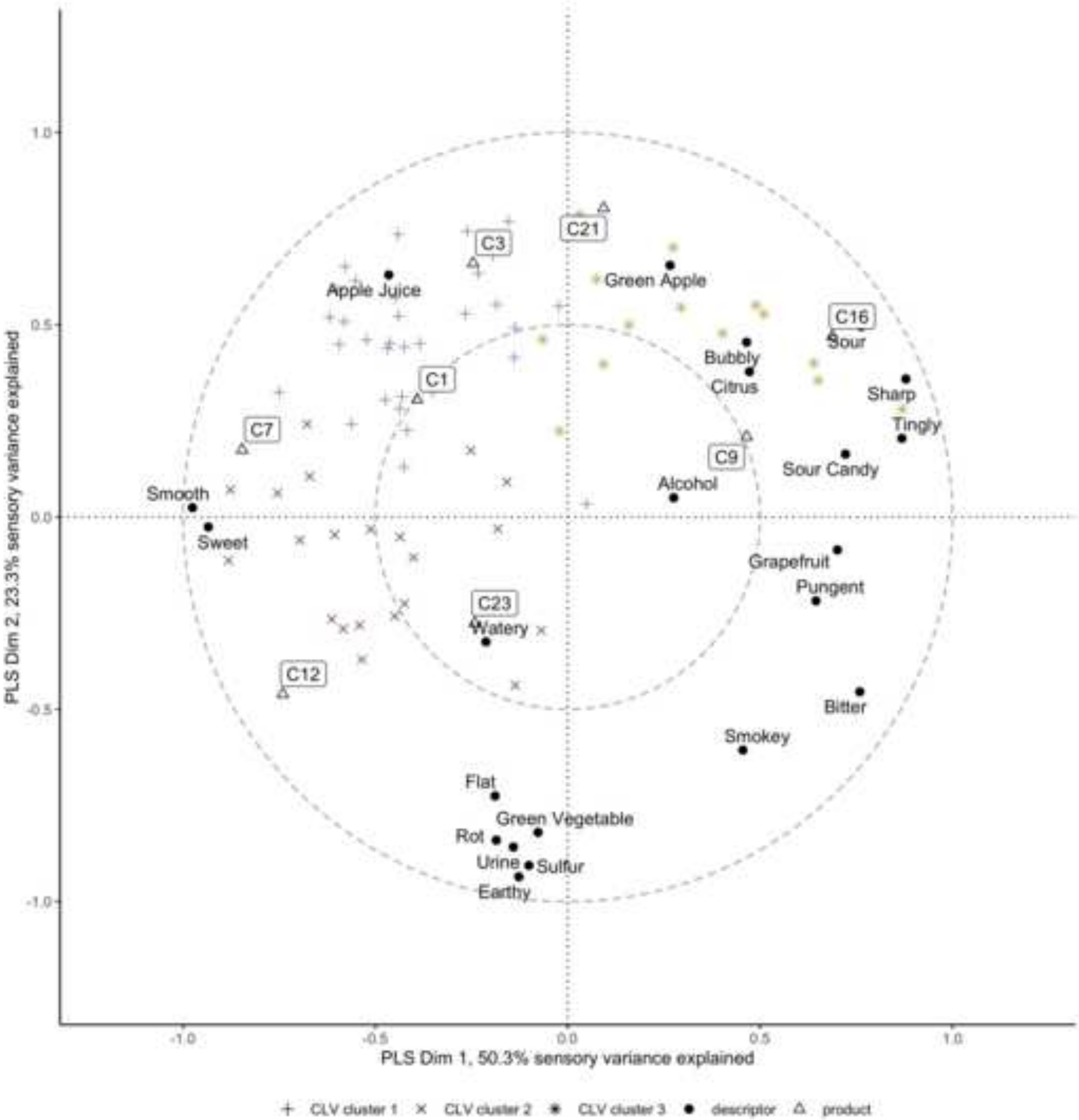

Loading of cider samples on latent variables describing consumer liking
Loading of DA descriptors on latent variables describing consumer liking
Cluster 1, n = 32
Cluster 2, n = 21
Cluster 3, n = 14
Loading on latent component
C1
C3
C7
C9
C12
C16
C21
C23

Figure 3



PLS Dim 2, 23.3% sensory variance explained
PLS Dim 1, 50.3% sensory variance explained
1.0
0.5
0.0
-0.5
-1.0
C21
C3
C1
C7
C16
C9
C23
C12
Apple Juice
Green Apple
Bubbly
Citrus
Sour
Sharp
Tingly
Sour Candy
Alcohol
Smooth
Sweet
Grapefruit
Pungent
Watery
Bitter
Smokey
Flat
Green Vegetable
Rot
Urine
Sulfur
Earthy
CLV cluster 1
CLV cluster 2
CLV cluster 3
descriptor
product

Exploring the sensory characteristics of Virginia ciders through descriptive analysis and external preference mapping

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Abstract

The cider industry has experienced recent growth within the USA and Virginia in particular. However, the sensory characteristics and drivers of consumer acceptance of ciders are largely uncharacterized. Therefore, this work describes the sensory profiles of commercial Virginia ciders and links these to consumer acceptance. In study 1, a descriptive analysis (DA) of 24 representative ciders from 16 producers in Virginia was conducted: 6 panelists defined 48 descriptive terms for ciders. In study 2, a consumer acceptance study was conducted on 8 ciders from the DA with 67 subjects. For the DA study, 22 descriptors were found to be significant, and multivariate analyses identified 6 groups. In the consumer study, external preference mapping was conducted to identify 3 clusters of consumers with distinctive patterns of sensor preference. The largest cluster favored sweet ciders without off-flavors; a second, smaller cluster favored sweetness even in the presence of off-flavors; and the smallest cluster disliked sweetness in ciders and was intolerant of off-flavors. We describe these groups' demographic and consumption profiles. All ciders' basic chemistry was within previously reported ranges, and expected relationships between flavor and chemistry were observed. We were able to establish sensory profiles for Virginia ciders, and tentatively link sensory profiles and consumer acceptance. Overall, this work adds to a small-but-growing body of knowledge about ciders' sensory properties. Producers can use the sensory profiles in comparison to other regions' ciders to establish regional sensory profiles, and the consumer preference map to understand how to capitalize on their ciders' distinct profiles.

Keywords: cider; descriptive analysis; sensory evaluation; consumer acceptance; preference mapping

Word Count: 6835

1. Introduction

Cider was once the most popular alcoholic beverage in North America in the18th and 19th centuries (34). In the modern US, “cider” typically refers to the unfiltered sweet juice made from apples, whereas “hard cider” refers to the fermented, alcoholic product made from apples, but in the rest of the world “cider” refers to the alcoholic beverage (12,32). In deference to the majority usage, in this manuscript we adopt the latter terminology: “cider” will refer to the alcoholic beverage. Over the intervening two and a half centuries, due to factors including urbanization due to industrialization, Prohibition, and the increased mass-production of competitive products such as beer, cider fell out of popularity, until it experienced a popular resurgence in the last two decades (32,34). Cider is a growing industry, and is a preferred beverage among younger consumers (16). The cider industry in the United States generated an annual revenue of $517.26 million USD between 2016 and 2021, with much consumer interest focusing on “craft” or locally produced ciders (6).

Virginia is the sixth largest producer of apples within the United States, and Virginia lists apples as its sixteenth top agricultural commodity (31). There are more than 200 apple varieties grown in the state of Virginia, including both cider and dessert apples (2,3). In the state of Virginia, there are currently 32 cider producers. Six of these producers also act as wineries, breweries, or distilleries. This information was collected by preforming a web search for Virginia cider producers with the key words: “Virginia”, “cider”, “hard cider”, “cider producer”, and “craft cider”. Results were crosschecked with information from the Virginia Association of Cidermakers (30).

Despite the growing popularity of cider in Virginia and the US as a whole, there is very little published knowledge on the nature, origins, or importance of sensory profiles of cider. Early work by Williams (36) produced a sensory lexicon for British cider; while this work showed the diverse possible sensory profiles in ciders, it is more than half a century old and applies largely to cider produced with different apple cultivars and with different processing methods and traditions than are currently used in Virginia and the US as a whole.

Currently, there is a knowledge gap in terms of defining descriptive language for not only Virginia ciders, but all ciders. Williams (1975) created a flavor wheel, but little work on descriptive language for cider has been completed since. Further research on European cider varieties demonstrated that there is a broad range of cider flavors, and that ciders differ in flavors based on production method (11) and place of origin (22); these conclusions highlight the need for more research into American ciders. In the US, Tozer et al. (27) demonstrated that consumers were not able to describe their sensory experience of ciders consistently, which led to a mismatch between their expectations and experiences. Fabien-Ouellet and Conner (4), in qualitative research with cider producers, identify this mismatch as a key barrier to continued growth of the US cider market sector.

The American Cider Association called for work to be conducted to develop a sensory lexicon for American ciders in 2019, but this has not yet been accomplished (15). However, several pilot studies exploring the diversity of flavors in American ciders illustrate the need for this work. For example, Jamir et al. (9) used rapid sensory methods to produce flavor profiles for a set of ciders from two different cultural groups (American and Chinese college students). The researchers found strong diversity in flavors both within and between groups, and highlighted the need for a standardized lexicon (9). Phetxumphou et al. (19) created a functional preliminary lexicon for Virginia ciders using open comments and Check-All-That-Apply (CATA) and suggested a descriptive analysis could help produce a broader and more detailed lexicon for all cider. Kessinger et al. (10) used sorting methods to show that Virginia ciders are diverse in flavors, and that without a standardized lexicon consumers and producers use different terms to describe the same ciders. Littleson et al. (14) used descriptive analysis (DA) to define a lexicon and quantify the sensory profiles of 4 experimental ciders produced with different varieties and fermentation protocols. To our knowledge, these authors were the first to report a DA approach with American ciders, and they were able to demonstrate quantitative, significant differences among their experimental ciders. Thus, it is clear that Virginian (and American) ciders have diverse sensory profiles, that DA is an effective tool to define these sensory profiles, and that these sensory profiles are key to allowing producers and consumers to effectively communicate and match expectations to experiences.

To address this knowledge gap, we report two main and one supplementary study on Virginia ciders. In the first study, a descriptive analysis (DA) was completed using n = 6 panelists who defined and evaluated a total of 48 attributes for k = 24 Virginia ciders. Next, a consumer study was completed to understand the relationships between these sensory attributes and overall liking, willingness to pay and purchasing intent for Virginia ciders: a subset of k = 8 representative ciders from those used in the DA were evaluated by k = 67 cider consumers, and external preference mapping was conducted. Finally, to supplement the sensory analyses, a standard panel of cider chemistry was measured on all k = 24 ciders used in the DA.

2. Materials and Methods

2.1. Study 1: Descriptive analysis of Virginia hard ciders

2.1.1. Samples

For the DA study, samples were chosen by contacting the 32 known Virginia cider producers identified in a web search (30). Each cidery was requested to suggest their “flagship” cider that was “most typical” and “best represented” their cidery. Out of the 32 producers, 16 producers responded with 1-2 suggested ciders to include in the study. In the end, a total of 24 Virginia ciders were identified and purchased from retailers in the Blacksburg, VA area or shipped from producers’ online shops. Samples are described in Table 1; we have anonymized producers and ciders. Based on information from packaging or website descriptions, 17 of these ciders were blends, 5 of them were single cultivars, and 2 could not be determined. Additionally, 13 were packed in 750mL bottles, 2 in 500mL bottles, 4 in 16oz cans, 3 in 12 oz cans, 2 in 12 oz bottles.

2.1.2. Subjects

Panelists were recruited from Virginia Tech and the Blacksburg, VA, USA communities. Panelists were screened to ensure that they were over the age of 21, not currently pregnant, had previously consumed alcoholic beverages, no known allergies to alcohol, apple cider, or any other fermented beverage, and were fully vaccinated against COVID-19. Because of restrictions on gatherings imposed by the COVID-19 pandemic, a total of 6 panelists participated in this study (4 male, 2 female). All panelists were between the ages of 21-30. Panelists did not receive compensation for participating in the study but were able to take snacks at the end of every training and evaluation session. Subjects gave informed signed consent for their participation. This study was approved by the Virginia Tech Institutional Review Board (IRB 19-1067).

2.1.3. Experimental Design

For all sessions, ciders were placed in a commercial refrigerator a day before the sessions to ensure each of the ciders were chilled to approximately 2 ºC. For each session, 1.5 oz of each cider sample used in that session was poured 10 minutes before the session started into black wine glasses labeled with blinding codes and covered with a watch glass. Panelists were instructed to smell and taste the ciders and expectorate the sample after tasting. Panelists were also instructed to clean their palates between samples by taking a sip of water and a bite of an unsalted saltine cracker.

Training and data collection followed the guidelines for DA laid out by Heymann et al. (7). Briefly, panelists participated in 8, 1-hour training sessions. In training sessions, panelists were served with 3-4 cider samples from the sample set in Table 1 per session, and were exposed to all samples at least once. Panelists generated descriptors for the ciders and suggested and approved reference standards (see Table 2).

After training was completed, data collection was accomplished in individual booths with neutral lighting, using Compusense Cloud (Guelph, ON, Canada). A design was adapted from a previous study on sparkling wines by Hood White & Heymann (8) to minimize both product waste and sensory changes from carbonation loss. All panelists evaluated all samples in duplicate, in a randomized, Williams Block Design. However, each panelist received the same samples on the same day of testing, so presentation order randomization was between replicates, rather than between each panelist. This was done in an effort to present samples on the day the bottle or can was opened, while also limiting the cost of samples, due to some of the more expensive samples evaluated being available in larger format bottles.

Ciders were poured 10 minutes prior to a panelist's arrival, and then the remainder of the bottle or can was transferred to an air-tight, 1000 mL glass flask equipped with a nalgene cap. All panelist sessions on a given day were in a 3-hour block. Six (6) cider samples were presented to panelists per session, and the sample set was evaluated in duplicate over the course of the individual sessions. Panelists rated the intensity of each descriptor in each cider on a 15-point line scale ranging from “None” to “Very High”. Panelists were presented with all references standards and were asked to review them once a week during evaluation sessions.

2.1.4. Data Analysis

All statistical analyses were completed in R (23) according to the standard methods laid out by Heymann et al. (7). The data from the descriptive analysis was first analyzed by a three-way multivariate analysis of variance (MANOVA) (*sample* x *panelists* x *replication*) with two-way interactions. A three-way univariate analysis of variance (ANOVA) (*sample* x *panelists* x *replication*) was completed for each of the individual descriptive terms, with two-way interactions. For each descriptor, if *sample* x *subject* or *sample* x rep *interactions* were significant, a pseudomixed test was conducted using the larger interaction effect as the error term (7). Following these omnibus tests, Tukey’s Honestly Significant Differences (HSD) test was used to identify significant pairwise differences for each descriptor among samples. For all tests, significance was defined as $p < 0.05$. Principal Component Analysis (PCA) was used to visualize relationships among both the cider samples and sensory attributes. Groups of ciders were identified using Hierarchical Cluster Analysis (HCA) with Ward’s method on the PCA space.

2.2. Study 2: Consumer acceptance and preference mapping

2.2.1. Samples

In order to select a representative sample of ciders from the DA study for further evaluation, the PCA plot was used to choose eight samples: two from every quadrant of the first two dimensions of the PCA (see Figure 1 and Table 1). Within each quadrant, samples that were not close to each other were selected to maximize sample variation among those select for this subset. Samples were purchased from retailers in the Blacksburg, VA, USA area or shipped from producers’ online shops

2.2.2. Subjects

Subjects (N = 67) were recruited from the Blacksburg, VA, USA and Virginia Tech community. Subjects were screened to ensure that they were over the age of 21, not currently pregnant, had previously consumed alcoholic beverages, had no known allergies to alcohol, apples, apple cider, or any other fermented beverage, and were fully vaccinated against COVID-19. This study was approved by the Virginia Tech Institutional Review Board (IRB 21-1045).

2.2.3. Experimental Design

Subjects were presented a total of 8 cider samples in randomized, sequential, monadic order as 1.5 oz pours in black wine glasses which completely obscured the appearance of the ciders. The cider was chilled at in the refrigerator at 1 ºC, and serving commenced only as panelists entered the booths. On each study day, as the first panelists came in, cider was transferred from original packaging into air-tight, 1000 mL glass flasks equipped with airtight screw caps. The flasks were subsequently stored in the refrigerator for 3 hours after first filling. After that time period (or if the volume was exhausted), the flasks were emptied and refilled to maintain approximately consistent carbonation (8).

Subjects were first asked a series of demographic and consumption questions: age range, gender identity, income range, education level, and cider consumption frequency. For each of the 8 cider samples, subjects rated liking on a standard 9-point hedonic scale. Then, subjects were asked to rate their purchasing intent on a 5-point scale, ranging from “definitely will not buy” to “definitely will buy”. Finally, subjects used a marked line scale to indicate how much they would be willing to pay for a 6-pack of 12oz cans of that particular cider, with prices ranging from $11-$15 USD in $0.50 increments. This packaging size was chosen because 12 oz 6-packs accounted for the plurality (47%) of all off-premise cider sale shares in 2021 (17). The price range was based on the median of the price range for this volume of cider for all 24 ciders in the study. All data was collected using Compusense Cloud (Guelph, Ontario, Canada).

2.2.4. Data Analysis

All statistical analyses were completed in R (23). Consumer data was treated in several ways. First, external preference mapping and clustering was accomplished using the Clustering around Latent Variables (CLV) approach (29). Briefly, CLV simultaneously identifies clusters of consumers with similar patterns of liking for a particular set of products and sets of products with a similar set of attributes that fit those consumer liking patterns in an iterative, optimization framework (28). Following CLV, Partial Least Squares Regression (PLS-R) was used to visualize the relationships among the identified consumer clusters, the products, and the sensory attributes.

For each cluster, demographic and purchasing data were tabulated as proportions. Fisher’s Exact Test was used to test for significant differences in patterns between clusters. Purchasing intent was treated as numerical, and is reported as mean and standard deviation for each cider for each cluster. For each subject and cider, willingness-to-pay (WTP) was only considered for ciders rated 3-5 on the 5-pt purchase scale; after that filtering, WTP was calculated as mean and standard deviation for each cider for each cluster.

2.3. Study 3: Supplemental chemical analysis of Virginia ciders

2.3.1. Samples

All 24 ciders from the DA (Table 1) were analyzed for basic cider chemistry parameters (see below).

2.3.2. Experimental Design

The following analyses were completed on each of the cider samples, pH (Ion probe, AOAC Official Method 960.19); Titratable Acidity (Titration, AOAC Method 960.12); Volatile Acidity (Cash Still and Titration, AOAC Method 964.08,TTB Method SSD:TM:502 modifications); Total SO_2 (Aeration & Oxidation, modifications for Free Sulfite Quantification SSD:TM:500); Free SO_2 (Aeration & Oxidation, modifications for Free Sulfite Quantification SSD:TM:500); Residual Sugars (Megazyme Sucrose/D-Fructose/D-Glucose Assay Kit Assay Kit, Megazyme International, Wicklow, Ireland); Total Polyphenols (Folin-Ciocalteu (F-C)); Malic Acid (Megazyme Malic Acid Enzymatic Kit, Megazyme International, Wicklow, Ireland); CO_2 (Anton Paar: PBA (Package Beverage Analyzer)); ABV (Anton Paar: PBA (Package Beverage Analyzer)).

2.3.3. Data Analysis

All statistical analyses were completed in R (23). For each measurement, a one-way univariate analysis of variance (ANOVA) was performed with sample as the independent variable to identify any significant differences. For each measurement, Tukey's Honestly Significant Differences (HSD) test was used to identify any pairwise differences among samples. Significance was identified at $p < 0.05$. The chemical analysis data was expressed in mean ± standard deviation. Alcohol and CO_2 were not measured in duplicate because of limited sample quantity, and so were not included in ANOVA and posthoc testing.

3. Results and Discussion

3.1. Descriptive analysis

A descriptive analysis (DA) was conducted with 6 trained panelists to determine the sensory attributes of 24 Virginia ciders. The panel defined and approved a total of 48 attributes for the Virginia ciders: 13 flavor (retronasal) attributes, 20 aroma (orthonasal) attributes, 3 taste attributes, and 12 mouthfeel attributes (see Table 2). Each of the attributes was anchored by a reference that was approved and defined by the 6 panelists in consensus (Table 1).

A three-way MANOVA showed there was not a significant interaction between samples and replicates (approx. $F_{1104,1567} = 0.99, NS$) but that there was a significant interaction between samples and subjects (approx. $F_{5520,3798} = 1.38, p < 0.05$), which is common in DA studies. To account for this, 3-way pseudomixed univariate ANOVA was conducted for each of the 48 attributes, resulting in a finding of significant differences among samples for 22 of these attributes (see Table 2).

Principal Component Analysis (PCA) was used to visualize the overall pattern of variation among samples in mean attribute intensity for the significant attributes. Figure 1 shows the PCA score (product) and loading (attribute) plots for the first two dimensions of the PCA analysis, accounting for a total of 59.96% of variance. The expected variance explained by any principal component in the absence of variable correlation would be $100/22 = 4.09\%$, making these two dimensions highly effective in explaining a much greater than expected amount of variation. Non-significant attributes were projected into the PCA space as supplementary variables in order to help explain the space (1). The first dimension was most positively correlated with attributes *sour, tingly, sharp, sour candy*, and *bubbly*, and most negatively correlated with attributes *smooth, flat, watery, sweet,* and *earthy*. The second dimension was most positively correlated with terms like *smokey, bitter, pungent, urine*, and *sulfur*, and most negatively correlated with *apple juice, green apple, sweet, smooth*, and *bubbly*. The second dimension particularly was positively correlated with a number of potential off-flavors in cider, although it is interesting to note that the presence of the potentially desirable *bitter* taste is correlated with these same terms. The cider samples themselves can also be understood in terms of their association with the flavor terms: C9, C16 and C15 were given high intensity ratings for *smokey, bitter pungent, grapefruit, alcohol*, and *citrus*; C6, C5, C4, C13, C2, C19, C21, C11 and C3 were characterized by descriptors such as *apple juice, green apple, bubbly, sour candy, sharp, sour*, and *tingly*; C8, C7, C18, C1, C20, C22, and C24 were described as *sweet, smooth,* and *watery*; and lastly C14, C23, C10, C17 and C12 were characterized as *rot, sulfur, urine, earthy, flat,* and *green vegetable*.

The cider samples were clustered into six groups using Hierarchical Cluster Analysis (HCA) based on the distances among the samples in the space defined by the PCA. Six clusters were selected manually because of the presence of two clear isolates in the main descriptive space of the PCA: C15 and C12. As is evident from the PCA scores and loadings plots (Figures 1), specifying 6 clusters produces compact clusters with reasonably well-defined sensory characteristics. The two outliers (C15 and C12) are already well separated in the first two dimensions, but can be even more clearly distinguished in Dimension 3 (results not shown).

The clusters represent groups of ciders with similar sensory attributes—these are possible prototypes for cider characters in Virginia (see Figure 1 for reference to the following). The ciders in Cluster 1 were mostly associated with *sweet, smooth, watery, flat,* and *apple juice*. Cluster 2 was associated with *sweet, smooth, rot, earthy, green vegetable, flat,* and to a lesser degree *urine* and *sulfur*. Cluster 3 was associated with *citrus* and *alcohol* attributes, as well as to a lesser degree the cluster of attributes *sharp, tingly, sour, bubbly*, etc. Cluster 4 is the singular C12, which is associated with a number of potential off-flavors associated with fermentation problems and/or and microbiological instability, such as *sweet, urine*, and *sulfur*. Cluster 5 is associated with *sour, tingly, sharp, sour candy, green apple*, and *bubbly*. Lastly, cluster 6 contains the other singular sample, C15, which is associated with *smokey, bitter*, *grapefruit, alcohol,* and *pungent*.

Interestingly, 5 of the ciders contained the apple variety Virginia Hewes Crab, which is a crab apple grown in Virginia. While the current study was not designed to assess cultivar characteristics, it is worth considering whether ciders made with the same apple have similar flavors. Samples C2, C4, C5, and C17 were described as single cultivar ciders containing Virginia Hewes Crab, while C16 was blended with a total of seven other apple varieties in addition to the Virginia Hewes Crab. In the PCA plot it is apparent that 4 of these ciders have relatively similar characteristics: C2, C4, C5, and C16. However, one of the single-cultivar ciders containing this apple (C17) is quite distinct from the other 4. Therefore, it is fair to conclude that even though all these ciders contain the same cider apple, their flavor profiles are not predictably similar. This could be due to a variety of reasons, such as but not limited to fermentation method, adjuncts, cider style, apple maturity, filtration, chemical and microbiological stabilization, or packaging method and materia (35).

3.2. Consumer studies

In Study 2, 67 cider consumers rated their overall liking for 8 representative ciders from the DA sample set (Table 1), and answered questions about demographics and purchasing and consumption habits (Table 3). This was a relatively small sample size for a consumer study, as recruitment and sampling efforts were hindered by the continued impact of the COVID-19 pandemic. However, results can still provide some insight into possible preference and consumption patterns for cider consumers.

3.2.1 Preference mapping and clustering

Using the Clustering around Latent Variables (CLV; 29) technique, consumers were clustered into groups based on their patterns of liking for ciders with distinct sensory profiles. Here, we report the patterns of liking for the ciders in general and in the identified clusters; below (section 3.2.2 and 3.2.3) we discuss the demographic and purchasing patterns in the identified clusters.

The CLV analysis identified 3 clusters of consumers based on patterns of liking (Figure 2). In cluster 1 (n = 32), the samples that were most liked overall were C1, C3, C7, and C21. The attributes that were most positively loaded for consumers in cluster 1 were *apple juice, smooth, sweet,* and *green apple*. The second largest cluster, cluster 2 (n = 21) most preferred ciders C7 and C12, with a mild liking for C23, and consumers in this cluster showed strong preferences for the attributes *sweet* and *smooth*, and in contrast to the other two clusters also showed (smaller) positive loadings for flaws such as *urine*, *sulfur*, and *earthy*. The third and smallest group of consumers, cluster 3 (n = 14) preferred a distinct set of samples: C3, C9, C16, and C21. The attributes that were most positively loaded for cluster 3 were *sour, sour candy, sharp, green apple, tingly, bubbly,* and *grapefruit.* Because CLV provides both patterns of liking (the ciders liked by each cluster) *and* explanations based on the attributes describing those patterns, we are able to draw some conclusions about the type of consumers in each cluster. Cluster 1 might be termed "modern cider" drinkers who prefer sweeter ciders, but had low tolerance for potential flaws and off flavors. Meanwhile, cluster 2 also preferred sweeter ciders, but did not mind the presence of potential off-flavors—we could call these cider drinkers "casual" or "novice" cider drinkers. Finally, cluster 3 actively disliked sweetness in ciders, but was also generally intolerant of potential flaws and off-flavors: we call these cider drinkers "craft cider" drinkers since their liking was driven by tart and complex ciders.

In order to visualize the relationship between consumers, attributes, and products, Partial Least Squares Regression (PLS-R) was used to explain the pattern of consumer preferences simultaneously with the sensory attributes identified through the DA (Figure 3). Consumers were colored according to their cluster from CLV. This figure is particularly helpful for elucidating the preferences of the two smaller clusters (clusters 2 and 3). While no consumers actively prefer potential flaws like *rot* or *sulfur* (in the negative direction on dimension 2 of Figure 3), consumers from cluster 2 are much likelier to rate ciders with these attributes more favorably than other groups. Conversely, *only* consumers from cluster 3 are likely to rate ciders with low *sweetness* and other related attributes highly (in the positive direction of dimension 2 of Figure 3). Interestingly, as can be seen by looking at Figures 2 and 3, only *smokey* was disliked by all clusters.

Mean liking scores overall and by cluster are given in Table 4. While overall sample C7 was the most liked sample, which was closely associated with attributes of *sweetness* and *smooth*, cluster 3 did not prefer this sample. Instead, Cluster 3 overall preferred C16, which is associated attributes with *sharp*, *citrus*, and *tingly*. Meanwhile, C12, which was highly disliked overall and by both cluster 1 and 3, and which was most associated with the cluster of potential off-flavors, is the second most liked cider in cluster 2 (Figure 2).

3.2.2 Consumer cluster demographics and purchasing behavior

For each demographic and consumption question, proportions are reported overall and by cluster from CLV in Table 3. Clusters did not differ by age range or gender identity (Fisher's Exact Test, $p > 0.05$). Given the small sample size and because a general population sample was recruited, this was not surprising. Overall, subjects were mostly female (62.1%) young (73.1% age 21-30), highly educated (more than 52% holding at least a US bachelor's degree), and with relatively low household income (the plurality of 38.8% reported income of less than $25,000 USD). This sample makes sense given the university population in Blacksburg, VA, USA where the study was conducted. The sample size was too small to detect significant patterns between the clusters, which are reported in Table 3 for completeness.

3.2.3. Purchasing intent and willingness-to-pay

Overall and within-cluster purchasing intent (on a scale of 1 to 5) for each cider is reported in Table 4. Overall, cider C7 was rated on average highest on the scale, with a mean rating of 3.75—this was the sweetest cider according to both DA and cider chemistry (measured residual sugar, Table 5). This result is not surprising, since overall, it had the highest mean overall liking score among all consumers. The within-cluster results closely followed the patterns of liking—this is also unsurprising, as liking and purchasing intent are nearly perfectly correlated (r = 0.91). However, it is important to note that a reported purchase intent of 3 is "neutral", so despite the strong correlation it is not entirely clear that any cluster was strongly enthusiastic about any particular cider besides C7 in cluster 1 (Table 4).

Overall and within-cluster willingness-to-pay (WTP) for each cider sample is reported in Table 4. WTP was only collected from consumers who indicated a neutral to positive purchasing intent (3, 4, or 5 on the given scale) for each cider. The results indicate that on average no consumer was willing to pay above $13.00 for a 6-pack of 12-ounce cans of any of these ciders. For all 67 subjects, all the ciders were within the $12.00 range, with sample C7 receiving the highest WTP at $12.80, and C9 the lowest at $12.00. There was variation within clusters for these results, which reflects a lower correlation between overall liking and WTP (r = 0.69) and purchase intent and WTP (r = 0.75). For example, in cluster 1, C7 received the highest purchasing intent rating, but C7 was rated the second highest price at $12.80, while C1 was rated at $12.90. This is interesting as C1 has both a lower mean purchasing intent rating and overall liking within this cluster. In cluster 2, consumers were likewise most willing to spend the most on sample C7, but they were also willing to spend more on purchasing C12, which received the lowest WTP from cluster 1 and which no-one from cluster 3 was willing to purchase. Following their inferred preferences from CLV, subjects from cluster 3 differed in their patterns, being willing to spend the most on sample C3, which was neither the most liked sample nor had a high purchasing intent rating overall. As noted above, in cluster 3 no consumer indicated that they would even consider purchasing sample C12 on the purchasing intent scale, so WTP could not be calculated. The low cost for each of the samples could be since these ciders were not overall well liked among the consumers. The most liked cider was rated a 7 on average on the 9-point hedonic scale among all consumers, which was sample C7. Additionally, since WTP was calculated only for subjects who rated their purchasing intent for a sample above 2, these prices may only reflect a small number of consumers overall and in each cluster.

3.3. Cider chemistry

3.3.1. Basic cider chemistry

A comprehensive cider chemistry panel was conducted on all 24 ciders from the DA study to enable comparison of basic quality metrics between Virginia ciders in this study and those reported in the literature for ciders produced elsewhere worldwide. In addition, these results could be used qualitatively to provide context for the DA results, and to compare those results to generally understood relationships between sensory and chemical data for cider. Results for analyses are given in Table 8. All analyses were conducted in duplicate except for alcohol and CO_2. One-way ANOVA for all analyses with replication indicated that samples varied significantly in the measured chemistry (Table 8). This is to be expected for the diverse range of ciders included in the study.

The alcohol content for these ciders ranged from 4.81% to 9.86% ABV. These ranges were high compared to previous reports in the literature (e.g., 26). Symoneaux et al. (26) did not report any cider with ABV over 6.3%, while 18 of the ciders used in this study had an ABV% over 7.0%. This could be due to apples in Virginia being grown in warmer climates than those used to make the ciders studied by Symoneaux et al (26), which would cause a higher sugar content in the apples (and associated higher potential alcohol content). There could also be stylistic and production process differences between the ciders in our study compared to the French ciders studied by Symoneaux et al (26). Malic acid range was also found to higher compared to results reported from the study by Qin et al. (22). Qin et al. reported malic acid concentration from 0.02 to 3.56 g/L, while in this study malic acid ranged from < 0.020 g/L to 8.44 g/L. This can be attributed to variation across apple cultivars, as well as the fact that several ciders from the former study underwent malolactic fermentation. It is also possible that exogenous malic acid additions were made in the production of some of the Virginia ciders, which would elevate the malic acid concentration. As malic acid is the main fruit acid present in apples and ciders, we focus on this chemical, but it is worth noting that the titratable acidity ranges of ciders in this study follow the same pattern. In these ciders, TA ranged from 2.60 to 8.28 g/L malic acid equivalents, whereas in the Qin et al (22) study the range was smaller and lower, from 2.41 to 6.39 g/L malic acid equivalents. Meanwhile, pHs ranged from 3.61 to 4.09, which is consistent with the commercial ciders reported in previous studies (9,22,26).

Residual Sugar (RS) levels, measured in g/L, were quite different than those reported in previous studies (22,26). These previous studies reported much higher RS than the range reported in Table 8, indicating that the ciders used in those studies were likely to be perceived as more sweet, and possibly more full-bodied and less sour or bitter. In this study, RS ranged from below the level of detection to 38 g/L, whereas Symoneaux et al (26) reported RS from 12.7 to 52.1 g/L, and Qin et al (22) reported RS from 8.87 to 75.44 g/L. Given that these previous studies included or even focused on European styles that are not generally fermented to dryness (22,26), this is unsurprising, and indicates the need for much more work to characterize cider styles so that sensible comparisons can be made.

Measured polyphenol concentration ranged from 144 to 778 mg/L gallic acid equivalents (GAE), which was consistent with range determined by the Folin-Ciocalteu method on a sample set of 17 commercial ciders from the Eastern USA from Ma et al. (2019). Volatile acidity (VA) ranged from 0.21 to 2.15 g/L acetic acid equivalents in this study. The range of VA for these ciders were consistent with a previous study on Asturian ciders (20). All ciders this study were carbonated, and the CO_2 readings ranged from 1.48 g/L to 7.89 g/L, showing a broad range of carbonation among the ciders in this study. Both free and total SO_2 were measured in all cider samples. Analysis of total SO_2 confirmed that all samples were well below the regulatory limit. Likewise, free SO2 levels were within a normal-to-low range, and therefore unlikely to cause deleterious sensory effects in any sample. However, other studies did not report this potentially informative measurement, so we did not compare the measured range in these ciders (Table 8).

The results from the chemical analysis indicate that Virginia ciders are generally within the expected range of cider chemistry reported in other studies, with some specific and potentially important differences. Specifically, the ciders in this study were higher in alcohol and lower in residual sugar than ciders in other, similar studies, which may indicate a tendency towards higher sugar content in Virginia-grown apples and/or more complete fermentations (conversion of sugar in juice to alcohol) in Virginia ciders that is distinct from cider fermentations in other regions.

3.3.2. Connecting cider chemistry to sensory outcomes

It is possible to find associations among the measured cider chemistry and the quantitative results of the DA, which provides support for the quality and utility of the DA results. For example, in the DA analysis Samples C9, C15, and C16 were closely related to the alcohol attribute (Figure 1). All three of these ciders had an ABV above 7%, with C15 and C16 having the highest ABV among all the samples at 9.68% and 8.99%. Further, C16 had the highest mean reading of VA among all samples, at 2.15 g/L. Since high levels of VA can be perceived as nail polish or vinegar, this could explain why panelists associated it with descriptors like pungent, sharp, and sour (33).

Titratable acidity (TA) can be an indicator of sensory sourness or tartness within samples (33). The terms *sour*, *sour candy*, *sharp* and *green apple* are all closely related attributes according to the PCA (Figure 1), and samples, C5, C2, and C11 among others were found to be associated with these descriptors. C2 had the highest mean intensity rating of *sharp* and *sour* among panelists, and was also found to have a mean TA reading of 6.16 g/L malic acid equivalents (Table 5). Similarly, sample C5 was found to have the highest mean TA among all other samples (Table 5) and was closely associated with the *sharp* and *sour* descriptors.

Sweetness perception in DA is also associated with cider chemistry, in this case measured residual sugar (RS). Ciders C7, C8, and C24 had measured RS over 25.0 g/L (Table 5), and were also most closely associated with the *sweet* and *smooth* attributes in the DA (Figure 1). However, it is interesting to note that RS does not *solely* explain sensory sweetness: C22, C20, and C18 were associated with *sweet* (Figure 1), but had undetectable levels of RS (Table 5). This is very likely due to interactions between taste and aroma (21).

CO_2 is known to impact the sensory profiles of beverages (8), with high concentrations of CO_2 correlated to perceived sourness (37). All ciders described as *bubbly* were also described as *sour*, and *sour candy*. Among these, C11 and C9 had the highest concentrations of CO_2 (Table 5), and were also described using the *sour* and *sour candy* attributes (Figure 1). Conversely, sweetness perception can reduce the overall carbonation mouthfeel in beverages (37). This effect can be observed in this study: most ciders with a high intensity rating in *sweet* did not have high rating of *bubbly* or *sour* (Figure 1).

It has long been thought that polyphenol content in fermented beverages is related to total polyphenols (13,34). Samples C9, C15, and C16 were closely associated with the *bitter* attribute, with high mean intensity ratings (Figure 1). However, the polyphenol content for these samples were solidly in the middle of the range of the samples in the current study (Table 5). This shows that within these samples, bitterness perception may not be only impacted by polyphenol concentration—there are presumably both interactions with other sensory attributes (such as *sweet*) and other causes that can be traced to cider chemistry (5).

Overall, the observation of the expected associations between cider chemistry and the measured sensory attributes from the DA provide a measure of assurance that the panel was well-trained, and that DA results can reliably inform and contribute to the advancement of research on cider production factors.

3.4. Limitations and Future Work

A major limitation of the current work is the sample size used in the consumer study. A sample of n = 67 consumers is obviously not a fully representative sample. In part this sample size is due to the difficulty of conducting consumer research during the COVID-19 pandemic. Thus, this part of the research should be treated as exploratory, rather than confirmatory: the patterns of consumer liking observed can be used as hypotheses to test in future research. However, the clear and provocative patterns of reported liking, which to some degree align with those hinted at in previous research (4,27) indicate that these will be productive avenues for further, better-powered consumer research. In particular, research to explore the “modern” vs “craft” segments that emerged in this small sample should be encouraged.

A second limitation of the current study is the selection of cider chemistry to associate with sensory outcomes. In this study, the cider chemistry measured was based in large part on producer-relevant analyses, but these are unlikely to be able to explain the full range of flavors and aromas in cider identified by DA, which are likely to originate from volatile aroma compounds that require different analytical strategies (33). Future studies that aim to better characterize and identify the highest impact odorants in Virginia ciders should consider employing flavor-chemistry approaches like gas chromatograpy-olfactometry (GC-O).

Further research should also be undertaken to survey the flavor profiles of American ciders beyond Virginia. While Virginia is a major producer of cider with a broad range of producers and products, the current study cannot compare these products to other ciders produced in the United States simply because there is no published research on those products. Therefore, it would be of interest to determine the sensory profiles of ciders in the United States and, from the perspective of Virginia producers, what makes Virginia ciders distinctive.

Finally, it would benefit both researchers and producers to compile sensory research from this and other studies into a usable, comprehensive sensory lexicon for ciders in the style of the widely adopted wine wheel (18). The wine wheel, as noted by Sela Bowen et al. (24) and Shapin (25) is a powerful tool for producers and consumers to communicate the often ineffable flavor of wines. As the US cider industry grows, a similar tool for these products would help consumers, who clearly can have distinct sensory preferences and expectations, understand how to select ciders; it would also help producers target their products appropriately. The current research is a key contribution towards such a tool, which is critical future work.

4. Conclusions

In this research, a trained panel employed descriptive analysis to quantify the sensory profile of 24 Virginia ciders using 48 attributes, 22 of which were found to differ significantly among the samples. A representative subset of 8 of these ciders were evaluated for liking and willingness-to-purchase by a panel of 67 consumers. Using external preference mapping, 3 distinct clusters of consumers were identified with quite distinct liking profiles. Finally, producer-relevant cider chemistry was found to be associated with sensory profiles, which supports the quality of the sensory profiling work through the DA.

This research contributes to the larger project of understanding the origin and significance of flavors in ciders produced in Virginia and the United States as a whole. The terms that were used in the descriptive analysis are consistent with but expand on previous studies on Virginia ciders (10,10,14). This indicates that there is an underlying, common set of attributes which can ultimately be catalogued to create a sensory lexicon for American ciders, analogous to the famous wine wheel (18). Uniquely, this research investigated the connections among sensory profile and consumer preference: the finding that distinct consumer segments exist for different cider sensory profiles further supports the need to investigate and develop a consistent sensory lexicon for cider.

Acknowledgements

This work was funded by the Virginia Department of Agriculture and Consumer Services (VDACS) and the United States Department of Agriculture (USDA) through Specialty Crop Block Grant #301-20-026. The authors would also like to thank Ann Sandbrook and Ken Hurley of the VA Tech Enology Services lab for their assistance with chemical analyses of cider.

Interest Statement

No potential conflict of interest was reported by the authors.

Data Availability Statement

Data and code are available from the corresponding author upon reasonable request.

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674 **Tables**

676 **Table 1.** Cider sample descriptions; please note that the ciders and producers have been anonymized.

Sample	Packaging Format	Blend or Single Cultivar	Apple Varieties	Location in Virginia
C1*	*750 mL Bottle*	*Blend*	*Albemarle Pippin, Gold Rush, Pink Lady, Virginia Gold, undesignated*	*North Garden*
C2	*750 mL Bottle*	*Single*	*Virginia Hewes Crab*	*North Garden*
C3*	*750 mL Bottle*	*Blend*	*N/A*	*Monterey*
C4	*750 mL Bottle*	*Single*	*Virginia Hewes Crab*	*Monterey*
C5	*750 mL Bottle*	*Single*	*Virginia Hewes Crab*	*Richmond*
C6	*750 mL Bottle*	*Single*	*Harrison*	*Richmond*
C7*	*12 oz Bottle*	*Blend*	*N/A*	*Nellysford*
C8	*12 oz Bottle*	*Blend*	*N/A*	*Nellysford*
C9*	*16 oz Can*	*N/A*	*N/A*	*Roseland*
C10	*12 oz Can*	*Blend*	*N/A*	*Richmond*
C11	*750 mL Bottle*	*Blend*	*Albemarle Pippin, Gold Rush*	*Keswick*
C12*	*16 oz Can*	*Blend*	*Granny Smith, undesignated*	*Mineral*
C13	*12 oz Can*	*Blend*	*N/A*	*Alexandria*
C14	*750 mL Bottle*	*Blend*	*N/A*	*Middleburg*
C15	*500 mL Bottle*	*Blend*	*N/A*	*Middleburg*
C16*	*750 mL Bottle*	*Blend*	*Harrison, Ashmead's Kernel, Winesap, Golden Russet, Arkansas Black, Black Twig, Albemarle Pippin, Virginia Hewes Crab*	*Warm Springs*
C17	*750 mL Bottle*	*Single*	*Virginia Hewes Crab*	*Warm Springs*
C18	*750 mL Bottle*	*N/A*	*N/A*	*Abingdon*
C19	*750 mL Bottle*	*Blend*	*N/A*	*Abingdon*
C20	*12 oz Can*	*Blend*	*N/A*	*Leesburg*
C21*	*16 oz Can*	*Blend*	*N/A*	*Winchester*
C22	*500 mL Bottle*	*Blend*	*N/A*	*Winchester*
C23*	*750 mL Bottle*	*Blend*	*Gold Rush, Albemarle Pippin, Winesap*	*Charlottesville*
C24	*16 oz Can*	*Blend*	*Golden Delicious, Red Delicious and Granny Smith*	*Roseland*

*Cider was selected for use in study 2 (consumer preference mapping study).

Table 2. Sensory attributes and reference standards as defined by the DA panel.

Aroma (orthonasal aroma)		Fruity	2 oz fruit smoothie (Bolthouse Farms Berry Boost)
Alcohol*	15% ABV EtOH	Grape	2 green grapes, sliced in half
Cinnamon Spice Apple	Canned apple pie filling (Kroger)	Green Apple*	2 1” slices granny smith apple (Simple Truth)
Citrus*	1” lemon peel, 1” lime peel in 0.5 oz 5% ABV EtOH	Maple Syrup	1 tbsp Vermont maple syrup (Kroger)
Earthy*	Handful of grass plucked from outside	Red Wine	2 oz cabernet sauvignon wine (Bay Bridge)
Fermented	1 tbsp 2% Greek yogurt (Fage), 1/8 tsp apple cider vinegar, 1/8 tsp white vinegar	Red Apple	2 1” slices honey crisp apple
Fermented/Yeast	1 packet of dry active yeast in 500mL water	Sour Candy*	1 piece sour candy (WarHead Black Cherry)
Floral	¼ tsp of rose water (Heritage Store)	Watery*	1 oz apple juice (Simple Truth Organic), 1 oz water
Grassy	Clumps of cut grass with dirt from outside	White Wine	2 oz pinot grigio wine (Dark House)
Grapefruit*	1” grapefruit peel in 0.5 oz 5% ABV	**Taste**	
Green Apple Jolly Rancher	1 Green Apple Jolly Rancher. 0.5 oz 5% EtOH	Bitter*	2 oz caffeine solution (1.6 mg/mL)
Green Vegetable*	Frozen broccoli (Kroger), microwaved 6 mins	Sour*	2 oz citric acid solution (0.005 mg/mL)
Lemon	1” lemon slice, 0.5 oz 5% EtOH	Sweet*	2 oz sucrose solution (30 mg/mL)
Metallic	2 pennies, panelists instructed to rub pennies on hands, and smell their hands	**Mouthfeel**	
Peach	2 fresh peach slices	Bubbly*	2 oz citrus soda (Sprite)
Petroleum	Verbal anchor	Dry	1 oz 100% cranberry juice (Ocean Spray), 1 oz 100% pomegranate juice (POM Wonderful)
Pear	2 fresh pear slices	Flat*	2 oz seltzer water (San Pellegrino), poured an hour before panelist arrival
Rot*	2 slices of red apples (microwaved 2 mins), 1/8 tsp apple cider vinegar	Full-Bodied	2 oz merlot wine (Dark Horse)
Smokey*	1/8 tsp “liquid smoke” (Colgan), 500mL water	Heavy	2 oz of apple juice (100 mL Simple Truth Organic) thickened with ¼ tsp of cornstarch
Sulfur*	Hard-boiled egg (Simple Truth), microwaved for 2 mins	Pungent*	1 tsp wasabi sauce (Snow Fox)
Urine*	Verbal anchor	Mouth-Watering	2 oz 100% cranberry juice (Ocean Spray)
Flavor (retronasal aroma)		Sharp*	2 oz of apple juice (400 mL Simple Truth Organic) with added 1.4 tsp brewer’s grade Malic Acid
Acidic	1 tbsp apple cider vinegar, 8 oz water juice	Linger	2 oz black tea (1 bag Lipton black tea, brewed 5 minutes in 16 oz water)
Apple Juice*	2 oz apple juice (Simple Truth)	Smooth*	2 oz chardonnay wine (Flip Flop)
Beer	2 oz Coors Light	Sticky	2 oz of drink mix (200 mL Grape Kool-Aid) thickened with ¼ tsp of cornstarch
Champagne	2 oz prosecco (Lamarca)	Tingly*	¼ tsp popping candy (Strawberry Pop Rocks)

*This descriptor was found to be significantly different among samples in pseudomixed, 3-way ANOVA ($p < 0.05$).

Table 3. Demographic and consumption behavior questions, given as proportions of all subjects and of the clusters found from external preference mapping via CLV.

Question	Response	Overall (n = 67)	Cluster 1 (n = 32)	Cluster 2 (n = 21)	Cluster 3 (n = 14)
Gender	*Male*	*35.8*	*28.1*	*47.6*	*35.7*
	Female	*61.2*	*68.8*	*52.4*	*57.1*
	Non-Binary	*2.99*	*3.12*	*0*	*7.14*
	Prefer to Self-Describe	*0*	*0*	*0*	*0*
Age	*21-30*	*73.1*	*78.1*	*71.4*	*64.3*
	31-40	*8.96*	*6.25*	*4.76*	*21.4*
	41-50	*0*	*0*	*0*	*0*
	51-60	*11.9*	*9.38*	*14.3*	*14.3*
	60+	*5.97*	*6.25*	*9.25*	*0*
Education	*Some High School*	*0*	*0*	*0*	*0*
	High School Graduate	*1.49*	*0*	*0*	*7.14*
	Some College	*7.46*	*15.6*	*0*	*0*
	Associate Degree	*2.99*	*3.12*	*4.76*	*0*
	Bachelor's Degree	*52.2*	*56.2*	*42.9*	*57.1*
	Master's Degree	*26.9*	*18.8*	*42.9*	*21.4*
	Doctorate	*8.96*	*6.25*	*9.52*	*14.3*
Cider Consumption Frequency	*Everyday*	*0*	*0*	*0*	*0*
	A Few Times a Week	*4.48*	*6.25*	*4.76*	*0*
	Once a Week	*8.96*	*15.6*	*4.76*	*0*
	Once or Twice a Month	*34.3*	*18.8*	*38.1*	*64.3*
	Occasionally	*52.2*	*59.4*	*52.4*	*35.7*
Income*	*Less than $25,000*	*38.8*	*40.6*	*42.9*	*28.6*
	$25,000 - $49,000	*20.9*	*25*	*19.0*	*14.3*
	$50,000 - $75,000	*14.9*	*9.38*	*9.52*	*35.7*
	$76,000 - $99,999	*2.99*	*3.12*	*0*	*7.14*
	$100,000 - 150,000	*4.48*	*6.25*	*4.76*	*0*
	Greater than $150,000	*10.4*	*9.38*	*9.52*	*14.3*
	Prefer not to answer	*7.46*	*6.25*	*14.3*	*0*

*All values are in $USD.

Table 4. Mean and standard deviation for liking (1-9 scale), purchase intent (1-5 scale), and willingness to pay (WTP in $USD; $11-$15 scale) for ciders overall and in each cluster identified in external preference mapping with CLV.

	Overall			Cluster 1 (*n* = 32)			Cluster 2 (*n* = 21)			Cluster 3 (*n* = 14)		
Sample	**Liking**	**Purchase intent**	**WTP**	**Liking**	**Purchase intent**	**WTP**	**Liking**	**Purchase intent**	**WTP**	**Liking**	**Purchase intent**	**WTP**
C1	*3.87 ± 2.06*	*2.01 ± 1.01*	*12.50 ± 1.04*	*3.66 ± 2.22*	*2.06 ± 1.16*	*12.90 ± 1.33*	*3.95 ± 1.99*	*2.00 ± 0.89*	*12.30 ± 0.65*	*4.21 ± 1.85*	*1.93 ± 0.83*	*12.00 ± 0.67*
C3	*5.55 ± 2.14*	*2.94 ± 1.18*	*12.70 ± 1.17*	*5.47 ± 1.97*	*3.00 ± 1.22*	*12.70 ± 1.26*	*5.24 ± 2.51*	*2.67 ± 1.15*	*12.80 ± 0.98*	*6.21 ± 1.93*	*3.21 ± 1.12*	*12.60 ± 1.29*
C7	*7.00 ± 1.72*	*3.75 ± 1.15*	*12.80 ± 1.07*	*7.53 ± 1.24*	*4.00 ± 1.05*	*12.80 ± 1.01*	*7.14 ± 1.56*	*3.86 ± 1.01*	*12.90 ± 1.26*	*5.57 ± 2.17*	*3.00 ± 1.3*	*12.30 ± 0.73*
C9	*4.61 ± 1.87*	*2.34 ± 0.95*	*12.00 ± 0.66*	*4.41 ± 1.66*	*2.31 ± 0.82*	*11.80 + 0.72*	*4.48 ± 1.94*	*2.14 ± 0.91*	*12.20 ± 0.77*	*5.29 ± 2.20*	*2.71 ± 1.2*	*12.00 ± 0.45*
C12	*3.88 ± 2.32*	*2.04 ± 1.15*	*12.30 ± 0.99*	*2.78 ± 1.62*	*1.59 ± 0.91*	*11.80 ± 0.82*	*6.38 ± 1.77*	*3.19 ± 0.93*	*12.50 ± 1.01*	*2.64 ± 1.22*	*1.36 ± 0.5*	*N/A**
C16	*4.18 ± 2.43*	*2.21 ± 1.21*	*12.20 ± 0.95*	*2.94 ± 1.90*	*1.59 ± 0.67*	*11.60 ± 0.48*	*4.19 ± 2.29*	*2.24 ± 1.37*	*12.10 ± 0.67*	*7.00 ± 0.96*	*3.57 ± 0.76*	*12.30 ± 1.14*
C21	*5.79 ± 1.85*	*2.99 ± 1.12*	*12.50 ± 0.98*	*6.12 ± 1.93*	*3.19 ± 1.00*	*12.50 ± 0.96*	*5.00 ± 1.05*	*2.57 ± 1.16*	*12.80 ± 1.11*	*6.21 ± 1.63*	*3.14 ± 1.23*	*12.10 ± 0.92*
C23	*5.55 ± 1.77*	*2.96 ± 1.02*	*12.50 ± 1.06*	*5.44 ± 1.83*	*3.03 ± 0.97*	*12.60 ± 1.25*	*5.62 ± 1.77*	*2.81 ± 1.08*	*12.50 ± 0.85*	*5.71 ± 1.73*	*3.00 ± 1.11*	*12.20 ± 0.77*

*N/A indicates that no subject in this cluster indicated intent to purchase this sample.

Table 5. Mean and standard deviation for cider chemistry parameters.

Sample	ABV (% v/v)	CO_2 (g/L)	Malic Acid (g/L)	pH	FSO_2 (mg/L)	TSO_2 (mg/L)	TA (g/L)*	VA (g/L)†	RS (g/L)	Glucose (g/L)	Fructose (g/L)	Sucrose (g/L)	TPH (mg/L)§
C1	7.58	4.97	4.72 ± 0^{g}	3.82 ± 0.01^{ef}	0.5 ± 0.71^{f}	32 ± 0^{lm}	4.41 ± 0.03^{i}	0.21 ± 0.02^{g}	8.8 ± 0^{f}	4.1 ± 0^{f}	4.7 ± 0^{fg}	ND^{e}	298 ± 1.41^{fg}
C2	8.1	5.01	6.16 ± 0^{c}	3.66 ± 0.01^{ijk}	2 ± 0^{f}	29 ± 1.41^{mn}	6.5 ± 0.01^{d}	0.3 ± 0.02^{fg}	6.6 ± 0^{g}	3 ± 0^{g}	3.6 ± 0^{h}	ND^{e}	778 ± 12.73^{a}
C3	7.52	4.35	5.52 ± 0^{d}	3.67 ± 0.04^{hij}	2 ± 0^{f}	40.5 ± 0.71^{k}	5.98 ± 0.1^{f}	0.03 ± 0^{h}	9.3 ± 0.14^{f}	3.5 ± 0^{fg}	3.7 ± 0.14^{h}	2.1 ± 0^{b}	632.5 ± 21.92^{c}
C4	7.56	4.08	4.33 ± 0^{i}	3.9 ± 0.01^{d}	2 ± 0^{f}	29 ± 1.41^{mn}	5.3 ± 0.02^{g}	0.28 ± 0.01^{fg}	9.6 ± 0.14^{f}	3.1 ± 0^{fg}	5.3 ± 0.14^{f}	1.2 ± 0^{cd}	351 ± 7.07^{e}
C5	7.95	4.65	8.44 ± 0^{a}	3.73 ± 0^{gh}	1 ± 0^{f}	20 ± 1.41^{op}	7.84 ± 0.04^{b}	0.23 ± 0^{g}	ND^{h}	ND^{h}	ND^{i}	ND^{e}	427.5 ± 3.54^{d}
C6	7.82	4.99	5.09 ± 0^{f}	3.69 ± 0.03^{hij}	2 ± 0^{f}	38.5 ± 4.95^{kl}	5.48 ± 0.13^{g}	0.28 ± 0^{fg}	ND^{h}	ND^{h}	ND^{i}	ND^{e}	349 ± 5.66^{e}
C7	4.93	3.86	2.46 ± 0^{m}	3.71 ± 0.01^{ghi}	19 ± 1.41^{b}	94.5 ± 0.71^{f}	3.86 ± 0.02^{lmn}	0.31 ± 0^{efg}	38 ± 0^{a}	16 ± 0^{a}	22 ± 0^{b}	ND^{e}	163.5 ± 2.12^{klm}
C8	4.88	3.79	2.55 ± 0^{l}	3.8 ± 0^{ef}	18 ± 1.41^{b}	131.5 ± 2.12^{d}	3.79 ± 0.07^{mno}	0.32 ± 0.03^{efg}	36.5 ± 0.71^{a}	13.5 ± 0.71^{b}	23 ± 0^{a}	ND^{e}	233.5 ± 3.54^{i}
C9	7.21	4.99	0.02 ± 0^{v}	3.91 ± 0.03^{d}	2 ± 0^{f}	37.5 ± 2.12^{kl}	3.42 ± 0.01^{q}	0.45 ± 0.02^{d}	ND^{h}	ND^{h}	ND^{i}	ND^{e}	151 ± 1.41^{lm}
C10	5.46	4.22	0.42 ± 0^{r}	3.98 ± 0^{c}	15.5 ± 2.12^{bc}	62 ± 0^{i}	2.6 ± 0.03^{r}	0.38 ± 0.01^{def}	20 ± 1.41^{d}	6.5 ± 0.71^{e}	13.5 ± 0.71^{d}	ND^{e}	161 ± 2.83^{klm}
C11	7.5	7.87	6.42 ± 0^{b}	3.83 ± 0.01^{e}	2 ± 0^{f}	144 ± 0^{c}	6.24 ± 0.04^{e}	0.3 ± 0.01^{efg}	10 ± 0^{f}	1 ± 0^{h}	8 ± 0^{e}	1 ± 0^{cd}	242 ± 9.9^{hi}
C12	6.06	3.94	1.54 ± 0^{p}	3.99 ± 0.01^{c}	13 ± 2.83^{c}	109.5 ± 3.54^{e}	3.38 ± 0.04^{q}	0.68 ± 0.04^{c}	29 ± 0^{b}	11.5 ± 0.71^{c}	16.5 ± 0.71^{c}	1 ± 0^{cd}	142.5 ± 7.78^{m}
C13	8.5	5.54	0.15 ± 0^{s}	4.02 ± 0.03^{bc}	3 ± 0^{ef}	11 ± 0^{q}	3.52 ± 0.03^{pq}	0.86 ± 0.01^{b}	1 ± 0^{h}	ND^{h}	ND^{i}	1 ± 0^{cd}	281 ± 4.24^{fg}
C14	8.09	5.11	0.05 ± 0^{t}	4.09 ± 0.01^{a}	7 ± 0de	70.5 ± 4.95^{h}	2.58 ± 0.01^{r}	0.42 ± 0.01^{de}	1 ± 0^{h}	ND^{h}	ND^{i}	1 ± 0^{cd}	144 ± 7.07^{m}

C15	9.68	4.23	5.18 ± 0^{e}	3.65 ± 0.01^{jk}	4.5 ± 2.12^{def}	53 ± 2.83^{j}	6.78 ± 0.02^{c}	0.29 ± 0.01^{fg}	1.5 ± 0.71^{h}	ND^{h}	ND^{i}	1.5 ± 0.71^{bc}	397.5 ± 3.54^{d}
C16	8.99	4.85	<0.020^{w}	3.76 ± 0.02^{fg}	< 1^{f}	2.5 ± 0.7^{l}	8.28 ± 0.04^{a}	2.15 ± 0.11^{a}	ND^{h}	ND^{h}	ND^{i}	ND^{e}	283 ± 8.49^{fg}
C17	8.63	1.48	<0.020^{w}	4.06 ± 0.01^{ab}	2 ± 0^{f}	9 ± 1.41^{qr}	4.12 ± 0.01^{jk}	0.96 ± 0.01^{b}	ND^{h}	ND^{h}	ND^{i}	ND^{e}	702.5 ± 20.51^{b}
C18	7.19	4.26	1.13 ± 0^{q}	3.82 ± 0.01^{d}	2 ± 0^{f}	22 ± 0no	4.04 ± 0.09^{kl}	0.28 ± 0.03^{fg}	14.85 ± 0.07^{e}	4 ± 0.14^{fg}	4 ± 0^{gh}	6.85 ± 0.2^{a}	269.5 ± 2.12^{gh}
C19	7.22	4.86	2.81 ± 0^{k}	3.91 ± 0.01^{d}	2 ± 0^{f}	156.5 ± 0.71^{b}	4.32 ± 0.13^{ij}	0.3 ± 0.03^{fg}	ND^{h}	0 ± 0^{h}	ND^{i}	ND^{e}	222.5 ± 0.71^{ij}
C20	8.5	3.77	3.64 ± 0^{j}	3.9 ± 0.01^{d}	8 ± 0^{d}	82 ± 0^{g}	4 ± 0.01^{klm}	0.38 ± 0.02^{def}	ND^{h}	0 ± 0^{h}	ND^{i}	ND^{e}	307.5 ± 2.12^{f}
C21	7.07	7.31	4.56 ± 0^{h}	3.7 ± 0.02^{ghij}	< 1^{f}	44 ± 0^{k}	5.78 ± 0^{f}	0.31 ± 0^{efg}	ND^{h}	0 ± 0^{h}	ND^{i}	ND^{e}	179 ± 7.07^{kl}
C22	5.45	2.94	0.04 ± 0^{u}	3.8 ± 0.01^{ef}	< 1^{f}	12 ± 0^{pq}	3.56 ± 0.02^{opq}	0.45 ± 0.01^{d}	ND^{h}	0 ± 0^{h}	ND^{i}	ND^{e}	190 ± 2.83^{jk}
C23	7.36	4.85	1.91 ± 0^{o}	3.8 ± 0.01^{ef}	3 ± 0^{ef}	27 ± 1.41^{mno}	3.72 ± 0.04^{nop}	0.32 ± 0.01^{efg}	ND^{h}	0 ± 0^{h}	ND^{i}	ND^{e}	175 ± 5.66^{klm}
C24	4.81	4.19	2.11 ± 0^{n}	3.61 ± 0^{k}	82 ± 2.83^{a}	190.5 ± 2.12^{a}	4.73 ± 0.08^{h}	0.28 ± 0.01^{fg}	26.5 ± 0.71^{c}	10 ± 0^{e}	16 ± 0^{c}	0.5 ± 0.71^{de}	170.5 ± 9.19^{klm}

*Titratable Acidity (TA) is given as malic acid equivalents.
†Volatile Acidity (VA) is given as acetic acid equivalents.
§Total Polyphenol Content (TPH) is given as gallic acid equivalents.
$^{a-z}$Superscript letters indicate group separation according to Tukey's HSD; means with different superscripts are significantly different at a $p < 0.05$ level.
ND indicates "not detected", and was treated as "0" in calculation of ANOVA and Tukey's HSD.

Figures

Figure 1. Principal Components Analysis (PCA) plots of Principal Components 1 and 2 for results from the DA study. On the left, samples are plotted with colors and shapes representing membership of clusters from HCA on the same space. On the right, descriptors are plotted as correlations with the space, colored by whether they are significant (contributing to the PCA) or supplementary (projected into the PCA).

Figure 2. Clustering around Latent Variables (CLV) plot showing the resulting 3 clusters of (Caption) PCA Plot of Significant and Non-Significant Descriptors, Dimension 1, and Dimension 2. Significant descriptors are represented in purple, and non-significant attributes are represented in green.

Figure 3. Partial Least Squares Regression (PLS-R) showing the relationships among descriptors from the DA, consumer liking from the consumer study, and products from the consumer study.