Received: 3 November 2020 | Revised: 5 May 2021 | Accepted: 10 May 2021

DOI: 10.1111/1750-3841.15786

Journal of Food Science WILEY

SENSORY & CONSUMER SCIENCES

Strategic malting barley improvement for craft brewers through consumer sensory evaluation of malt and beer

Evan B. Craine[1] | **Stephen Bramwell**[2] | **Carolyn F. Ross**[3] | **Scott Fisk**[4] | **Kevin M. Murphy**[1]

[1] Department of Crop and Soil Sciences, Washington State University, Washington, USA

[2] Thurston County Extension, Washington State University, Washington, USA

[3] School of Food Science, Washington State University, Washington, USA

[4] Department of Crop and Soil Science, Oregon State University, Oregon, USA

Correspondence

Kevin M. Murphy, Department of Crop and Soil Sciences, Washington State University, WA, USA.

Email: kmurphy2@wsu.edu

Funding information

Washington State University Center for Sustaining Agriculture & Natural Resources (CSANR); Biologically Intensive Agriculture & Organic Farming (BIOAg) program, Grant/Award Number: 165.

Abstract: American craft brewers are targeting barley malt as a novel source of flavor and as a means of differentiation. However, fundamental tools have only recently emerged to aid barley breeders in supporting this effort, such as the hot steep malt sensory method, a wort preparation method recently approved by the American Society of Brewing Chemists for evaluation of extractable malt flavor. The primary objective of this study was to determine if insights into beer liking and sensory attributes can be gained through hot steep malt sensory using an untrained panel of craft beer consumers ($n = 95$). We evaluated consumer acceptance of hot steep and beer samples of different barley genotypes using a 9-point hedonic scale, check-all-that-apply (CATA), and open comment during separate sensory panels. Beers brewed with Washington State University breeding lines ($n = 4$), selected for all-malt craft brewing, generally had higher consumer acceptance than the industry-standard control variety (CDC Copeland). Genotype had a significant influence on the consumer acceptance of beer aroma, appearance, taste/flavor, sweetness, and overall liking but only on hot steep appearance. Significant differences between genotypes were found for 18% (*fruity* and *other*) and 46% (*chemical*, *citrus*, *earthy*, *fruity*, *stale*, and *sweet aromatic*) of CATA attributes for the hot steep and beer panels, respectively. Hot steep and beer liking and sensory attributes had low correlation coefficients. For example, beer overall liking was negatively correlated with *chemical* ($r = -0.338$, $p < 0.0001$) and positively correlated with *fruity* ($r = 0.265$, $p < 0.0001$). This study demonstrates that untrained craft beer consumers can better differentiate among genotypes using beers than hot steep samples.

Practical Application: In general, Washington State University barley breeding lines had higher consumer acceptance than the control variety, CDC Copeland. Each genotype had a distinctive beer flavor profile, such as 12WA_120.14 (*fruity* and *sweet aromatic*), which had the highest consumer acceptance ratings, and 10WA_107.43 (*citrus*), which has been released as the variety "Palmer." The results illustrate that the use of different barley genotypes presents varied sensory properties in the final beer and that particular malt and beer sensory attributes may influence consumer acceptance.

KEYWORDS

beer flavor, malt flavor, hot steep, barley breeding, CATA

1 | INTRODUCTION

In 2019, American craft brewers increased their market share by volume to 13.6%, and retail dollar value was estimated at $29.3 billion. If current trends continue, American craft brewers are projected to use over 50% of the malt consumed in the United States, with 20% of market share by volume (Brewers Association, 2014, 2019). A significant gap must be overcome to meet the demand for high-quality malt suited to craft brewers.

In an effort to maintain high-quality malt, the Brewer's Association (BA) surveyed craft brewers and published malt quality guidelines for all-malt brewing. Respondents consistently emphasized malt flavor, setting it as priority number one, over other parameters such as malt extract, enzyme levels, and β-glucan content (Brewers Association, 2014). However, there is a lack of understanding on how myriad factors, such as genetics or malting process parameters, influence malt flavor either independently or through their interactions.

There is an emerging body of evidence demonstrating the influence of malting barley genotype (i.e., genetics) on beer flavor. Genotype is used in this instance to encompass genetically distinct barley, such as experimental types, breeding lines, and released varieties. Herb, Filichkin, Fisk, Helgerson, Hayes, Benso, et al. (2017) showed that genotype has the strongest influence on beer flavor, regardless of the degree of malt modification. Moreover, both genotype and growing environment can influence beer flavor (Herb, Filichkin, Fisk, Helgerson, Hayes, Meints, et al., 2017). Bettenhausen et al. (2018) showed that commercial malt source influenced beer metabolite profiles and both flavor and flavor stability as perceived by trained panelists. After 8 weeks of storage at 4°C, the beers differed by *fruity* and *corn chip* profiles, the latter two attributes associated with numerous metabolite classes (e.g., purines/pyrimidines, volatile ketones, and amines). In a subsequent study, a consumer, brewery, and laboratory panels evaluated four distinct barley genotypes brewed in a lager-style beer. The results suggest that the four beer samples have different flavor profiles as perceived by the three panels. The beer with the highest overall liking had desirable traits such as *refreshing*, *crisp*, *citrus*, *sweet*, and *light* (Bettenhausen et al., 2020). Windes et al. (2021) found that a beer made with the variety Violetta had the highest overall liking and was more *sweet* and *floral* than a beer made with Calypso, which had the lowest degree of liking. In that study, consumers identified *crisp* and *refreshing* as ideal lager traits. Variation in barley genetics gives rise to distinctive beer flavors and is likely a function of how the genotype interacts with the malting process, which ultimately determines the macronutrient composition and enzymatic and metabolic profiles of the malt (Briggs, 1998; Herb, Filichkin, Fisk, Helgerson, Hayes, Meints, et al., 2017).

American craft brewers are pivoting away from the global commodity market to locally produced barley malts as a source of novel flavors and a mode of differentiation (First Key Consulting, 2019). Malting barley breeders are poised to play a unique role in supporting this effort and are challenged with identifying and balancing the needs of various stakeholders while developing new varieties. Assessing barley malt quality is considered destructive, expensive, and time-consuming. Thus, malt quality evaluations, which could help determine if a breeding line should be advanced toward release as a new variety, are typically reserved for a limited number of breeding lines in the advanced stages of the breeding process. Sensory evaluation has historically not been routinely performed as part of the breeding selection process. Moreover, fundamental tools have only recently emerged to aid breeders in evaluating and selecting genotypes with desirable flavor attributes.

The hot steep malt sensory method, a rapid and standardized wort preparation method recently approved by the American Society of Brewing Chemists (ASBC), was designed to be a practical and affordable method for evaluation of extractable malt flavor (ASBC, 2017; Liscomb, 2016). This relatively new method provides industry stakeholders and researchers a standardized and common approach to malt sensory evaluation. The method may also be an effective tool for breeders who wish to integrate malt flavor evaluations into the breeding process. However, the application of the hot steep method in research studies is limited. Bettenhausen et al. (2021) found that sensory and metabolomics for 12 commercial malts varied by *cereal* (e.g., Maillard reaction products), *grassy* (e.g., benzenoids and fatty acid esters), and *dough*. Windes et al. (2020) reported distinct and subtle differences among barley genotypes for hot steep and beer samples and detected distinct metabolomic profiles attributed to the barley genotypes. However, Windes et al. (2020) did not conduct a hot steep consumer panel and could only provide limited insight into the ability of the hot steep method to predict beer sensory and consumer acceptance.

Sensory evaluation via trained panels can be time- and resource-intensive (Dawson & Healy, 2018). In wine, check-all-that-apply (CATA) methods have been used to gain insights into consumer perception beyond liking, with consumer-based CATA having similar discriminability as descriptive analysis with a trained panel (Alencar et al., 2019). Moreover, studies have shown that novice consumers perform wine perceptive discrimination comparably to experts (Ballester al., 2008). Beer consumers are becoming increasingly discerning, and it is possible to gain a deeper level of understanding about their product experiences beyond basic preference (Jaeger et al., 2019). Using a panel of untrained craft beer consumers to evaluate liking and sensory profiles of barley genotypes, representing Washington State University (WSU) barley breeding lines selected for all-malt craft brewing and an industry-standard control variety (CDC Copeland), this study aimed to determine the relationships between hot steep and beer liking and sensory attributes. A leading question in this area of research is if insights into beer consumer acceptance and sensory attributes can be gained through hot steep malt sensory. Therefore, the study objectives were to determine (1) relationships between grain, malt, and beer quality and consumer acceptance and sensory profiles; (2) relationships between genotype and consumer acceptance of hot steep and beer; (3) relationships between genotypes and CATA sensory profiles; (4) relationships between consumer acceptance and sensory attributes; (5) factors influencing willingness to pay and marketability.

TABLE 1 Malting conditions used for the genotypes in the study

Genotype	Steep	Germination	Kiln
Copeland	8 hr wet (16 hr air) 8 hr wet (12 hr air) 2 hr wet	96 h	5 hr @ 50°C 5 hr @ 55°C ΔT = 9 @ 60°C 6 hr @ 72°C 4 hr @ 85°C
120.14 120.17	8 hr wet (16 hr air) 8 hr wet (12 hr air) 2 hr wet	120 hr	5 hr @ 50°C 5 hr @ 55°C ΔT = 9 @ 60°C 6 hr @ 72°C 4 hr @ 85°C
117.17 107.43	5 hr wet (19 hr air) 5 hr wet (15 hr air) 2 hr wet	120 hr	5 hr @ 50°C 5 hr @ 55°C ΔT = 9 @ 60°C 6 hr @ 72°C 4 hr @ 85°C

Note: The steep regime consists of alternating periods of water immersion and air rest.

[a]Steep water temperature was 14°C for Copeland, 120.14, 120.17, and 18°C for 117.17 and 107.43.

[b]Germination temperature was 15°C for Copeland, 120.14, and 120.17, and 18°C for 117.17 and 107.43.

2 | MATERIALS AND METHODS

2.1 | Germplasm and grain production

Spring, two-row barley breeding lines, and a control variety (CDC Copeland, Crop Development Center, University of Saskatoon; hereafter Copeland) were grown in Montesano, WA, in 2017. Breeding lines included 10WA_117.17 (Radiant/Baronesse/3/WA 10701–99//Baronesse/Harrington (X06G10)/4/Pmut-422H/CDC Candle (05WA-344.1); hereafter 117.17), 11WA_107.43 (Farmington/Baronesse//Bob/Merit; hereafter 107.43), and 12WA_120.14 and 12WA_120.17 (WA 10701–99/NZDK 00–131//AC Metcalfe; hereafter 120.14 and 120.17, respectively). Barley was planted in triplicate 627.5 m^2 plots in a randomized complete block design on May 10 and harvested on September 6 and 7.

2.2 | Malting and malt quality

Preliminary malting of the genotypes, using a malting regime adapted (i.e., “standard”) to the control (Copeland), revealed differing levels of water-sensitivity and germination vigor among the genotypes resulting in inferior malt quality, compared to industry guidelines (Table S1). This process informed strategies to optimize malting conditions for each genotype, which are detailed in Table 1, to produce malts with proper modification and malt quality suitable to all-malt brewing for use in this study (Aaron Macleod & Scott Fisk, pers. comm.; Briggs, 1998). For example, compared to Copeland, genotypes 117.17 and 107.43 required shorter steeps with longer air rests at a higher temperature. This allowed for all surface moisture to be removed during air rests before going into the subsequent steep while still reaching target moisture levels for proper modification. All breeding lines were given an additional 24 h of germination time, compared to the control, to compensate for reduced germinative vigor in order to improve overall modification (Table 1). Malts were prepared using an automated malting system manufactured by Custom Lab Products (Milton Keynes).

Grain and malt quality was assessed at the Hartwick College Center for Craft Food & Beverage (Oneonta) using official methods of the ASBC. The three replicates of each genotype from the field trial were combined before analysis of grain quality traits, including moisture (ASBC Barley-5C), protein content (ASBC Barley-7D), and germination energy (GE)/water sensitivity (4 and 8 ml; ASBC Barley-3C; Table 2; Table S1). Malt quality traits include extract (ASBC Malt-4), color (ASBC Wort-9), β-Glucan content (ASBC Wort-18B), soluble to total protein (S/T) ratio (Kolbach index (KI); ASBC Wort-17), free amino nitrogen (FAN) content (ASBC Wort-12), diastatic power (DP; ASBC Malt-6C), and alpha-amylase (AA; ASBC Malt-7C).

TABLE 2 Grain quality of genotypes performed by Hartwick College Center for Craft Food and Beverage

Genotype	Moisture (%)	Protein (%, DB)	Test Weight (kg/hl)	Plump (6/64″ %)
Copeland	13.4	10.3	62.9	99.6
117.17	14.9	9.9	64.5	98.4
107.43	15	10	68.1	99.1
120.14	15.4	10.1	65.1	98.7
120.17	16.9	10.3	64.0	99.1

Note: Genotype samples represented bulked samples of the three replicates from the field trial.
DB = dry basis.

2.3 | Brewing and beer quality

A portion of seed produced from the field trial was reserved for planting field trials the subsequent year and for distillation research, limiting the quantity of grain available for sensory analysis. Given this constraint, the target fermentation volume was 11.34 L. A single fermentation replicate (11.34 L) was used to avoid the possibility of confounding factors (e.g., oxidation and off-flavors) arising from the use of multiple small fermentation volumes.

All beers were brewed on March 19, 2019, using a malt-forward, single-malt and single-hop recipe developed by the partner brewer (Aaron Hart, Moscow Brewing Company), and 2.5 kg of each malt was milled separately immediately before mashing at a temperature of 63–67°C for 60 min in a mash-lauter tun. Lautering consisted of recirculating the first 5.7 L of wort drawn off the mash bed, followed by sparging with 15.4 L of 82°C water in approximately 1 L increments. The wort was then boiled for 60 min. At 30 min into the boil, 28.35 g of pelletized 6.5% alpha acid “Tahoma” hops were added. The wort was rapidly chilled to 20°C using an immersion wort chiller, at which point a starting gravity (SG) measurement was taken for each genotype before 95 ml of yeast (1056 American Ale Yeast, Wyeast Laboratories) was pitched. Fermentation occurred in glass carboys between 17.7 and 20°C for 21 days before “cold crashing” at 4–5°C until bottling on April 19, 2019. A final gravity measurement was taken and used to calculate alcohol by volume content for each genotype with SG. Beers were bottled in amber, 354.88 ml bottles that were CO_2 purged before beer was added under carbonation using a bottling gun. Bottles were rested at 4°C until served to the panel on April 26, 2019.

2.4 | Consumer acceptance and sensory quality

A pre-screened panel ($n = 95$) of untrained panelists (hereafter consumers) was recruited from Pullman, WA, USA, using a listserv of individuals who have expressed interest in participating in such panels. An untrained panel was utilized to more accurately approximate the ability of average consumers to differentiate hot steep and beer flavor on the basis of genotype. A questionnaire was used for panel screening. Individuals were disqualified from participating if they were not over 21 years of age, were pregnant, or expected that they were pregnant, and if they did not purchase or consume craft beers at least once or twice a month. Consumers were also asked a series of questions regarding demographics, consumption patterns, and factors that influence beer purchasing. The study was reviewed and approved by the WSU Institutional Review Board (IRB; IRB #17398-002), and informed consent was obtained from subjects prior to their participation in the study.

Consumers attended both the hot steep and beer panels, which were conducted on April 24 and 26, 2019, respectively. Consumers attended a 5-min orientation on the first day of the hot steep evaluation panel. As part of the orientation, consumers were provided with a description of the hot steep method, instructions on how to taste the samples and complete the hedonic liking and CATA tasks, and an introduction to the CATA lexicon (i.e., attributes). Consumers received non-monetary compensation for their participation.

The evaluation was conducted in sensory booths under white light. Five samples (30 ml; one for each genotype) were each assigned a three-digit blinding code and randomly presented to each consumer using monadic presentation for both hot steep and beer panels. Samples were presented in a clear International Standards Organisation (ISO) wine glass fitted with an aroma cap to preserve the aroma. Hot steep samples were prepared the morning of the panel (ASBC, 2017) and were served at ambient temperature (approximately 20–22°C) within 4 h of being prepared; morning and afternoon batches were prepared separately by combining individual hot steeps for each genotype. Bottled beers were stored in a refrigerator at 4°C. Every half hour, when a group of eight consumers was scheduled to participate, one bottle of each genotype was removed from storage and immediately placed on ice to maintain a temperature of approximately 6°C. Samples were gently poured immediately before serving, and bottles were fitted with a champagne-style stopper between pours to limit off-gassing.

During the evaluation of each sample, consumers followed the instructions and indicated the degree of acceptance for overall liking, appearance, aroma, taste/flavor, sweetness, and bitterness using a 9-point hedonic scale (1 = dislike extremely, 9 = like extremely) provided by Compusense Cloud (Guelph). Consumers also performed a CATA task by selecting from an array of attributes specific to the hot steep and beer panels. Attributes were randomly presented across panelists, as attributes at the top of the list can be selected more frequently than those at the bottom of the list (Castura, 2009). A team of sensory scientists from Dr. Ross' team and members of Dr. Murphy's research group reached a consensus on the number and identity of attributes to include after tasting each hot steep and beer sample, with the goals of providing attributes that would best differentiate the hot steep and beer samples, limit "dumping," and not overwhelm the consumers. This is the crux of designing the CATA task and can be a major limitation of this methodology (Varela & Ares, 2012). These attributes were selected from the ASBCs' Base Malt and Beer Flavor Maps. The hot steep CATA attributes (n = 11) included *bready*, *breakfast cereal*, *earthy*, *floral*, *fruity*, *grainy*, *grassy*, *honey*, *nutty*, *stale*, and *other* (Table 6), while the beer CATA attributes (n = 13) included *butter*, *cereal*, *chemical*, *citrus*, *earthy*, *floral*, *fruity*, *grassy*, *nutty*, *stale*, *sweet aromatic*, *yeasty*, and *other* (Table 7). Definition and/or examples were provided on a sheet of paper posted in each sensory booth for each CATA attribute from the respective flavor maps. For example, the hot steep attribute *stale* includes cardboard, paper, leather, and rancid oil. A comments section was provided at the end of each sample evaluation to gather additional opinions and information. At the end of the evaluation for each beer sample, participants were asked about their willingness to purchase a six-pack of that sample. Between samples, consumers took a 45 s break and cleansed their palates using deionized water, grapes (hot steep and beer panel), and unsalted crackers (beer panel). Purified deionized water was filtered over a Milli-Q reagent water system containing carbon, deionizing, and trace organic filters (Millipore). Plastic cups used as cuspidors and napkins were provided to each consumer.

2.5 | Statistical analyses

All statistical analyses were conducted in R unless otherwise stated (R Core Team, 2019). The beer and hot steep data were analyzed separately. Consumer acceptance ratings were analyzed using a two-way ANOVA, with consumer and genotype as random effects, and mean separation was performed using Fisher's LSD with Bonferroni corrected p-values in the *agricolae* package (Mendiburu, 2019). Correlations were performed using *rcorr* (Harrel & Dupont, 2018). The *FactoMineR* package was used for correspondence analysis (CA) and to generate asymmetric biplots (Lê et al., 2008). Principal component analysis was performed using the *prcomp* function in the *stats* package. Variables were shifted to zero, centered and scaled to have unit variance. Ordered probit models were generated using *polr* in the *MASS* package (Venables & Ripley, 2002). CATA and willingness to pay analyses (e.g., Cochran's Q-test and critical difference (Sheskin) procedure) were performed using XLSTAT Version 21.4.2 (Addinsoft). Correlations tests (Spearman) between CATA contingency tables/mean liking values with grain/malt quality were performed in XLSTAT. Cluster analysis of consumers based on overall beer liking was also performed in XLSTAT using agglomerative hierarchical clustering and truncation based on entropy.

3 | RESULTS AND DISCUSSION

3.1 | Consumer panel composition

Consumers were recruited based on drinking craft beer once or twice a month. Of the consumers, 54 were female, 40 were male, and one did not identify as male or female. Consumer age ranged from 21 to over 71, with the majority of consumers in the age ranges 26–30 (31%), 21–25 (26%), and 31–40 (26%). As with all surveys, there are concerns regarding the representativeness of the craft beer drinkers that participated in this study. There are limitations to the extent that these results can be applied to craft beer drinkers in Washington State and the United States. Almost all of the consumers identified as a consumer of craft beer (94%), with the remaining consumers drinking craft beer sometimes. When asked their favorite brand of beer, 51% named a beer or brewery identified by the BA as an independent craft brewery (ICB; https://www.brewersassociation.org/independent-craft-brewer-seal/), while the remainder named a non-ICB "macro" or "craft" brand. Most of the consumers in this study pay $8.00–$8.99 or $9.00–$9.99 on average for a six-pack of beer, which is comparable to what US consumers pay for the average craft six-pack (nielsen.com, 2019). Nationally, weekly craft beer consumers and younger consumers are more likely to purchase beers with the BA ICB seal (nielsen.com, 2019).

TABLE 3 Malt quality of the genotypes (Copeland and numbered Washington State University breeding lines), compared to industry guidelines

	Extract FGDB (%)	Color (°SRM)	β-Glucans (ppm)	S/T (%)	FAN (mg/L)	DP (°L)	AA (DU)
BA[a]			**<140**	**35-45**	**<150**	**<150**	
AMBA[b]	**>81.0**	**1.6–2.8**	**<100**	**38–45**	**140–190**	**110–150**	**40–70**
Copeland	81.3	2.20	85	44.4	193	122	64.8
117.17	79.5	1.84	99	40.9	151	106	47.8
107.43	81.5	1.87	95	37.7	155	101	47.6
120.14	81.5	2.79	127	44.7	208	102	60.9
120.17	80.9	2.49	130	42.4	190	100	56.7

Note: [a]BA = Brewers Association Consensus Targets (2014). Provide guidelines for preferred malting barley characteristics for craft brewers.
[b]AMBA = American Malting Barley Association Malting Barley Breeding Guidelines (AMBA, 2018). Provide ideal commercial malt criteria for "all-malt" brewing.
FGDB = fine grind dry basis; SRM = standard reference method; S/T = soluble to total protein ratio; FAN = free amino nitrogen; DP = diastatic power; AA = α-amylase.

3.2 | Relationships between grain, malt, and beer quality and consumer acceptance and sensory profiles

Most importantly, the quality of the malt used in this study for both the hot steep and beer samples was similar enough that differences in liking and sensory attributes evaluated by consumers were likely to arise from differences in barley genotype rather than differences related to malt quality. The malts used in this study were properly modified malts, appropriate for beer sensory profiling to evaluate barley genotype contributions to beer flavor, and generally met industry guidelines for all-malt, craft brewing (Table 3). Modification is an imprecise term that represents the desirable changes in grain as it is made into malt (Briggs, 1998). These guidelines are intended to provide barley breeders with targets to maintain or improve malt quality and meet the needs of all-malt, craft brewers. We identified significant relationships between grain and malt quality parameters and sensory attributes for the hot steep and beer samples.

The most important factor influencing barley end-use–and therefore malt quality–is grain protein content (Marquez-Cedillo et al., 2000). An ideal protein range is between 9.5% and 12.5% (BMBRI, 2017). All genotypes studied fell within this range (Table 1).

Beer sensory profiling to assess genotype contributions to beer flavor is most relevant when properly modified malts of each genotype, such as those used in this study, are used (Herb, Filichkin, Fisk, Helgerson, Hayes, Benso, et al., 2017). The β-glucan content of all genotypes met BA guidelines, while β-glucan content of 120.14 and 120.17 exceeded American Malting Barley Association (AMBA) guidelines. β-glucan content is a key indicator of proper modification. Proper modification of malt relies on adequate degradation of endosperm cell walls, which primarily comprised β-glucans (Henrion et al., 2019; Herb, Filichkin, Fisk, Helgerson, Hayes, Benso, et al., 2017). While β-glucan in barley can lead to high viscosity wort and hinder the brewing process (Vis & Lorenz, 1998), the partner brewer did not identify any such challenges (Aaron Hart, pers. comm).

Another important indicator of proper modification is the ratio of S/T. All malts demonstrated acceptable S/T relative to industry guidelines, indicating balanced modification (Table 3). Certain aspects of malt quality, such as S/T and FAN, may have effects on yeast nutrition and therefore flavor (Herb, Filichkin, Fisk, Helgerson, Hayes, Benso, et al., 2017). Levels of FAN for all malts were above BA guidelines; however, 117.17 and 107.43 had a similar FAN level just slightly higher than BA recommendations. Malts with higher S/T and FAN levels produce wort and beer of a relatively darker color than malts with lower values (Bettenhausen et al., 2018; Herb, Filichkin, Fisk, Helgerson, Hayes, Benso, et al., 2017; MacLeod et al., 2012). Breeding lines had lower enzyme levels than Copeland although levels of starch degrading enzymes were adequate (BMBRI, 2017).

The beers in this study had comparable quality, with slight variation in color and percent alcohol by volume (ABV; Figure 1). Although differing beer visual appearances can lead to differences in expected taste/flavor, it has been shown that visual cues impact expectations of beer flavor but do not influence actual flavor ratings (Carvalho et al., 2017). Though red lights can be used to mask the color of products in sensory booths, they were not used in this study to simulate a more realistic consumer experience with the products. ABV values were 5.46% (Copeland), 5.72% (107.43), 5.85% (120.14), 6.11% (117.17) and 6.76% (120.17).

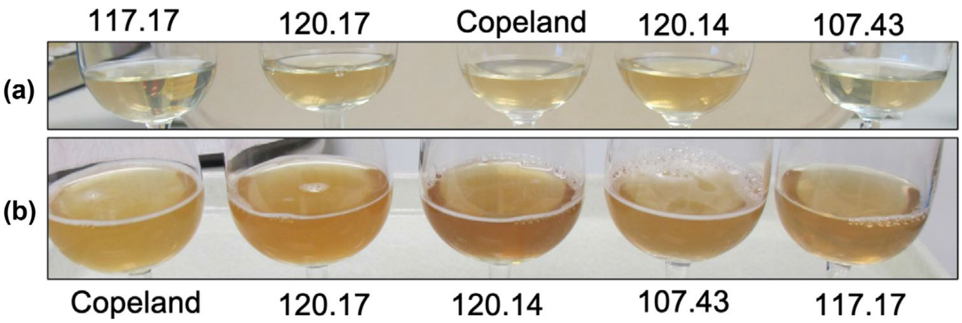

FIGURE 1 Images of (a) hot steep, and (b) beer samples as presented to consumers during each panel. Samples (30 ml) were served in clear wine glasses fitted with an aroma cap. Hot steep samples were served at room temperature, within 4 hr of preparation, and beers were kept on ice and poured immediately before serving to maintain temperatures close to 4°C. Washington State University barley genotypes are numbered and the control variety is "Copeland"

Though alcohol content can be a positive or negative beer attribute for consumers (Jaeger et al., 2019), alcohol content is likely not a large determinant of consumers' product evaluations as has been shown for beers ranging from 0.5% to 7.2% ABV (Jaeger et al., 2019) and 2.0% to 9.0% ABV (Cardello et al., 2016). The alcohol content is not necessarily related to the content of iso-α-acids, which contribute 80% of beer bitterness (Tanimura & Mattes, 1993), as low ABV beers can have high bitterness (e.g., 45 International Bitterness Unit (IBU); Maskell et al., 2015). Target IBUs of the beers were estimated at 18–20 (Aaron Hart, pers. comm.). Consumer acceptance of bitter beers can be highly variable and is influenced by genetic and psychophysical factors, personality traits, and preexisting preferences and expectations (Higgins & Hayes, 2019; Higgins et al., 2020).

Correlation analyses revealed a few significant relationships between grain and malt quality parameters and sensory attributes for the hot steep and beer samples. Generally, for the hot steep samples, genotypes with higher GE values at 8 ml had lower *earthy* citations for hot steep samples ($r = -0.975$, $p = 0.017$); genotypes with higher total protein generally had fewer *bready* citations ($r = -0.921$, $p = 0.017$); genotypes with a higher KI had fewer *earthy* citations ($r = -1.0$, $p = 0.017$). Beer samples had higher frequencies of *yeasty* citations with lower DP ($r = -0.975$, $p = 0.017$). Modification and its impact on malt quality parameters can influence malt and beer sensory as has been shown for under-modified malts with a *grainy* or *grassy* hot steep character and *grassy* or *earthy* beer flavor (Windes et al., 2020). While malt and beer quality characteristics may influence sensory characteristics such as appearance, taste, and flavor, linking these characteristics to consumer acceptance is difficult because of complex interactions among and multidimensionality of malt, beer, and sensory quality. While these factors do not appear to be directly predictive of one another (Windes et al., 2020), additional studies should be conducted to further investigate these relationships. For example, intentional manipulation of malt and beer quality parameters to create targeted variation as a factor in study design, coupled with consumer sensory evaluation, could provide additional evidence to elucidate why these relationships are weak.

3.3 | Relationships between genotype and consumer acceptance of hot steep and beer

To our knowledge, this is the first study to present consumer acceptance ratings (hereafter liking) of barley genotypes using malt hot steep and beer sensory evaluation based on appearance, aroma, taste/flavor, sweetness, bitterness, and overall liking.

Consumers had a significant effect on all hot steep and beer liking attributes ($p < 0.001$; Table 4). For hot steep, genotype had no effect on aroma, taste/flavor, sweetness, bitterness, or overall liking (Table 4). Interestingly, genotype had a significant effect on hot steep appearance liking, with 120.14 and 120.17 having higher ratings than the other genotypes (Table 5). Malt color may have influenced hot steep appearance liking as 120.14 and 120.17 were the darkest malts followed by Copeland, 107.43 and 117.17, although a lack of replication did not allow for statistical differences to be detected (Table 3). These results may also be influenced by consumer beer preferences. Separate two-way ANOVA showed that consumers reported significantly higher hot steep appearance liking when reporting amber ($F_{1460} = 5.384$, $p = 0.021$), pale ale ($F_{1460} = 9.202$, $p = 0.003$), and *hefeweizen* ($F_{1460} = 4.251$, $p = 0.040$) as a favorite beer; no effect was found when reporting lite ($F_{1460} = 0.003$, $p = 0.960$) and IPA ($F_{1460} = 0.939$, $p = 0.333$).

Compared to the hot steep panel, genotype had a significant effect on all beer liking attributes, except bitter-

TABLE 4 *F*-values and significance of the effects of consumer (all consumers; $n = 95$) and genotype on attribute liking presented separately for the hot steep and beer panels

Hot Steep	df	Aroma	Appearance	Taste/Flavor	Sweetness	Bitterness	Overall
Consumer	94	8.444***	8.575***	6.382***	5.586***	5.417***	7.109***
Genotype	4	0.13	7.589***	0.16	1.22	1.87	0.77
Beer	**df**	**Aroma**	**Appearance**	**Taste/flavor**	**Sweetness**	**Bitterness**	**Overall**
Consumer	94	2.337***	6.307***	4.191***	5.216***	5.850***	3.722***
Genotype	4	10.65***	3.599**	5.366***	3.370***	1.74	3.542**

**$p < 0.01$, ***$p < 0.001$.

TABLE 5 Mean separation of genotypes presented separately for hot steep and beer attribute likings as evaluated on a 9-point hedonic scale by the entire consumer panel ($n = 95$)

Hot steep genotype	Aroma	Appearance	Taste/flavor	Sweetness	Bitterness	Overall
107.43	5.13a	6.13b	5.79a	5.92a	5.61a	5.71a
117.17	5.09a	6.13b	5.79a	5.92a	5.40a	5.61a
120.14	5.13a	6.62a	5.83a	5.79a	5.37a	5.74a
120.17	5.08a	6.55a	5.85a	6.03a	5.71a	5.85a
Copeland	4.97a	6.25ab	5.89a	6.09a	5.55a	5.83a
Beer Genotype	**Aroma**	**Appearance**	**Taste/Flavor**	**Sweetness**	**Bitterness**	**Overall**
107.43	6.61ab	6.89ab	6.02a	5.85ab	5.40a	5.89abc
117.17	6.96a	6.91ab	6.01a	5.69ab	5.20a	5.68bc
120.14	6.93a	7.08a	6.31a	6.06a	5.59a	6.18a
120.17	6.33b	7.04a	6.24a	5.82ab	5.37a	6.05ab
Copeland	5.89c	6.67b	5.53b	5.53b	5.15a	5.52c

Note: Values that share a letter are not significantly different from each other (Fisher's LSD).

ness (Table 4). Copeland had lower consumer acceptance than at least one, and sometimes several, of the breeding lines for all attributes (Table 5). For aroma, 117.17 and 120.14 had higher ratings than 120.17 and Copeland; 120.14 and 120.17 had higher appearance liking than Copeland. For taste/flavor, ratings for the breeding lines did not significantly differ; however, all breeding lines had higher taste/flavor liking than Copeland. For sweetness, 120.14 had a higher liking than Copeland; 120.14 and 120.17 had higher overall liking than Copeland (Table 5). Consumer acceptance varied more for the beers than the hot steep for the genotypes studied, and these results suggest that the WSU breeding lines have the potential to replace Copeland in beers and receive higher consumer ratings.

Beer appearance liking may be influenced by beer color, as the beers made from 120.14 and 120.17 were visually darker and liked the most as in the hot steep. However, Copeland was not the lightest beer and was liked the least. In a previous study conducted using a WSU consumer panel, beer appearance liking was significantly higher for amber and IPA beers than for a lager (Waldrop & McCluskey, 2019). An ordered probit model showed that beer appearance liking was influenced by favorite beer styles; reporting amber (odds ratio = 1.291, $p = 0.023$) and *hefeweizen* (odds ratio = 1.306, $p = 0.016$) increased liking, while reporting lager or pilsner decreased liking (odds ratio = 0.748, $p = 0.006$). For example, for consumers who reported amber, the odds of being more likely to have a higher beer appearance rating were 1.291 times as high as those not reporting amber as a favorite style, holding all other variables in the model constant. A separate model showed that those reporting lager or pilsner had a lower overall liking of the beers in this study (odds ratio = 0.710, $p = 0.001$).

Overall liking may also be influenced by malt quality parameters. The preferred beer in the study by Bettenhausen et al. (2020) was made using a malt from a barley breeding line with higher FAN, DP, and AA than the control (also Copeland). Furthermore, the least preferred beer was under-modified (i.e., high β-glucan content). The beers in that study did not significantly differ in terms of color. For the two distinct sets of barley germplasm evaluated using a consumer panel by Windes et al. (2020), one significant difference was found for one of the sets. The preferred beer, made with violetta, had comparable FAN, DP, and β-glucan content to the least preferred beer, made with calypso. The present study builds on these studies by demonstrating that genotype can potentially influence beer consumer acceptance; however, the influence of malt quality on beer consumer acceptance is not well-defined as with beer sensory attributes.

Relationships between hot steep and beer liking attributes were investigated to determine if a strong positive correlation exists between consumer acceptance of a genotype presented as a hot steep sample, with consumer acceptance of the genotype presented as a beer sample. This would allow for the screening and selection of genotypes with high hot steep liking as an indirect selection method for genotypes with high beer liking (i.e., predictive ability). Overall liking was most positively correlated with taste/flavor for both hot steep ($r = 0.87$, $p < 0.0001$) and beer samples ($r = 0.91$, $p < 0.0001$) as has been shown for beer (Guinard et al., 2000). All hot steep liking attributes had positive correlations with overall beer liking (data not shown). Of the hot steep attributes, overall liking is the best predictor of overall beer liking ($r = 0.16$, $p = 0.0003$) relative to the other liking attributes, although this relationship is weak. This suggests that consumer sensory evaluation of hot steep samples may not be a justifiable strategy to evaluate and select genotypes with high beer overall liking. Moreover, Windes et al. (2020) provide limited insight into hot steep predictive ability. Additional studies, using different sensory evaluation methods or different sets of panelists or genotypes, should be conducted to further evaluate the utility of the hot steep method in the context of consumer sensory evaluation and determine if the relatively weak relationship between hot steep and beer consumer acceptance (i.e., predictive ability) found in this study is persistent.

3.4 | Relationships between genotypes and CATA sensory profiles

CA is tested for a significant association between genotypes and attributes. There was no significant association between genotypes and attributes for the hot steep panel (Pearson's chi-squared test: $\chi^2 = 34.997$, df = 40, $p = 0.695$). However, there was a significant association between genotypes and attributes for the beer panel (Pearson's chi-squared test: $\chi^2 = 71.885$, df = 48, $p = 0.014$). This may have been because the consumer panel was more familiar and adept at describing and differentiating beer samples than hot steep samples, as the panel was screened by consumption of beer rather than hot steep malted barley.

For the hot steep panel, *fruity* and *other* were the only attributes with significant differences found between genotypes. Copeland and 107.43 had lower *other* reports than 120.14, and 120.14 had a lower proportion of fruity citations than Copeland (Table 6). *Fruity* had the largest range in citation proportions, from 0.053 (120.14) to 0.200 (Copeland). Windes et al. (2020) report infrequent citation of *fruity* for hot steep samples, which may be due to the different barley genotypes studied. On the CA biplot, which presents genotypes in attribute space, 107.43 was positioned similarly to Copeland, and both had an association with *honey* and *earthy*; 120.17 and 117.17 were also positioned similarly, and both had associations with *nutty*, *stale*, *bready*, and *floral;* 120.14 was well-differentiated from the other genotypes and was associated with *grassy and grainy* (Figure 2(a)).

Although there were no significant differences among the genotypes for the hot steep attributes, except for *fruity* and *other*, the CA biplot demonstrates relationships between genotypes and attributes and presents differing hot steep descriptive profiles for the genotypes as perceived by consumers (Figure 2(a)). One limitation of the CATA method is that the results are qualitative rather than quantitative; differences between genotypes for CATA attributes are based on the proportion of citations rather than a difference in intensity. If samples had similar CATA sensory profiles, then potential differences among the genotypes arising from differing attribute intensities may not have been detected. To address these potential limitations of consumer-generated CATA, a future study could use a trained panel in addition to the consumer panel to provide quantitative data on attribute intensities, which may help objectively validate differentiation of samples from consumer acceptance ratings (Varela & Ares, 2012). This study benefited from using untrained consumers, which required almost no training time of the researchers. However, a potential disadvantage of this approach is that if the hot steep differences across genotypes were subtle or arose from complex attributes, then the ability of the consumers to effectively differentiate the samples may have been inadequate. A future study could incorporate consumer training to address this potential limitation. For example, 1 h of reference training has been shown to improve consumer sensory evaluation by increasing detection of complex attribute differences among samples and citation frequency, compared to untrained consumer CATA (Alexi et al., 2018). These changes in study design, in addition to using disparate hot steep samples, may result in a greater ability to differentiate hot steep samples if the sensory profiles are similar.

The genotype-dependent beers were well-differentiated by the consumers, with significant differences between the genotypes found for *chemical*, *citrus*, *earthy*, *fruity*, *stale*, and *sweet aromatic* (Table 7). On the CA biplot, 120.17 and Copeland were positioned similarly in attribute space (Figure 2(b)). These genotypes were associated with *earthy*

TABLE 6 Independent comparison of genotypes for each hot steep attribute using Cochran's *Q*-test to analyze check-all-that-apply (CATA) data

Hot steep attribute	107.43	117.17	120.14	120.17	Copeland	*p*-value
Bready	0.284 (a)	0.337 (a)	0.305 (a)	0.326 (a)	0.284 (a)	0.809
Breakfast Cereal	0.379 (a)	0.295 (a)	0.379 (a)	0.305 (a)	0.316 (a)	0.259
Earthy	0.421 (a)	0.400 (a)	0.316 (a)	0.358 (a)	0.347 (a)	0.349
Floral	0.158 (a)	0.200 (a)	0.189 (a)	0.263 (a)	0.158 (a)	0.223
Fruity	**0.126 (ab)**	**0.137 (ab)**	**0.053 (a)**	**0.158 (ab)**	**0.200 (b)**	**0.012**
Grainy	0.600 (a)	0.600 (a)	0.684 (a)	0.579 (a)	0.579 (a)	0.377
Grassy	0.505 (a)	0.558 (a)	0.600 (a)	0.526 (a)	0.526 (a)	0.498
Honey	0.463 (a)	0.411 (a)	0.411 (a)	0.421 (a)	0.495 (a)	0.462
Nutty	0.232 (a)	0.263 (a)	0.253 (a)	0.326 (a)	0.326 (a)	0.210
Stale	0.168 (a)	0.221 (a)	0.126 (a)	0.179 (a)	0.137 (a)	0.279
Other	**0.011 (a)**	**0.021 (ab)**	**0.074 (b)**	**0.021 (ab)**	**0.011 (a)**	**0.010**

Note: For CATA attributes with significant *p*-values (alpha = 0.05; bold rows), multiple pairwise comparisons using the critical difference (Sheskin) procedure allow separation of the genotypes by attribute. Cell values represent citation proportions. Values within a row that do not share a letter are significantly different.

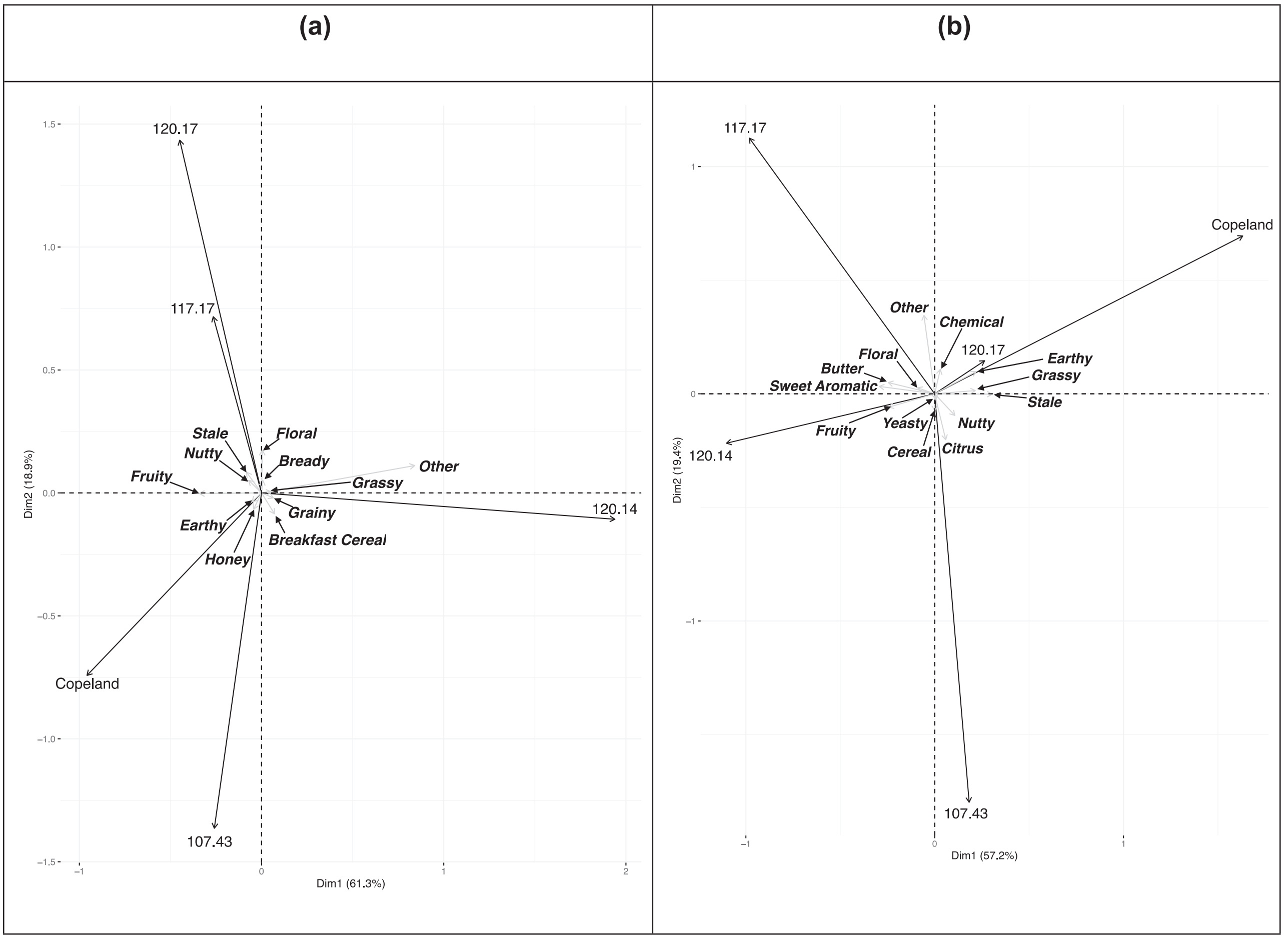

FIGURE 2 Asymmetric plot of the (a) hot steep, and (b) beer CATA CA. Rows (genotypes) are represented in column (attribute) space. If the angle between two arrows is acute, then there is a strong association between the corresponding row and column

TABLE 7 Independent comparison of genotypes for each beer attribute using Cochran's *Q*-test to analyze CATA data

Beer attribute	107.43	117.17	120.14	120.17	Copeland	*p*-value
Butter	0.116 (a)	0.179 (a)	0.147 (a)	0.137 (a)	0.074 (a)	0.146
Cereal	0.274 (a)	0.211 (a)	0.316 (a)	0.284 (a)	0.263 (a)	0.410
Chemical	**0.284 (ab)**	**0.400 (b)**	**0.221 (a)**	**0.379 (b)**	**0.326 (ab)**	**0.008**
Citrus	**0.368 (b)**	**0.221 (ab)**	**0.211 (a)**	**0.232 (ab)**	**0.242 (ab)**	**0.021**
Earthy	**0.211 (a)**	**0.211 (a)**	**0.263 (ab)**	**0.295 (ab)**	**0.421 (b)**	**0.002**
Floral	0.232 (a)	0.284 (a)	0.274 (a)	0.242 (a)	0.221 (a)	0.759
Fruity	**0.242 (ab)**	**0.274 (ab)**	**0.305 (b)**	**0.168 (ab)**	**0.147 (a)**	**0.017**
Grassy	0.232 (ab)	0.200 (ab)	0.147 (a)	0.179 (ab)	0.305 (b)	0.055
Nutty	0.189 (a)	0.126 (a)	0.158 (a)	0.158 (a)	0.189 (a)	0.650
Stale	**0.137 (ab)**	**0.084 (a)**	**0.116 (ab)**	**0.147 (ab)**	**0.221 (b)**	**0.028**
Sweet Aromatic	**0.221 (ab)**	**0.337 (bc)**	**0.411 (c)**	**0.242 (ab)**	**0.168 (a)**	**0.0001**
Yeasty	0.368 (a)	0.347 (a)	0.358 (a)	0.432 (a)	0.347 (a)	0.474
Other	0.032 (a)	0.105 (a)	0.063 (a)	0.042 (a)	0.084 (a)	0.078

Note: For CATA attributes with significant *p*-values (alpha = 0.05; bold rows), multiple pairwise comparisons using the critical difference (Sheskin) procedure allow separation of the genotypes by attribute. Cell values represent citation proportions. Values within a row that do not share a letter are significantly different.

as well as *grassy*. Copeland had lower *fruity* and *sweet aromatic* and higher *grassy* citations than 120.14, higher *earthy* citations than 107.43 and 117.17, and higher *stale* citations than 117.17 (Table 7). Herb, Filichkin, Fisk, Helgerson, Hayes, Benso, et al. (2017) found that Copeland had the greatest values for *fruit* and *grassy* across the three locations in which the variety was grown. In another study, Herb, Filichkin, Fisk, Helgerson, Hayes, et al. (2017) found that an "optimal" Copeland malt had higher *fruit*. Furthermore, Bettenhausen et al. (2018) found Copeland to be associated with *fruity* sensory traits. In a subsequent study, a "brewery" trained panel also identified Copeland as *earthy* but not *grassy*, and a "laboratory"- trained panel identified Copeland as *fruity* (Bettenhausen et al., 2020). Our results show that the Copeland beer samples had higher *grassy* citations than 120.14. However, the *fruity* nature of 120.14 and Copeland was the opposite for the beer, as 120.14 had more *fruity* citations than Copeland. Distinctive characteristics of genotypes perceived from a hot steep sample may be less apparent in the beer samples, as found by Windes et al. (2020), where attributes used to primarily describe hot steep samples (e.g., *grassy* and *grainy*), resulting in clear differentiation, were not cited as frequently in beers. When yeast and hops are added to produce beer, and they interact with malt, they may conceal the prevailing hot steep attributes. Windes et al. (2020) found relatively higher *floral* and *fruity* citation frequencies for beer, compared to the hot steeps. These relationships are likely a function of the malt, yeast, and hops used and will differ depending on how they interact to give rise to beer flavor profiles relative to the hot steep.

Compared to Copeland, there were noticeable differences among the breeding lines for the beer sensory attributes revealed through the CA biplot and analysis of the CATA. On the CA biplot, 120.14 had an association with *fruity* (Figure 2(b)) and had higher *fruity* than Copeland and higher *sweet aromatic* citations than 117.17 (Table 7); 107.43 had an association with *yeasty*, *cereal*, and *citrus* on the CA biplot and higher *citrus* citations than 120.14; 117.17 was associated with *other*, *butter*, and *floral* and had higher *chemical* citations than 120.14; 120.17 also had higher *chemical* citations than 120.14. ABV may influence reporting of *chemical*, as 120.17 and 117.17 had the highest ABV. However, 120.14 had intermediate ABV and lower *chemical* citations than 107.43 and Copeland. The differences observed between 120.14 and 120.17, which originated from the same parental genotypes and are considered "sister" breeding lines, indicate that parental selection for flavor attributes, while important, are perhaps not as critical as mid- to late-generation selection across genotypes.

3.5 | Relationships between consumer acceptance and sensory attributes

Of the sensory attributes, hot steep overall liking was most negatively correlated with *stale* ($r = -0.40$, $p < 0.0001$) and *earthy* ($r = -0.17$, $p = 0.0002$), and most positively correlated with *honey* ($r = 0.32$, $p < 0.0001$), followed by *nutty* ($r = 0.23$, $p < 0.0001$) and *floral* ($r = 0.21$, $p < 0.0001$). The strength of these relationships should be considered in the context of the nature of these data. Liking attributes were measured on a hedonic liking scale as an ordinal variable and sensory attributes were measured using a CATA and represent a binary variable. Both preference (i.e., liking) and perception of sensory attributes can vary widely by

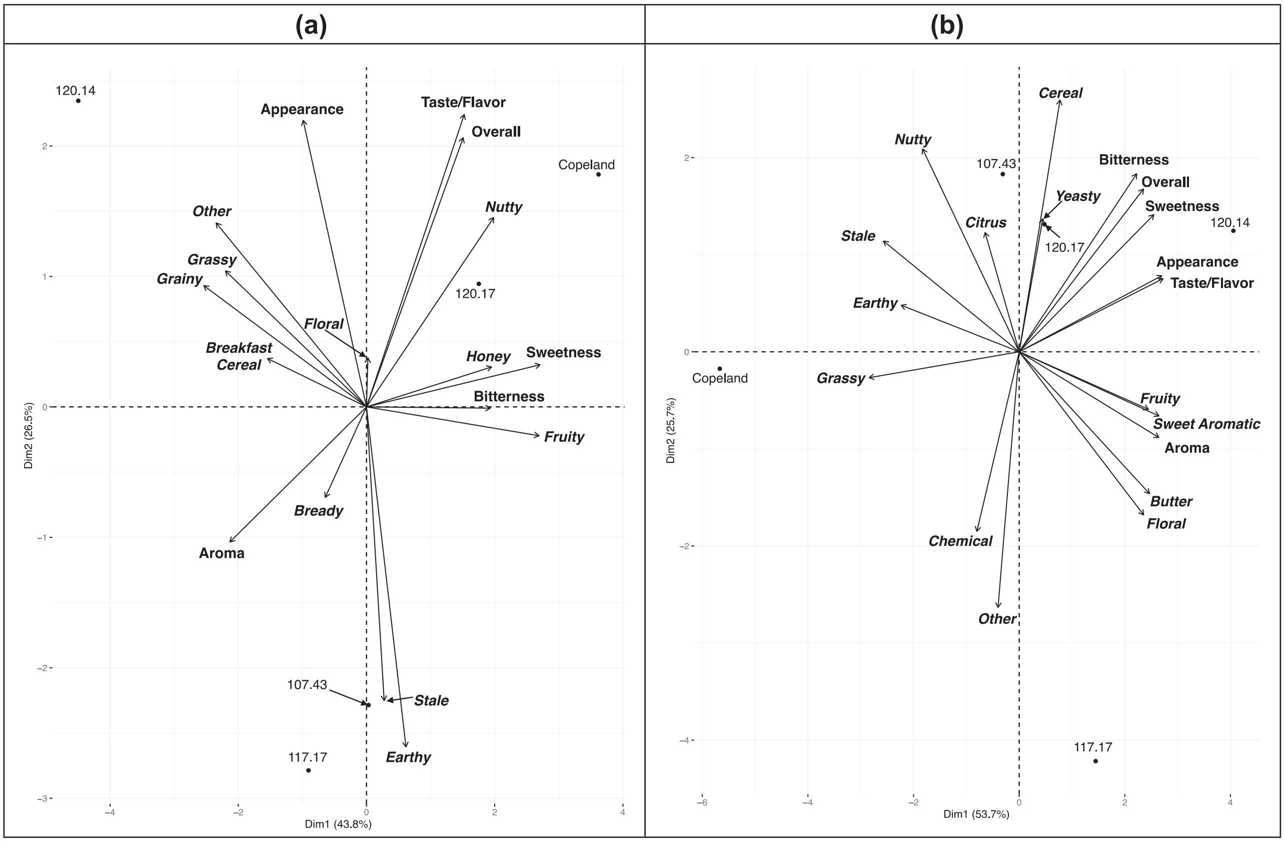

FIGURE 3 Correspondence analysis (CA). (a) Biplot representing principal component analysis of mean acceptance ratings for hot steep, and (b) beer, based on mean appearance, aroma, taste/flavor, sweetness, bitterness, and overall liking values, and frequency counts of check-all-that-apply (CATA) attributes. Liking attributes are bolded, and CATA attributes are bolded and italicized. Genotypes are in plain text. For each biplot, the factors are centered and scaled

person, which can present considerable variation in these data and ultimately influence the correlation coefficient. These results, in the context of consumer sensory evaluation, present significant relationships that can provide insight into explaining a portion of the overall variation. Principal component (PC) analysis further illustrated relationships between hot steep liking and CATA attributes and positioning of the genotypes; *honey* and *fruity* were related to sweetness and bitterness liking; *nutty* and *floral* were related to taste/flavor and overall liking; *bready* was related to aroma liking (Figure 3(a)).

Of the sensory attributes, beer overall liking was most negatively correlated with *chemical* ($r = -0.34$, $p < 0.0001$), followed by *stale* ($r = -0.25$, $p < 0.0001$), and most positively correlated with *fruity* ($r = 0.26$, $p < 0.0001$), *nutty* ($r = 0.21$, $p < 0.0001$), *sweet aromatic* ($r = 0.21$, $p < 0.0001$), *floral* ($r = 0.20$, $p < 0.0001$), and *citrus* ($r = 0.18$, $p < 0.0001$). In a study of genetically distinct malts, Bettenhausen et al. (2020) found that *citrus* and *floral* were associated with overall beer liking. Windes et al. (2020) do not provide correlations between beer overall liking and CATA attributes to allow for comparison. PC analysis also showed that beer liking attributes were related and that negative attributes included *stale*, *earthy*, *chemical*, *other*, and *grassy* (Figure 3(b)). *Nutty* was the only sensory attribute to have a positive correlation between the hot steep and beer samples ($r = 0.14$, $p = 0.002$). Windes et al. (2020) found that one genotype (Thunder) retained *sweet bread* characteristics in hot steep and beer. Additional studies should be conducted to identify which sensory attributes are present in both hot steep and beer samples of genotypes to provide additional evidence that may support using the hot steep method as an indirect selection method for identifying genotypes with distinctive or desirable beer sensory attributes.

Separate ordered probit models showed that demographic variables and consumption patterns influenced beer overall liking. In the first model, *age* (odds ratio = 1.149, p = 0. 028) and *level of education* (odds ratio = 1.136, p = 0.014) significantly affected overall beer liking. In the second model, beer overall liking was significantly affected by reporting *US Macro beers* (odds ratio = 0.383, p = < 0.001) and *US microbrew beers or craft beers* (odds ratio = 0.731, p = 0.029) as types of beer

TABLE 8 Independent comparison of genotypes at each willingness to pay price using Cochran's *Q*-test

Price	107.43	117.17	120.14	120.17	Copeland	*p*-values
$7.99	0.40(a)	0.32(a)	0.25(a)	0.34(a)	0.34(a)	0.257
$9.99	0.20(a)	0.24(a)	0.27(a)	0.18(a)	0.19(a)	0.375
$11.99	0.05(a)	0.06(a)	0.11(a)	0.08(a)	0.06(a)	0.582
$13.99	0.03(a)	0.00(a)	0.03(a)	0.03(a)	0.01(a)	0.287
I would not buy this beer	0.32(a)	0.38(a)	0.34(a)	0.37(a)	0.40(a)	0.657

Note: For attributes with significant *p*-values (alpha = 0.05; bold rows), multiple pairwise comparisons using the critical difference (Sheskin) procedure allow separation of the genotypes by attribute. Cell values represent citation frequencies. Values within a row that do not share a letter are significantly different.

liked best, reporting *there are only a few beers that I always order* (odds ratio = 1.137, $p = 0.046$), and reporting *I have a strong preference for one style of beer* (odds ratio = 1.248, $p = 0.026$).

3.6 | Relationships between genotypes and sensory attributes with willingness to pay and marketability

The majority of consumers would purchase a six-pack of the beers, with 68.4% of responses indicating that consumers would purchase a six-pack of beer at one of the provided price points, compared to not purchasing a six-pack of the beer (one-sample *Z*-test, $Z = 14.271$, two-tailed $p < 0.0001$; Table 8). There were no significant differences between the genotypes at each price point (Table 8). Effects of demographic and consumption pattern variables and sensory attributes on willingness to pay for a six-pack were explored using ordered probit models. Employment status, marital status, and level of education had a positive effect, while ethnicity had a negative effect. The presence of *citrus*, *nutty*, and *butter* all had a significant and positive effect on willingness to purchase.

Cluster analysis was performed to group consumers, determine the influence of clusters on overall beer liking, and investigate if consumer characteristics differed significantly between the clusters. Three distinct clusters were revealed based on beer overall liking. Cluster one (C1), two (C2), and three (C3) comprised 36, 30, and 29 consumers, respectively. Cluster (two-way ANOVA, $F_{4460} = 7.195$, $p < 0.001$) and the interaction between genotype and cluster (two-way ANOVA, $F_{8460} = 11.601$, $p < 0.001$) had a significant effect on beer overall liking. C1 had a lower mean liking (5.56) than C3 (6.23; Figure 4). C1 liked 107.43 less than the other genotypes, except 117.17. C2 liked Copeland less than the breeding lines (Figure 4). C3 liked 107.43 and 120.17 more than 120.14. Cluster composition differed slightly by consumer characteristics (Table S2); however, there were no significant differences between the clusters based on the variables included in the pre-screening questionnaire (data not shown).

Each of the beers used in this study could be effectively marketed to consumers. For example, 120.14 could be marketed to consumers in C2 at the higher price points (e.g., $11.99), as this cluster had the highest percentage of consumers paying $10 and above for a six-pack of beer and they liked 120.14 the most; 107.43 would be best marketed to consumers in C3 at a lower price point for similar reasons; 120.14 could be marketed as *fruity* and *sweet aromatic* or as one consumer commented "*This sample is the best balanced in terms of different flavor profiles–none really overwhelms but I am getting flavors of caramel, bubblegum, and graham crackers with floral aromas. A really nice beer";* 107.43 could be described as having a dominant *citrus* character, in addition to having a *crisp* attribute, as several consumers commented. With the consumer acceptance ratings, these results provide a nuanced perspective on how the WSU breeding lines could replace Copeland in beers. A larger group of consumers (> 150) may provide more reliable conclusions to be made.

This study demonstrates the importance of variety identity (i.e., genotype), and the potential to strategically develop malting barley with desirable flavor attributes via optimization of malt quality and subsequent consumer sensory evaluation of hot steep malt and beer samples. The 11WA_107.43 has been released as the variety "Palmer," selected specifically for the craft beer industry and will be available to farmers, maltsters, and brewers starting in 2021. The 120.14 was subsequently brewed at scale by the partner brewery and was marketed as a malt-forward beer brewed with a regionally grown, experimental barley variety. There are several advantages to advertising a beer as "local." For weekly craft beer drinkers, this is especially important, with 62% saying they buy local, compared to craft beer drinkers in general. Moreover, 57% of craft drinkers only buy beer sold in their town or city. Local craft beer accounts for 10.3% of craft dollar sales and earns a higher average six-pack price ($14.34, compared

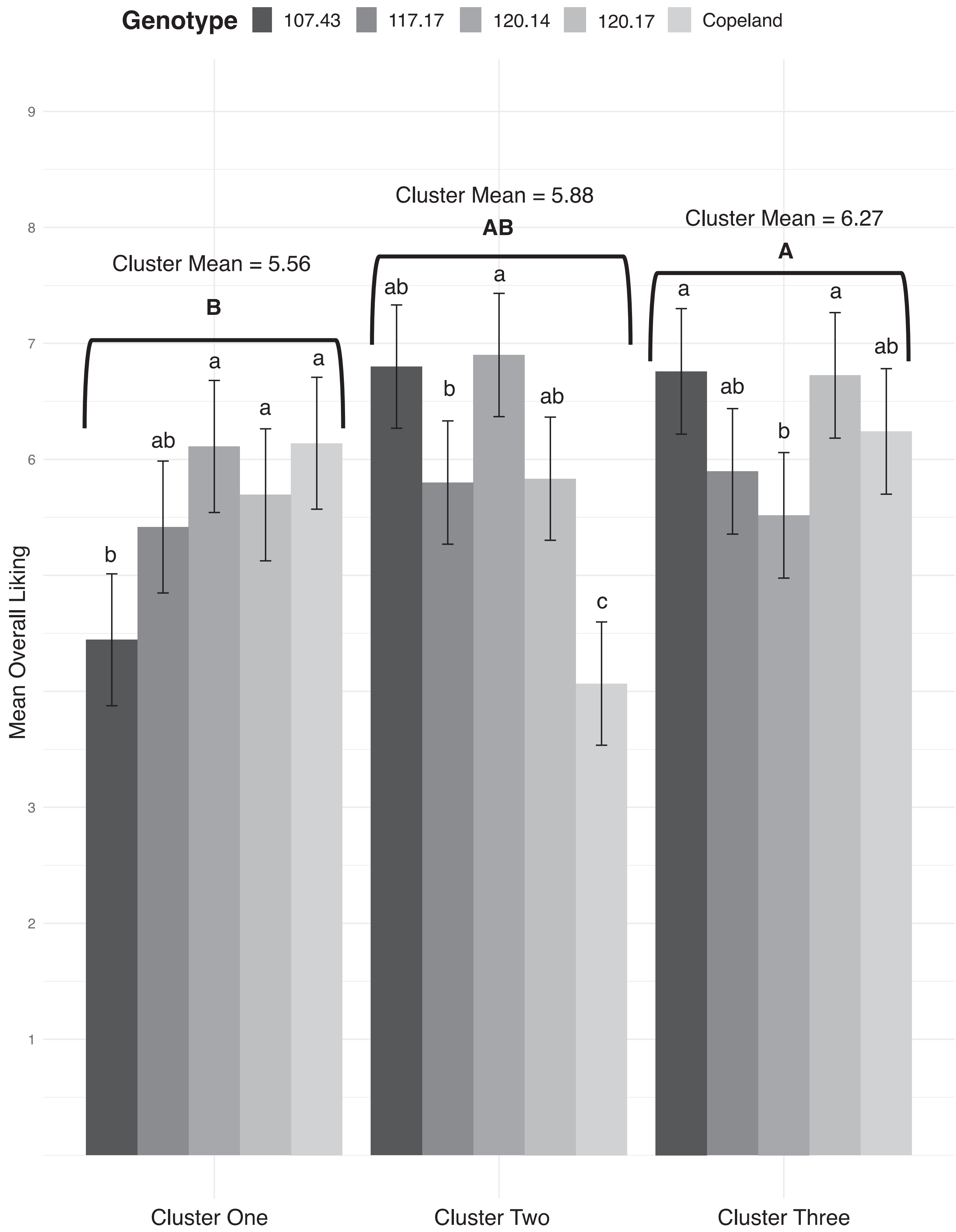

FIGURE 4 Beer overall liking mean values reported for each genotype by consumer cluster as evaluated along a 9-point hedonic scale. For the clusters (uppercase, bold letters) and within each cluster (lowercase letters, plain text), values that share a letter are not significantly different from each other (Fisher's LSD, Bonferonni corrected *p*-value, alpha = 0.05). Errors bars represent upper and lower 95% confidence intervals

to $9.26 average; nielson.com, 2019). Advertising “locally” bred, grown, and malted barley in “locally” brewed beers may compound this effect by portraying a holistic narrative grounded in a sense of place.

3.7 | Strategies for improving malting barley for craft brewers

The US Department of Agriculture Cereal Crops Research Unit (USDA CCRU, Madison, WI) provides barley breeders free malting of a finite number of lines. The CCRU malts all barley breeding lines using a consistently uniform malting regime, inevitably leading to varying levels of modification across samples. The subsequent malt quality analysis, scoring and ranking of genotypes using AMBA standards, provides the basis from which most public barley breeders evaluate and select breeding lines. This methodology effectively constrains barley breeders to the selection of genotypes with superior malt quality as a function of proper modification under stringent malting conditions. Consequently, the potential of otherwise outstanding breeding lines, in terms of agronomic performance or undiscovered flavor, is not realized. However, AMBA standards are not always as relevant to craft maltsters and brewers as they are to large-scale malthouses and breweries that prioritize efficiency. The optimization methodology used in this study illustrates the possibility of discovering malt quality and flavor contributions of breeding lines that would have otherwise been disregarded when evaluated under malting conditions standardized to the control (Copeland).

Although this methodology required a more involved malting process, craft maltsters and brewers may be more tolerant of such challenges than large-scale malthouses and breweries, and craft brewers may seek out these varieties as a means of differentiation. Moreover, barley breeding programs that are able to conduct in-house malting and malt quality analysis have flexibility in developing malting conditions, the amount of grain required for malting, the advantage of evaluating additional breeding lines earlier in the variety development process, and the opportunity to conduct the sensory evaluation. The hot steep method may be a valuable additional tool for barley breeders to incorporate into their evaluation and selection methods as a way to cull breeding lines with undesirable flavors and support the identification of novel flavors. Breeders must balance performance in the field, malthouse, and brewery in pursuit of flavor differentiation while meeting the needs of a diverse malting barley market increasingly interested in regionally adapted malting barley varieties.

4 | CONCLUSION

This study augments the case that barley genotype can decidedly influence beer flavor and shows that barley genotype can influence consumer acceptance of beers. Consumers provided acceptance ratings for hot steep and beer samples, which varied from “like slightly” to “like moderately.” The WSU breeding line 120.14 had higher acceptance ratings for all beer liking attributes, compared to the control (Copeland), except for bitterness. We found hot steep overall liking to have the strongest relationship, relative to the other liking attributes, with beer overall liking ($r = 0.16$, $p = 0.0003$). Of the sensory attributes, the *chemical* had the strongest negative ($r = -0.338$, $p < 0.0001$), and *fruity* had the strongest positive relationship ($r = 0.265$, $p < 0.0001$) with beer overall liking, while *stale* had the strongest negative ($r = -0.40$, $p < 0.0001$), and *honey* had the strongest positive relationship ($r = 0.32$, $p < 0.0001$) with hot steep overall liking. These attributes can inform malting barley improvement. This study confirms the ability of untrained craft beer consumers to differentiate beer samples using a CATA method; sensory attributes *chemical*, *citrus*, *earthy*, *fruity*, *stale*, and *sweet aromatic* differentiated the genotypes. Consumers were less adept at perceiving and reporting significant differences between hot steep samples. Some training, with reference standards or lexicon development, may improve consumer-based descriptive profiling of hot steep samples. The methods used in this study may be useful for future evaluations of barley breeding lines and malts to be used in beers, especially if future studies support the use of the hot steep method to predict beer sensory and consumer acceptance. Flexibility in evaluating malt quality and flavor may provide barley breeders additional opportunities to select and release new varieties to meet diverse market needs.

ACKNOWLEDGMENTS

The authors would like to give special thanks to Evan Mulvaney of Hidden River Farms for growing the barley for this project; Aaron Macleod of the Hartwick College Center for Craft Food and Beverage for grain & malt quality analysis, recommendations on optimized malting conditions, and helpful discussion on the preparation of the manuscript; Aaron Hart of Moscow Brewing Company for brewing; Beata Vixie and Dr. Ross’ Sensory Lab for assisting with the consumer panel; Lindsay Barr, Hannah Turner, and Casey Poirier for providing guidance for conducting the hot steep. This work was supported by USDA NIFA Hatch funds (accession no. 1014754).

AUTHOR CONTRIBUTIONS

Evan Craine: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Visualization; Writing-original draft; Writing-review & editing. Stephen Bramwell: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Writing-review & editing. Carolyn Ross: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision; Writing-original draft; Writing-review & editing. Scott Fiske: Methodology; Writing-original draft; Writing-review & editing. Kevin Murphy: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Writing-original draft; Writing-review & editing.

FUNDING

Funding was provided through the Washington State University Center for Sustaining Agriculture & Natural Resources (CSANR) Biologically Intensive Agriculture & Organic Farming (BIOAg) program (Project ID: 165).

CONFLICT OF INTEREST

There are no conflicts of interest to declare.

ORCID

Evan B. Craine https://orcid.org/0000-0002-6252-8973
Carolyn F. Ross https://orcid.org/0000-0002-5319-1950

REFERENCES

Alencar, N. M. M., Ribeiro, T. G., Barone, B., Barros, A. P. A., Marques, A. T. B., & Behrens, J. H. (2019). Sensory profile and check-all-that-apply (CATA) as tools for evaluating and characterizing syrah wines aged with oak chips. *Food Research International*, *124*, 156–164. https://doi.org/10.1016/j.foodres.2018.07.052

Alexi, N., Nanou, E., Lazo, O., Guerrero, L., Grigorakis, K., & Byrne, D. V. (2018). Check-all-that-apply (CATA) with semi-trained assessors: Sensory profiles closer to descriptive analysis or consumer elicited data?. *Food Quality and Preference*, *64*, 11–20. https://doi.org/10.1016/j.foodqual.2017.10.009

ASBC Methods of Analysis (2017). *Sensory analysis method-14: Hot Steep Malt Sensory Evaluation Method*. American Society of Brewing Chemists. https://www.asbcnet.org/Methods/SensoryAnalysis/Pages/default.aspx

AMBA. (2018). *Malting barley breeding guidelines*. American Malting Barley Association, Inc.

Ballester, J., Patris, B., Symoneaux, R., & Valentin, D., (2008). Conceptual vs. perceptual wine spaces: Does expertise matter?. *Food Quality and Preference*, *19*(3), 267–276. https://doi.org/10.1016/j.foodqual.2007.08.001

Bettenhausen, H. M., Barr, L., Broeckling, C. D., Chaparro, J. M., Holbrook, C., Sedin, D., & Heuberger, A. L. (2018). Influence of malt source on beer chemistry, flavor, and flavor stability. *Food Research International*, *113*, 487–504. https://doi.org/10.1016/j.foodres.2018.07.024

Bettenhausen, H. M., Benson, A., Fisk, S., Herb, D., Hernandez, J., Lim, J., Queisser, S. H., Shellhammer, T. H., Vega, V., Yao, L., Heuberger, A. L., & Hayes, P. M. (2020). Variation in sensory attributes and volatile compounds in beers brewed from genetically distinct malts: an integrated sensory and non-targeted metabolomics approach. *Journal of the American Society of Brewing Chemists*, *78*(2), 136–152. https://doi.org/10.1080/03610470.2019.1706037

Bettenhausen, H. M., Barr, L. Omerigic, H., Yao, L., & Heuberger, A. L. (2021). Mass spectrometry metabolomics of hot steep malt extracts and association to sensory traits. *Journal of the American Society of Brewing Chemists*, 1–13 https://doi.org/10.1080/03610470.2020.1869499

BMBRI (2017). *Quality factors in malting barley*. http://bmbri.ca/variety-development/quality-factors-in-malting-barley/

Brewers Association. (2014, April). *Malting barley characteristics for craft brewers*. https://www.brewersassociation.org/best-practices/malt/malting-barley-characteristics/

Brewers Association. (2019). *Brewers association releases annual growth report*. https://www.brewersassociation.org/press-releases/brewers-association-releases-annual-growth-report/

Briggs, D. E. (1998). *Malts and malting*. Springer US.

Cardello, A. V., Pineau, B., Paisley, A. G., Roigard, C. M., Chheang, S. L., Guo, L. F., Hedderley, D. I., & Jaeger, S. R. (2016). Cognitive and emotional differentiators for beer: An exploratory study focusing on "uniqueness. *Food Quality and Preference*, *54*, 23–38. https://doi.org/10.1016/j.foodqual.2016.07.001

Carvalho, F. R., Moors, P., Wagemans, J., & Spence, C. (2017). The influence of color on the consumer's experience of beer. *Frontiers in Psychology*, *8*, 2205. https://doi.org/10.3389/fpsyg.2017.02205

Castura, J. C. (2009). Do panellists donkey vote in sensory choose-all-that-apply questions? *8th Pangborn Sensory Science Symposium*, 26–30 July, Florence, Italy.

Dawson, J. C., & Healy, G. K. (2018). Flavor evaluation for plant breeders. *Plant Breeding Reviews*, *41*, 215–262.

First Key Consulting. (2019, January). *Growing demand from craft maltsters*. https://www.firstkey.com/growing-demand-from-craft-maltsters/

Guinard, J. -X., Uotani, B., Mazzucchelli, R., Taguchi, A., Masuoka, S., & Fujino, S. (2000). Consumer testing of commercial lager beers in blind versus informed conditions: relation with descriptive analysis and expert quality ratings*. *Journal of the Institute of Brewing*, *106*(1), 11–20. https://doi.org/10.1002/j.2050-0416.2000.tb00035.x

Harrel, F. E. J., & Dupont, C. (2018). *Hmisc: Harrell miscellaneous*. https://CRAN.R-project.org/package=Hmisc

Henrion, M., Francey, C., Lê, K. -A., & Lamothe, L. (2019). Cereal β-glucans: The impact of processing and how it affects physiological responses. *Nutrients*, *11*(8), 1729. https://doi.org/10.3390/nu11081729

Herb, D., Filichkin, T., Fisk, S., Helgerson, L., Hayes, P., Benson, A., Vega, V., Carey, D., Thiel, R., Cistue, L., Jennings, R., Monsour, R., Tynan, S., Vinkemeier, K., Li, Y., Nguygen, A., Onio, A., Meints, B., Moscou, M., … Thomas, W. (2017a). Malt modification and its effects on the contributions of barley genotype to beer flavor. *Journal of the American Society of Brewing Chemists*, *75*(4), 354–362. https://doi.org/10.1094/ASBCJ-2017-4976-01

Herb, D., Filichkin, T., Fisk, S., Helgerson, L., Hayes, P., Meints, B., Jennings, R., Monsour, R., Tynan, S., Vinkemeier, K., Romagosa, I., Moscou, M., Carey, D., Thiel, R., Cistue, L., Martens, C., & Thomas, W. (2017b). Effects of barley (*Hordeum vulagre* L.) variety and growing environment on beer flavor. *Journal of the American Society of Brewing Chemists*, *75*(4), 345–353. https://doi.org/10.1094/ASBCJ-2017-4860-01

Higgins, M. J., & Hayes, J. E. (2019). Regional variation of bitter taste and aftertaste in humans. *Chemical Senses*, *44*, 721–732. https://doi.org/10.1093/chemse/bjz064

Higgins, M. J., Bakke, A. J., & Hayes, J. E. (2020). Personality traits and bitterness perception influence the liking and intake of pale ale style beers. *Food Quality and Preference*, *86*, 103994. https://doi.org/10.1016/j.foodqual.2020.103994

Jaeger, S. R., Xia, Y., Le Blond, M., Beresford, M. K., Hedderley, D. I., & Cardello, A. V. (2019). Supplementing hedonic and sensory consumer research on beer with cognitive and emotional measures, and additional insights via consumer segmentation. *Food Quality and Preference*, *73*, 117–134. https://doi.org/10.1016/j.foodqual.2018.11.015

Lê, S., Josse, J., & Husson, F. (2008). FactoMineR: A package for multivariate analysis. *Journal of Statistical Software*, *25*(1), 1–18. https://doi.org/10.18637/jss.v025.i01

Liscomb, C. (2016). The hot steep sensory method: A rapid and standardized sensory evaluation method for malt flavor. *2016 World Brewing Congress*, 13–17 August, Denver, CO. https://www.asbcnet.org/events/archives/2016/proceedings/Documents/175_Liscomb.pdf

MacLeod, A. L., Edney, M. J., & Izydorczyk, M. S. (2012). *Quality of western Canadian malting barley—2011*. Canadian Grain Commission pp. 1–20.

Marquez-Cedillo, L. A., Hayes, P. M., Jones, B. L., Kleinhofs, A., Legge, W. G., Rossnagel, B. G., Sato, K., Ullrich, S. E., Wesenberg, D. M., & North American Barley Genome Mapping Project. (2000). QTL analysis of malting quality in barley based on the doubled-haploid progeny of two elite North American varieties representing different germplasm groups. *Theoretical and Applied Genetics*, *101*(1), 173–184. https://doi.org/10.1007/s001220051466

Maskell, P. D., Hughes, P. S., & Maskell, D. L. (2015). When is a beer not a beer: Iso-α-acids not necessarily proof of ethanol consumption? *Journal of Analytical Toxicology*, *39*(2), 160–160. https://doi.org/10.1093/jat/bku122

Mendiburu, F. d. (2019). *Agricolae: Statistical procedures for agricultural research*. https://CRAN.R-project.org/package=agricolae

The Nielson Cooperation. (2019, July 23). *Power hour: Nielsen shares 2019 craft beer consumer insights*. Brewbound. https://www.brewbound.com/news/power-hour-nielsen-shares-2019-craft-beer-consumer-insights

R Core Team. (2019). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Tanimura, S., & Mattes, R. D. (1993). Relationships between bitter taste sensitivity and consumption of bitter substances. *Journal of Sensory Studies*, *8*(1), 31–41. https://doi.org/10.1111/j.1745-459X.1993.tb00200.x

Varela, P., & Ares, G. (2012). Sensory profiling, the blurred line between sensory and consumer science. A review of novel methods for product characterization. *Food Research International*, *48*(2), 893–908. https://doi.org/10.1016/j.foodres.2012.06.037

Venables, W. N., & Ripley, B. D. (2002). *Modern applied statistics with s* (4th ed.). Springer. http://www.stats.ox.ac.uk/pub/MASS4

Vis, R. B., & Lorenz, K. (1998). Malting and brewing with a high β-glucan barley. *LWT–Food Science and Technology*, *31*(1), 20–26. https://doi.org/10.1006/fstl.1997.0285

Waldrop, M. E., & McCluskey, J. J. (2019). Does information about organic status affect consumer sensory liking and willingness to pay for beer? *Agribusiness*, *35*(2), 149–167. https://doi.org/10.1002/agr.21567

Windes, S., Bettenhausen, H. M., Simaeys, K. R. V., Clawson, J., Fisk, S., Heuberger, A. L., Lim, J., Queisser, S. H., Shellhammer, T. H., & Hayes, P. M. (2021). Comprehensive analysis of different contemporary barley genotypes enhances and expands the scope of barley contributions to beer flavor. *Journal of the American Society of Brewing Chemists*, 1–25. https://doi.org/10.1080/03610470.2020.1843964

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Evan B. Craine, Stephen Bramwell, Carolyn F. Ross, Scott Fisk, Kevin M. Murphy. Strategic malting barley improvement for craft brewers through consumer sensory evaluation of malt and beer. *J Food Sci*. 2021;1–17. https://doi.org/10.1111/1750-3841.15786