Bourbon and Rye Whiskeys Are Legally Distinct but Are Not Discriminated by Sensory Descriptive Analysis

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Abstract: We present a Descriptive Analysis (DA) of a large representative sample (24 whiskeys) of two legally distinct types of American whiskeys: bourbon and rye whiskey (respectively distilled from a fermented "mashbill" of at least 51% corn or rye). We wanted to determine whether a trained panel could find sensory differences between these two products. We used standard DA: 11 judges were trained for 10 hours to develop a lexicon of 24 flavor, taste, and mouthfeel descriptors for the 24 whiskey samples (15 bourbons and 9 ryes). Then, subjects rated each whiskey sample on each attribute, using unstructured line scales, in standard good sensory-evaluation conditions, and in triplicate. Results were analyzed using MANOVA, Barycentric Discriminant Analysis, and Hierarchical Cluster Analysis. Overall, while 10 descriptors significantly differentiated the whiskeys, no attribute or combination of attributes was predicted by mashbill: The judges did not find differences in sensory character between bourbon and rye whiskeys as categories. However, significant differences could be attributed to the *producer* of the whiskey and to age at bottling. These results are important because American whiskey has recently become staggeringly popular, and because there is a consistent belief that bourbon and rye whiskeys—as categories—have distinct sensory characteristics.

Keywords: alcohol, attributes, principal component analysis, sensory, sensory evaluation

Practical Application: This research contradicts popular and expert beliefs about the distinction between the popular and important American rye and bourbon whiskeys. A comprehensive sensory DA study of 24 American whiskeys with different mashbills (9 ryes and 15 bourbons) shows that—while each whiskey is individually distinct on a number of sensory dimensions—sensory differences between rye and bourbon whiskeys as product categories cannot be predicted by mashbill. For producers, consumers, and researchers, this research points to the need for new theories on the origins of flavors in whiskey, as it is now clear that the grain content alone cannot predict sensory qualities.

Introduction

Over the last 15 years, American whiskey has seen staggering growth in popularity: Between 2002 and 2017, sales on a per-case volume of American whiskey have grown 76%, and in 2017 sales of American whiskey generated $3.4 billion in revenue for distillers (DISCUS, 2017a). In particular, "rye" whiskey (defined below) has experienced explosive sales growth in the last decade: Between 2009 and 2017, per-case sales volume for rye whiskey has increased 934%, with an accompanying 109% increase in supplier revenue from rye whiskey (DISCUS, 2017b).

The majority of American whiskeys are "bourbon" and "rye" whiskeys, which are distinguished from the other major whiskeys—Scotch and Irish whisk(e)y—not only by country of origin, but by several distinctive ingredient and processing requirements ("Title 27: Alcohol, Tobacco, and Firearms. Part 5: Standards of Identity for Distilled Spirits," 1969). "Bourbon," which is distilled from a mashbill of at least 51% corn, and "rye," which is distilled from a mashbill of at least 51% rye grain, make up a majority of American whiskeys. A third major category of American whiskey, "Tennessee whiskey," must be distilled in the state of Tennessee and is generally (but not always) filtered through charcoal prior to barrel-aging; in other respects Tennessee whiskey is similar to bourbon and will not be discussed further here. All three major American whiskeys are distinct from Scotch and Irish whisk(e)y, which are distilled from mashbills that are majority or completely malted barley and are—almost exclusively—aged in oak barrels that have previously been used and/or are not charred, but "neutral" or lightly toasted (Bryson, 2014). Thus, American whiskeys are distinguished by their new, charred-oak character and their grain basis.

In addition, both bourbon and rye whiskeys are required to be distilled to not more than 160° proof (80% v/v ethanol) and stored at not more than 125° proof (62.5% v/v ethanol) in new, charred oak barrels ("Title 27: Alcohol, Tobacco, and Firearms. Part 5: Standards of Identity for Distilled Spirits," 1969). For both types of whiskey, aging for 2 years in new charred-oak confers the legally protected term "straight" ("Title 27: Alcohol, Tobacco, and Firearms. Part 5: Standards of Identity for Distilled Spirits," 1969). Straight American whiskeys of the same type, produced in the same state, can be blended and retain the right to be called "straight bourbon" or "straight rye," providing that the requisite 51% mashbill requirements are

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met. Therefore, the minimum *legal* difference between American bourbon and rye whiskeys is 2% grain content by weight in the original mashbill, prior to distilling—all other production and processing requirements are identical. Furthermore, bourbon whiskey can make up any proportion of the minority of the mashbill with rye grain, and rye whiskey can do the same with corn.

There is very little published research into the sensory character or flavor chemistry of American whiskey. The few articles on the sensory attributes of any whiskey are largely focused on Scotch whisky (Lee, Paterson, Piggott, & Richardson, 2001a, 2001b; Piggott & Jardine, 1979; Piggott, Sheen, & Apostolidou, 1990)—and because of the ingredient and processing differences between these whiskies and American whiskeys, the results cannot generalize. In the last decade, Poisson and Schieberle (2008a) published an aroma reconstruction study to confirm volatile aroma analysis of an American bourbon and included a small sensory component. However, these results are specific to a single product (one American bourbon and two reconstructed aroma mixes based on this product) and use descriptive attributes taken from Scotch lexicons (Lee et al., 2001a), so the results of the study are probably not authoritative for American whiskeys in general. Quite recently, Lahne, Collins, and Heymann (2016) reported a sorting study of ten bourbon and rye whiskeys, in which untrained subjects were unable to distinguish the rye and bourbon whiskeys from each other: That is, while the whiskeys themselves had presumably distinct sensory profiles, their similarities were not predicted by stated mashbill. The lack of definitive sensory differentiation between rye and bourbon whiskeys is mirrored in the flavor-chemistry and chemometric literature. Although volatile analysis of American whiskey dates back to the mid-20th century (Kahn, Laroe, & Conner, 1968; Kahn, Shipley, LaRoe, & Conner, 1969; Liebmann & Scherl, 1949; Schoeneman, Dyer, & Earl, 1971), there is still no definitive chemometric difference found between bourbons and ryes (Collins, Zweigenbaum, & Ebeler, 2014; Lahne, 2010; Poisson & Schieberle, 2008b).

This inability to discriminate between rye and bourbon whiskeys contrasts strongly with popular beliefs. For example, in a 2006 newspaper article celebrating the renewed popularity of rye whiskey, *New York Times* wine critic Eric Asimov writes: "Unlike bourbon, which is characteristically sweet, smooth and rounded, rye has a dry, jangly, brash nature [. . .] In its simplest form, rye is a little grassy and sour" (Asimov, 2006b). This oppositional description between bourbon and rye is very common in popular and enthusiast literature on flavor as illustrated by Lew Bryson who—in his book *Tasting Whiskey*—states: "Rye won't get you that luxurious river of corn you get in some bourbons [. . .] it will fly up your nose in a hot herbal rush [. . .] with a flame of bitter, oily ryegrass" (2014, p. 157). In the same book, in fact, Bryson categorizes within bourbons according to their rye content, opposing "rye" flavor to "smooth + mellow" flavor (Bryson, 2014, p. 145). Along the same lines, Michael Jackson, one of the most authoritative spirits critics in the world, writes that: "what the rye grain gives to bread it also gives to whiskey [. . .] it is reminiscent of a bittersweet fruit—perhaps a hint of apricot—spicy, a little oily, almost peppermint" (2017, pp. 188–189). The anonymous author of the methodical www.whiskyanalysis.com website summarizes a review of online whiskey descriptions by claiming that "little rye is needed to produce noticeable levels of the classic 'spiciness' this grain imparts" ("Methodology – Bourbon Classification," 2018). This popular discourse is both widespread and common: Bourbon is sweet, luxurious, and mellow but rye is bitter, herbal, and spicy.

So, despite the popular belief that rye and bourbon whiskeys differ predictably in their sensory characteristics, the only modern sensory study of the two whiskey types shows that *untrained* subjects do not perceive a difference between mashbills (Lahne et al., 2016), but perhaps untrained assessors could not distinguish rye from bourbon because they had only limited experience with these products. To test this possibility, we decided to use a more sensitive method and explicitly train assessors: The main objective of this research, therefore, is to determine whether rye and bourbon whiskeys—legally distinct and popularly considered vastly different—can be differentiated based on sensory Descriptive Analysis (DA) using trained panelists.

Materials and Methods

Samples

For this study, 24 whiskeys were selected and purchased from Nugget Markets (Davis, CA, USA). The whiskeys were selected to be a representative sample of commercially available, American straight whiskeys. These whiskeys were selected using data from a previous study identifying the nonvolatile constituents of American whiskeys to span the space of nonvolatile compositions (Collins et al., 2014), as well as to represent the diversity of producers, owners, ABVs, and ages generally available to the public. Only "straight" whiskeys (aged a minimum of 2 years) and whiskeys that followed the Code of Federal Regulations production rules to be called "bourbon" or "rye" were included in the study ("Title 27: Alcohol, Tobacco, and Firearms. Part 5: Standards of Identity for Distilled Spirits," 1969). A total of 9 ryes and 15 bourbons (described in Table 1) were included in the sample—this proportion of rye versus bourbon probably over-represents the presence of rye in the marketplace, since for the last 60 years it has been a specialty (although increasingly popular) product (Bryson, 2014).

All samples were diluted 1:1 (v/v) with distilled water (Jack, 2003) in order to increase the potential release of volatiles from the ethanolic matrix (Ickes & Cadwallader, 2017, 2018). This procedure had the additional effect of making the samples less fatiguing and more accessible to panelists, while preserving the producers' decisions about relative bottling strength (ABV; see Table 1).

Mention of any brand names or manufacturers does not imply financial or other support from associated companies or, conversely, and endorsement of these products. See Section 5 for statement of research support and independence.

Subjects

Panelists were recruited from the UC-Davis/Davis, CA population. To participate in the study, panelists had to be at least 21 years old, willing to drink whiskey, and available for training and evaluation sessions. A total of 11 panelists participated in this study (7 male, 4 female). Panelist ages ranged from 21 to 63 years old.

Panelists did not receive any compensation for participation in this study, but an assortment of snacks and treats were made available to all subjects after each training and evaluation session.

Sensory evaluation of whiskeys

This study is based on a generic DA of the whiskey samples (Heymann, King, & Hopfer, 2014). In all sessions, samples were presented as 15 mL aliquots in opaque, black wineglasses covered with plastic watch glasses and labeled with randomly generated 3-digit codes. Panelists were instructed to both smell and taste samples, were asked to expectorate after each tasting, and cleaned their

Table 1–Whiskey samples.

Owner	Producer	Product name	Type	ABV	Age
Beam Suntory	Kentucky Springs Distilling Company, Clermont KY	Basil Hayden's	Bourbon	40%	8 years
		Jim Beam Black	Bourbon	43%	8 years
		Jim Beam Rye	Rye	40%	4 years*
		Knob Creek Bourbon	Bourbon	50%	9 years
		Knob Creek Rye	Rye	50%	2 years
		Old Crow	Bourbon	40%	3 years*
		Old Overholt	Rye	40%	3 years*
	Burks Distillery, Loretto KY	Maker's Mark	Bourbon	45%	6 years*
Brown-Forman	Brown-Forman Distillery, Shively KY	Old Forester Classic	Bourbon	43%	4 years
	Woodford Reserve Distillery, Versailles KY + Brown-Forman Distillery, Shively KY	Woodford Reserve Bourbon	Bourbon	45.20%	7 years*
		Woodford Reserve Rye	Rye	45.20%	2 years
Chatham Imports	Kentucky Bourbon Distillers, Bardstown, KY	Michter's Straight Rye	Rye	42.40%	2 years
Diageo	MGP Indiana, Lawrenceburg, IN	Bulleit Rye	Rye	45%	2 years*
Gruppo Campari	Austin Nichols, Lawrenceburg KY	Russell's Reserve Rye	Rye	45%	6 years
		Wild Turkey 101	Bourbon	50.50%	8 years*
Heaven Hill	Heaven Hill Bernheim Distillery, Louisville KY	Elijah Craig 12-year	Bourbon	47%	12 years
		Rittenhouse	Rye	50%	4 years
Kirin	Four Roses Distillery, Lawrenceburg KY	Four Roses Single Barrel	Bourbon	50%	8 years*
		Four Roses Yellow Label	Bourbon	40%	2 years
Luxco	Heaven Hill Bernheim Distillery, Louisville KY	Ezra Brooks Single Barrel	Bourbon	49.50%	12 years
Sazerac	Buffalo Trace Distillery, Frankfort KY	Blanton's	Bourbon	46.50%	9 years*
		Buffalo Trace	Bourbon	45%	2 years*
		EH Taylor Small Batch	Bourbon	50%	4 years*
		Sazerac	Rye	45%	6 years*

*Age of whiskey determined from media articles or press releases, but not legally declared on bottle.

palates in between samples using distilled water and unsalted saltine crackers. Panelists were told that they were evaluating American whiskeys, but beyond this they were not informed of the nature of the samples or the purpose of the study.

Panelists participated in 10, 1-hr training sessions over 3 weeks. In every training session, panelists evaluated three different samples, ensuring that over the entire training panelists were exposed to each whiskey at least once. Training sessions were carried out in a focus-group setting (except for the final session, see below), led by the first author. For the first training session, panelists tasted the samples and generated terms that described the sensory differences between the samples. From this initial, large set of descriptors (over 45 terms were initially generated), panelists worked to identify synonymous terms or concepts. In subsequent sessions, this "term reduction" was facilitated by the provision of reference standards for each term (see Table 2 for the final list of references); as panelists evaluated new whiskeys and discussed their sensory properties, they agreed on terms that were synonymous or did not distinguish the whiskeys—and so could be dropped—and finally refined and reformulated the reference standards. This way, through the training period, panelists generated a "consensus" sensory vocabulary (Heymann et al., 2014; Lawless & Heymann, 2010) while also becoming more familiar with the products, and thus more sensitive to the sensory differences among these products (Chambers, Allison, & Chambers, 2004).

After nine training sessions, panelists had ceased to generate new sensory terms and had agreed on a minimal, 24-term sensory lexicon for American whiskeys (see Table 2). Panelists were then tested on their reliable use of the terms: Panelists were provided with a list of descriptors and the set of references in opaque, black wineglasses labeled with randomly generated 3-digit codes. Panelists were considered trained when they were able to reliably match the descriptors and the anonymized references. Panelists then spent one final 1-hour training session learning to use the sensory data-collection software (FIZZ; Biosystèmes, France). This training session also provided initial panelist feedback, giving the panelists an opportunity to compare their performance against the groups' and correct their scale-use and use of descriptors (Heymann et al., 2014).

Data collection was carried out in individual sensory booths in conditions described in Lawless and Heymann (2010). Panelists—who were unaware of the true number of samples—evaluated each sample in triplicate, with six samples presented per session, for a total of 12, 30 to 60 min evaluation sessions per panelist. Panelists were allowed to participate in a maximum of two evaluations per day in order to avoid degradation of panelist performance. Before each session, each panelist took a reference test as described above to align use of descriptive terms. Samples were presented to panelists in a sequential, monadic design, randomized according to a Latin Square design. Panelists were instructed to both taste and smell samples, and to rate each sample for each descriptor on an unstructured, 9-cm line scale, anchored with "not detectable" on the left end and "most intense" on the right end. Line scale responses were converted to 10-pt scores for data analysis. Panelists were also allowed, for each sample, to define and rate an "other" attribute (although this option was not used by any panelist). All data were collected through the FIZZ sensory software (Biosystèmes, France).

Data analysis

Data were imported into the `R` statistical environment. The following `R`-packages were used: PTCA4CATA, tidyverse, and ExPosition.

DA data (24 attributes, see Table 2) were analyzed by a 3-way MANOVA (*product* × *subject* × *replication*) to protect against familywise error inflation (Rencher, 2002). Then, pseudomixed (Heymann et al., 2014) 3-way ANOVA analyses with the same factors were conducted for each individual descriptive term. The significant MANOVA results were followed by Barycentric Discriminant Analysis (BADA; Abdi, Williams, & Valentin, 2013;

Table 2–Descriptive terms and references used for whiskey descriptive analysis.

Type	Descriptor	Reference
Aroma	vanilla/oak	1 Evoak "High Vanilla" barrel-stave sample, sprayed with distilled water*
	raw wood/cedar	1.75 g oak chips + 0.25 g pine sawdust + 3 drops cedar extract, sprayed with distilled water*
	toasted malt	1.5 g Belgian Special B malted barley + 1.5 g Briess Victory malted barley
	earthy	0.5 g dirt in 10 mL 5% (v/v) ethanol/water solution
	leather	2 cm leather shoelace, sprayed with distilled water
	soapy	1 g Ivory soap in 10 mL 5% (v/v) ethanol/water solution
	medicinal/rubber	2 rubber bands, verbal description "the smell of an old-fashioned bandage"
	hay	2 pinches dried grass + 2 pinches alfalfa leaves
	nutmeg/spice	0.25 g fresh-grated nutmeg in 10 mL 5% (v/v) ethanol/water solution
	maple/caramel	5 mL maple syrup + 1 mL caramel solution in 10 mL 5% (v/v) ethanol/water solution
	oxidized/baked apple	1 slice apple baked at 350 °F for 10 minutes in 10 mL 5% (v/v) ethanol/water solution*
	dried fruit/raisin	½ dried date + ½ dried fig + 2 raisins in 10 mL 5% (v/v) ethanol/water solution
	plum/cherry	1 fresh cherry + 1 slice fresh black plum in 10 mL 5% (v/v) ethanol/water solution*
	banana/tropical	1 dried banana chip in 10 mL 5% (v/v) ethanol/water solution*
	citrus/cola	2 mL Shasta cola in 10 mL 5% (v/v) ethanol/water solution
	tree nuts	1 chopped walnut + 1 chopped hazelnut + 1 chopped almond + 1 drop IFF Black Cherry Extract in 10 mL 5% (v/v) ethanol/water solution
	peanut	2 roasted peanuts chopped in 10 mL 5% (v/v) ethanol/water solution*
	floral/violet	5 mL Crème Yvette + 2 drops McCormick Artifical Rum Extract in 10 mL 5% (v/v) ethanol/water solution*
Taste	bitter	750 mg caffeine in 1000 mL distilled water*
	sweet	10 g sucrose in 1000 mL distilled water*
Mouthfeel	astringent	420 mg alum in 1000 mL distilled water
	hot/alcohol	250 mL Ketel One vodka in 750 ml distilled water*
	cooling	15 drops IFF Eucalyptus Extract in 500 mL distilled water (panelists were instructed to pinch nose)
	viscous	1 g carboxymethylcellulose in 500 mL distilled water

*Attributes marked with a * were shown to significantly differentiate (at a $P < 0.05$ level) between products in a 3-way (product, judge, replication), pseudomixed ANOVA. See Section 2 for full statistical details.

see also Rossini, Verdun, Cariou, Qannari, & Fogliatto, 2012)—a robust generalization of traditional Discriminant or Canonical Variate Analysis (CVA, Peltier, Visalli, & Schlich, 2015). Discriminant analysis following MANOVA is a multivariate analogue of *post hoc* comparisons following ANOVA (Rencher, 2002). BADA can be used to visualize both traditional biplots (Heymann et al., 2014; Peltier et al., 2015) illustrating relationships between and among whiskeys and attributes and to analyze other preexisting classifications: in this case, for example, whether rye or bourbon whiskeys are significantly differentiated according to sensory attributes. BADA was used to construct (linear) discriminant functions to determine whether sensory information was predicted by the mashbill of the product (i.e., whether the product was rye or bourbon). In addition, age, ABV, and producer (see Table 1) were examined as potential variables to explain the significant sensory differences.

Protection of human subjects

All procedures and methods for this study were approved by the UC Davis Institutional Review Board. Subjects gave their informed consent for participation.

Results and Discussion

Overall DA results

The DA panel selected 24 attributes to describe the whiskeys, comprising 18 flavor attributes, two taste attributes, and four mouthfeel attributes (see Table 2). In a three-way MANOVA, there were significant differences in the multivariate pattern of sensory attributes between products (Wilk's $\Lambda_{24,23,460} = 0.13$, $P < 0.0001$). Following this "omnibus" test, the 24 individual attributes were examined for significant differences using three-way, "pseudomixed" ANOVAs (Heymann et al., 2014)—utilizing mean-square error for *judge* × *product* and/or *rep* × *product* interactions in calculating *F*-ratios for significance when these interactions were significant. Note that the omnibus MANOVA test protects against experimentwise-error inflation (Rencher, 2002), and so a significance criterion of $\alpha = 0.05$ was retained. Following these pseudo-mixed univariate ANOVAs, 10 attributes were identified as varying significantly between products (see Table 2). Significant differences between product means were calculated by Fisher's LSD and are provided in Table 3. Overall, intensity ratings for all sensory attributes were relatively low; although panelists had no trouble discriminating among the whiskeys, no attribute had a mean rating of over 7 (out of 10) for any whiskey.

Because of the large number of results, visualization of the mean differences is most informative: when displayed in "radar plots." From these plots (see Figure 1 and 2) it is clear that there is significant distinction in the pattern of sensory attributes among the 24 products and that whiskeys take on a number of distinct sensory profiles. For example, Old Crow Bourbon presents high levels of peanut flavor and low levels of hot/alcohol mouthfeel and vanilla/oak flavor; Old Forester Bourbon has unusually high levels of floral/violet and banana flavor, as well as hot/alcohol mouthfeel and low levels of vanilla/oak; and Russell's Reserve Rye presents an unusual combination of floral/violet, oxidized/baked apple and vanilla/oak flavors, as well as strong hot/alcohol mouthfeel (see Figure 2). As a product set, however, these 24 whiskeys tended to be perceived as displaying high levels of wood-derived flavors (vanilla/oak, raw wood/cedar) and mouthfeels and tastes derived from the high-alcohol content of the distillates (hot/alcohol, bitter), and lower overall levels of fruit- and nut-related aromas and flavors (see Figure 1). These figures, derived from univariate analyses, do not show any indication of sensory differences originating from mashbill: Groups of rye and bourbon whiskeys do not appear to have any consistent sensory profile.

In order to visualize the multidimensional differences between whiskeys, Barycentric Discriminant Analysis (BADA) was used to

Table 3–Mean intensities for significant sensory attributes from descriptive analysis.

Whiskey	Vanilla/ oak	Raw wood/ cedar	Oxidized/ baked apple	Plum/ cherry	Banana	Peanut	Floral/ violet	Bitter	Astringent	Hot/ Alcohol
Four Roses Single Barrel Bourbon	4.63^{bcde}	4.11^{bcde}	$2.77^{abcdefg}$	1.98^{abcde}	3.02^{cdefg}	0.34^{fg}	3.86^{abcde}	4.32^{a}	2.06^{abc}	5.08^{ab}
Four Roses Yellow Bourbon	4.55^{bcde}	3.17^{fg}	2.67^{bcdefg}	1.58^{cdef}	2.43^{g}	1.03^{bcdef}	3.17^{defgh}	3.18^{fgh}	1.12^{fg}	3.16^{ijk}
Buffalo Trace Bourbon	4.37^{bcde}	3.42^{defg}	3.22^{abc}	2.53^{a}	3.42^{bcd}	0.54^{efg}	3.31^{cdefgh}	4.05^{abcd}	1.77^{bcde}	4.34^{cdef}
Basil Hayden's Bourbon	4.25^{cde}	4.23^{abc}	2.58^{bcdefg}	1.61^{cdef}	2.67^{efg}	1.59^{b}	2.76^{gh}	3.41^{defgh}	1.04^{g}	2.77^{k}
Blanton's Bourbon	5.03^{abc}	4.07^{bcde}	$2.92^{abcdefg}$	2.18^{abc}	2.70^{efg}	0.52^{efg}	3.37^{cdefgh}	3.78^{abcdef}	1.99^{abcd}	4.44^{abcdef}
Bulleit Rye	4.43^{bcde}	3.05^{fg}	$2.73^{abcdefg}$	1.69^{bcdef}	2.90^{cdefg}	0.25^{g}	4.12^{abc}	3.29^{efgh}	1.85^{abcde}	3.5^{ghij}
EH Taylor Bourbon	4.63^{bcde}	4.15^{bcd}	2.93^{abcdef}	2.08^{abcd}	2.61^{fg}	0.54^{efg}	4.05^{abcd}	4.08^{abcd}	1.89^{abcde}	5.15^{a}
Elijah Craig 12-year Bourbon	5.76^{a}	4.59^{ab}	$2.79^{abcdefg}$	1.46^{def}	3.00^{cdefg}	0.56^{efg}	3.09^{efgh}	4.18^{abc}	2.10^{abc}	4.68^{abcde}
Ezra Brooks Bourbon	5.01^{abcd}	3.77^{cdef}	2.61^{bcdefg}	1.59^{cdef}	2.60^{fg}	0.53^{efg}	3.80^{abcdef}	$3.61^{abcdefgh}$	2.39^{a}	4.49^{abcdef}
Jim Beam Black	4.13^{de}	4.62^{ab}	2.26^{fg}	1.24^{f}	2.37^{g}	1.26^{bcde}	2.86^{gh}	3.88^{abcdef}	1.44^{defg}	3.8^{fghi}
Jim Beam Rye	4.55^{bcde}	3.62^{cdefg}	2.23^{g}	1.55^{cdef}	2.77^{defg}	1.36^{bcd}	2.82^{gh}	3.50^{cdefgh}	1.76^{bcde}	3.32^{hijk}
Knob Creek Bourbon	4.68^{bcde}	3.5^{cdefg}	2.39^{efg}	1.36^{ef}	3.54^{bc}	1.02^{bcdef}	2.91^{fgh}	4.24^{abc}	2.11^{abc}	4.94^{abcd}
Knob Creek Rye	4.39^{bcde}	4.21^{abc}	2.38^{efg}	1.78^{bcdef}	2.56^{g}	1.07^{bcdef}	2.87^{gh}	4.30^{ab}	2.29^{ab}	5.05^{abc}
Michter's Rye	5.22^{ab}	4.90^{a}	$2.84^{abcdefg}$	1.66^{cdef}	2.77^{defg}	0.47^{fg}	3.15^{defgh}	3.93^{abcde}	1.72^{bcdef}	3.90^{fgh}
Maker's Mark Bourbon	4.41^{bcde}	3.97^{bcde}	3.12^{abcd}	2.08^{abcd}	3.01^{cdefg}	0.80^{cdefg}	4.11^{abc}	3.20^{efgh}	1.51^{cdefg}	4.15^{efg}
Old Crow Bourbon	3.93^{e}	3.07^{fg}	2.38^{efg}	1.68^{bcdef}	3.33^{bcde}	2.49^{a}	2.66^{gh}	3.03^{gh}	1.38^{efg}	3.05^{jk}
Old Forester Bourbon	4.15^{cde}	3.37^{efg}	3.28^{ab}	2.58^{a}	4.39^{a}	0.65^{defg}	4.14^{abc}	4.14^{abcd}	2.22^{ab}	4.65^{abcde}
Old Overholt Rye	3.79^{e}	3.02^{g}	2.66^{bcdefg}	1.44^{def}	2.92^{cdefg}	1.38^{bcd}	2.50^{h}	2.97^{gh}	1.55^{cdefg}	3.16^{ijk}
Rittenhouse Rye	4.41^{bcde}	3.65^{cdefg}	2.45^{defg}	2.18^{abc}	2.91^{cdefg}	1.02^{bcdef}	3.14^{defgh}	4.20^{abc}	1.76^{bcde}	4.97^{abcd}
Russell's Reserve Rye	4.54^{bcde}	3.15^{fg}	3.18^{abc}	2.06^{abcd}	2.69^{efg}	0.65^{defg}	4.18^{abc}	3.81^{abcdef}	1.79^{abcde}	4.30^{def}
Sazerac Rye	4.53^{bcde}	3.38^{efg}	3.10^{abcd}	2.33^{ab}	3.03^{cdefg}	0.35^{fg}	4.52^{a}	$3.71^{abcdefg}$	1.72^{bcdef}	4.01^{efgh}
Wild Turkey 101 Bourbon	4.19^{cde}	4.08^{bcde}	2.55^{cdefg}	1.98^{abcde}	2.82^{defg}	1.39^{bc}	3.55^{bcdefg}	3.86^{abcdef}	1.93^{abcde}	4.72^{abcde}
Woodford Reserve Bourbon	4.55^{bcde}	3.62^{cdefg}	3.41^{a}	2.45^{a}	3.83^{ab}	0.87^{bcdefg}	4.29^{ab}	$3.56^{bcdefgh}$	2.26^{ab}	4.38^{bcdef}
Woodford Reserve Rye	4.49^{bcde}	3.67^{cdefg}	3.00^{abcde}	2.08^{abcd}	3.25^{bcdef}	1.02^{bcdef}	2.61^{h}	2.91^{h}	1.59^{cdefg}	4.31^{def}

[a-h]For each attribute, means that are not labeled with the same superscript letter are significantly different by Fisher's LSD.

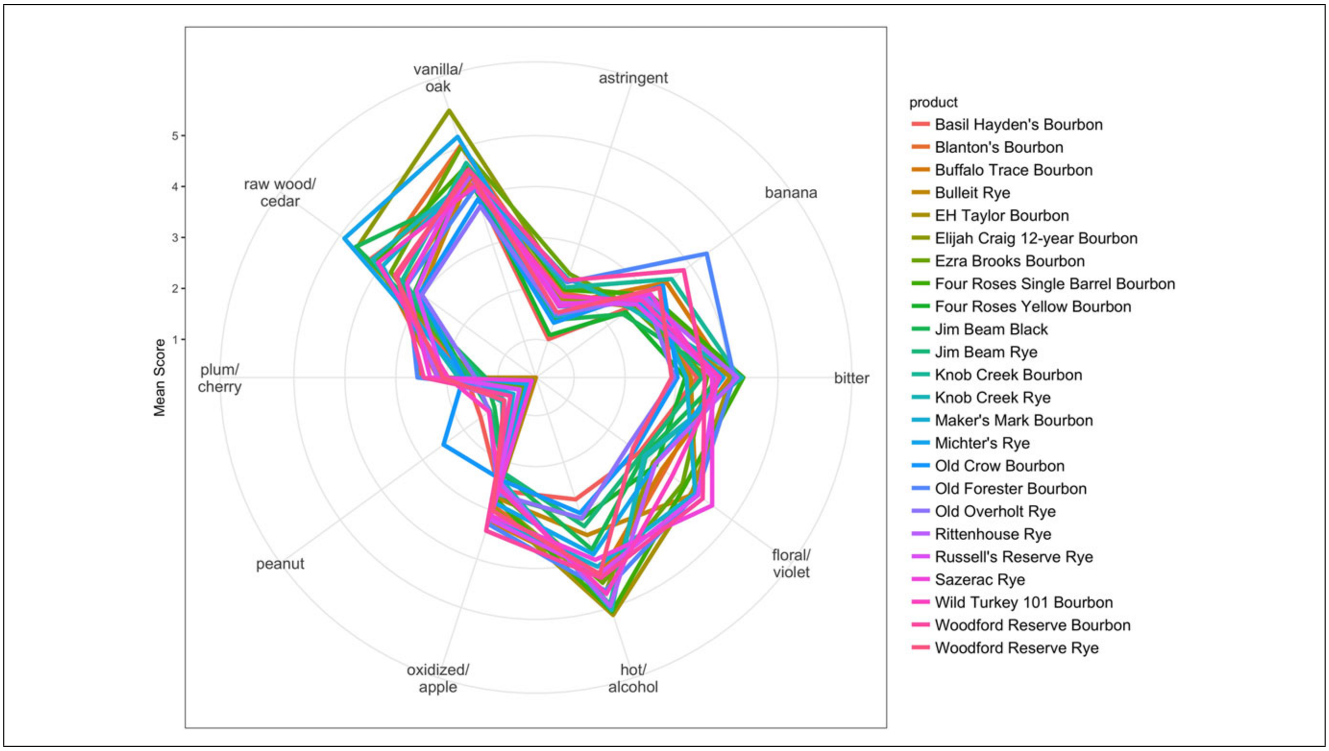

Figure 1–Radar plots for sensory attributes significantly differentiating the samples by 3-way ANOVA (values and LSD separation given in Table 3).

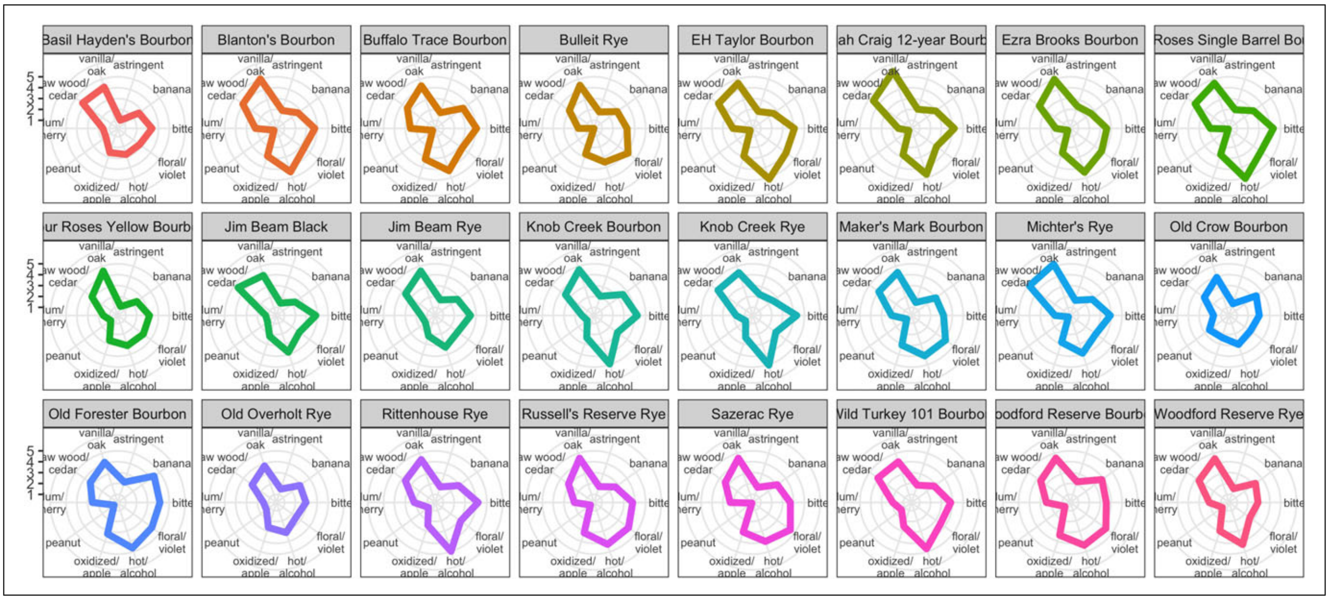

Figure 2–Individual radar plots for each whiskey showing sensory profile of attributes which significantly differentiate whiskeys by 3-way ANOVA (values provided in Table 3). The axes (sensory attributes) are the same as in Figure 1—differences in sensory profile can be compared between any two whiskeys by the shape of the plot.

find dimensions of maximum separation between the whiskeys, taking advantage of the individual subjects and replications. Thus, the BADA found the best dimensions to separate the 33 observations (11 judges and three replications) for each whiskey. Overall, the first four dimensions of the BADA solution explained 71% of the total variance among the whiskeys' sensory profiles ($\lambda_1 = 0.05$, $\lambda_2 = 0.03$, $\lambda_3 = 0.01$, $\lambda_4 = 0.01$; $\tau_1 = 34.6\%$, $\tau_2 = 19.2\%$, $\tau_3 = 10.7\%$, $\tau_4 = 6.66\%$). The first two dimensions of the results are visualized in Figure 3, with whiskeys colored and labeled according to their mashbill. The sensory-attribute loadings that drive the separation are visualized in the same space (Figure 4) and indicate what sensory differences drive the spatial arrangement of whiskeys. For example, the first dimension separates whiskeys, including Old Crow Bourbon, Old Overholt Rye, Basil Hayden's Bourbon, and Four Roses Yellow Bourbon—which are characterized by peanut, tree nut, hay, and earthy flavors—from whiskeys including Old Forester Bourbon, Four Roses Single Barrel Bourbon, Woodford Reserve Bourbon,

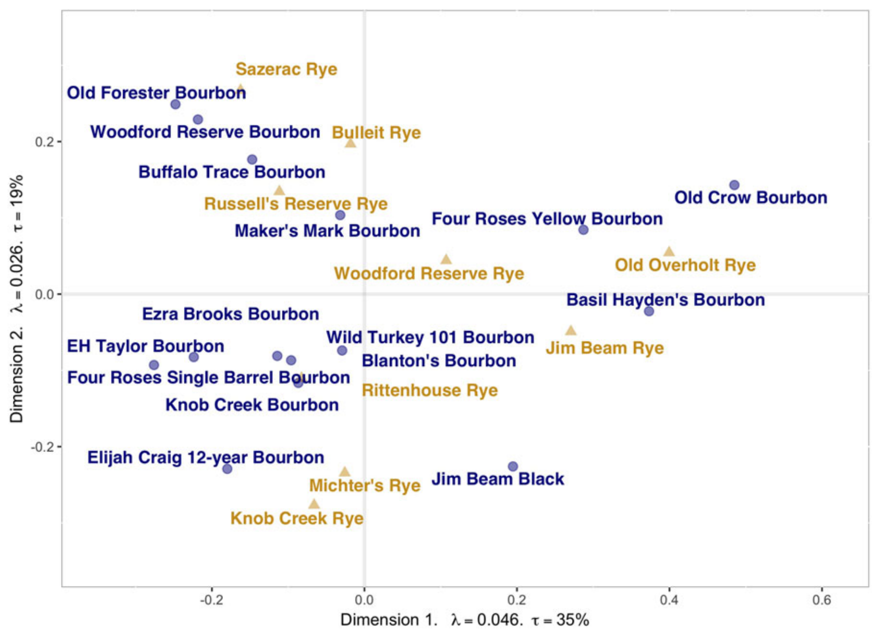

Figure 3–Score (or factor) plot for Barycentric Discriminant Analysis (BADA) of whiskey samples characterized by 24 sensory attributes. Bourbon whiskeys are colored blue with circular points, and rye whiskeys are yellow with triangular points.

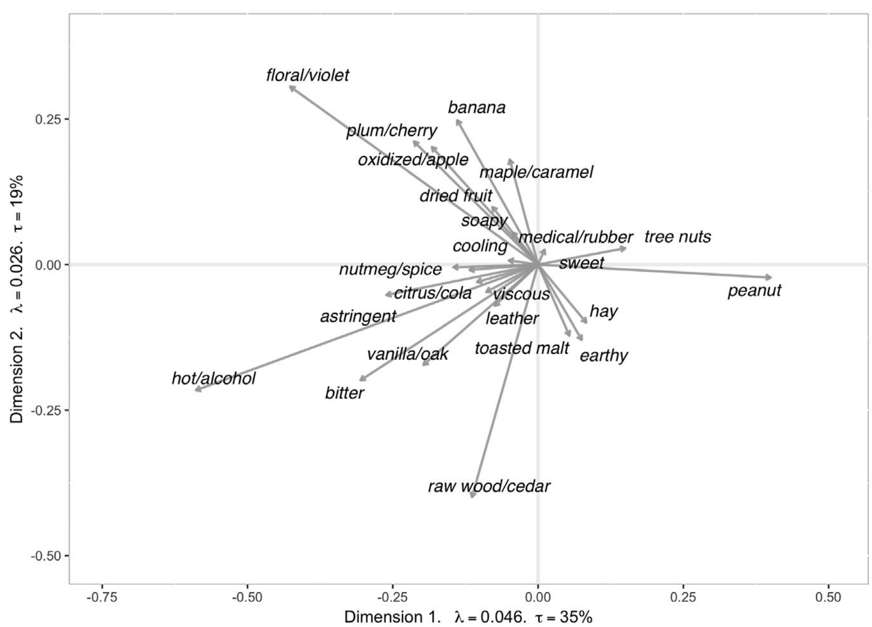

Figure 4–Loadings plot for BADA of whiskey samples, illustrating contribution of sensory attributes to Dimensions 1 and 2.

and EH Taylor Bourbon—which are characterized more strongly by floral/violet flavors, bitter tastes, and hot/alcohol mouthfeel. The second dimension separates whiskeys including Old Forester Bourbon, Sazerac Rye, and Woodford Reserve Bourbon—which are characterized by floral/violet, banana, plum/cherry, and oxidized/baked apple flavors—from whiskeys including Knob Creek Rye, Michter's Rye, Jim Beam Black Bourbon, and Elijah Craig 12-Year Bourbon—which are characterized more strongly by raw wood/cedar, vanilla/oak, toasted malt, and earthy flavors, as well as bitter taste and hot/alcohol mouthfeel. In this sensory map, as well as in the third and fourth dimensions (not shown), there is no dimension or combination of dimensions that appears to separate whiskeys with different mashbills: rye and bourbon whiskeys do not appear to be separable on the basis of multimensional, sensory profile.

Comparison of sensory results for bourbon and rye whiskeys

If the flavor of whiskeys is determined by mashbill, then the overall multivariate configuration of sensory attributes for rye should be different from whiskeys. A three-way MANOVA (*mashbill* × *judge* × *replication*) for the results of the DA did not show any significant main effects or interactions for the dichotomous "mashbill" variable (Wilk's $\Lambda_{24,1,746} = 0.96$, *NS*). At least initially, there is no reason to think that mashbill has an effect on the sensory attributes identified in this analysis. A Barycentric Discriminant Analysis attempting to classify whiskeys confirms the results of the MANOVA (this follows, as they operate on the same underlying data structure): Results (visualized in Figure 5) show that no whiskey is consistently classified accurately on the basis of its sensory profile (individual profiles are visualized in Figure 2).

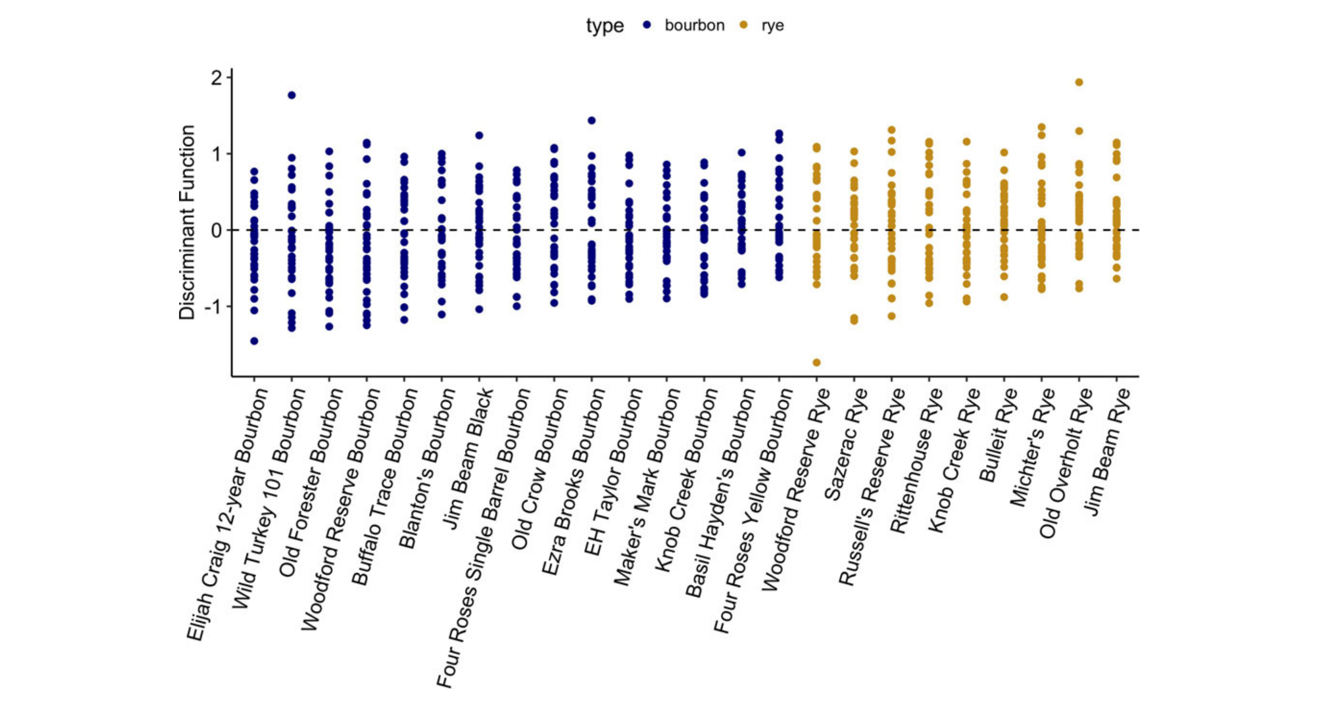

Figure 5–Classification by BADA of whiskey samples, based on sensory attributes, as "rye whiskey" or "bourbon whiskey"—no significant classification is possible.

A hierarchical cluster analysis (HCA) using Ward's criterion and based on dissimilarities between mean attribute ratings for each whiskey (the data provided in Table 3 and visualized in Figure 1 and 2) shows that, in fact, there is no grouping of whiskeys by mashbill. In the two major groups of whiskeys found there are both rye and bourbon whiskeys; even at lower levels of the dendrogram there are no consistent groupings of bourbon and rye whiskeys (see Figure 6). In fact, it appears that one of the two major clusters mostly contains whiskeys from a single producer, Beam/Suntory: it includes all of the whiskeys produced at the Clermont distillery with the exception of the Knob Creek line (see Table 1)—which is marketed as separate from other Beam products (Bryson, 2014)—as well as a bourbon from Four Roses/Kirin and a rye from Brown-Forman. This sensory similarity is probably due to the relatively high levels of "peanut" flavor found in these products, which can be directly seen in the BADA diagrams (and which is notably absent from the Knob Creek whiskeys, see Figure 2).

Other predictors of sensory variability in whiskeys

If mashbill does not predict sensory profile in American whiskeys, the HCA above implies that perhaps a "house" effect from producer might. In a 3-way MANOVA (*producer* × *judge* × *replication*), there was a significant effect of producer (listed in Column 2 of Table 1) on the overall sensory profile of whiskeys (Wilk's $\Lambda_{24,9,642} = 0.52$, $P < 0.0001$). This effect can be visualized by barycentric projection of mean producer profile into the space defined by the BADA of the whiskeys (cf. Abdi, Williams, & Béra, 2018). As is clear in Figure 7, separation of whiskeys from Beam's Kentucky Spring distillery from the rest of the products drives the first dimension, whereas the second dimension is driven by the separation of several strongly differentiated individual products, like those from Brown-Forman (especially Old Forester bourbon) from those from Heaven Hill's distillery (bottled by several companies in this study).

A major, known contributor to a whiskey's sensory profile is the age at bottling (i.e., time spent in barrel). While the standards of identity for American whiskey do not require exact age labeling ("Title 27: Alcohol, Tobacco, and Firearms. Part 5: Standards of Identity for Distilled Spirits," 1969), it is possible to ascertain approximate *minimum* age for each whiskey in this study from their technical label ("straight" or "bonded") and producer declarations on bottle or in other marketing material (see Table 1). Since this is an approximate measure of age it is best treated as a categorical variable, and in order to avoid low-cell counts, whiskey ages were categorized as "low age" (≤ 3 years), "medium age" ($3 < \text{age} < 8$) and "high age" (≥ 8 years). Based on this new variable, a three-way MANOVA (*age* × *judge* × *rep*) showed that there was a significant effect of age category on the overall multivariate sensory profile of whiskeys (Wilk's $\Lambda_{24,2,733} = 0.87$, $P < 0.0001$). Therefore, the age of a whiskey appears to significantly predict the overall sensory profile of the whiskey. In particular, wood-associated flavors like vanilla/oak and raw wood/cedar, as well as hot/alcohol mouthfeel and bitterness are higher in whiskeys in the "high" age category, and more floral and fruit-related flavors are associated with "medium" and "low" age whiskeys (see Figure 4 and 8).

American whiskeys cannot be discriminated by mashbill

American whiskeys have diverse flavor profiles and characteristics: In a rigorous sensory DA, a trained panel of judges was able to significantly differentiate 24 different whiskeys (9 ryes and 15 bourbons). This result supports the popular belief that flavor complexities exist in American whiskeys, and that the culture of connoisseurship that exists around these products is based in empirical difference.

But our results also contradict the common belief that mashbill is the primary predictor of the sensory characteristics of an American whiskey—and, in particular, the putative contrast

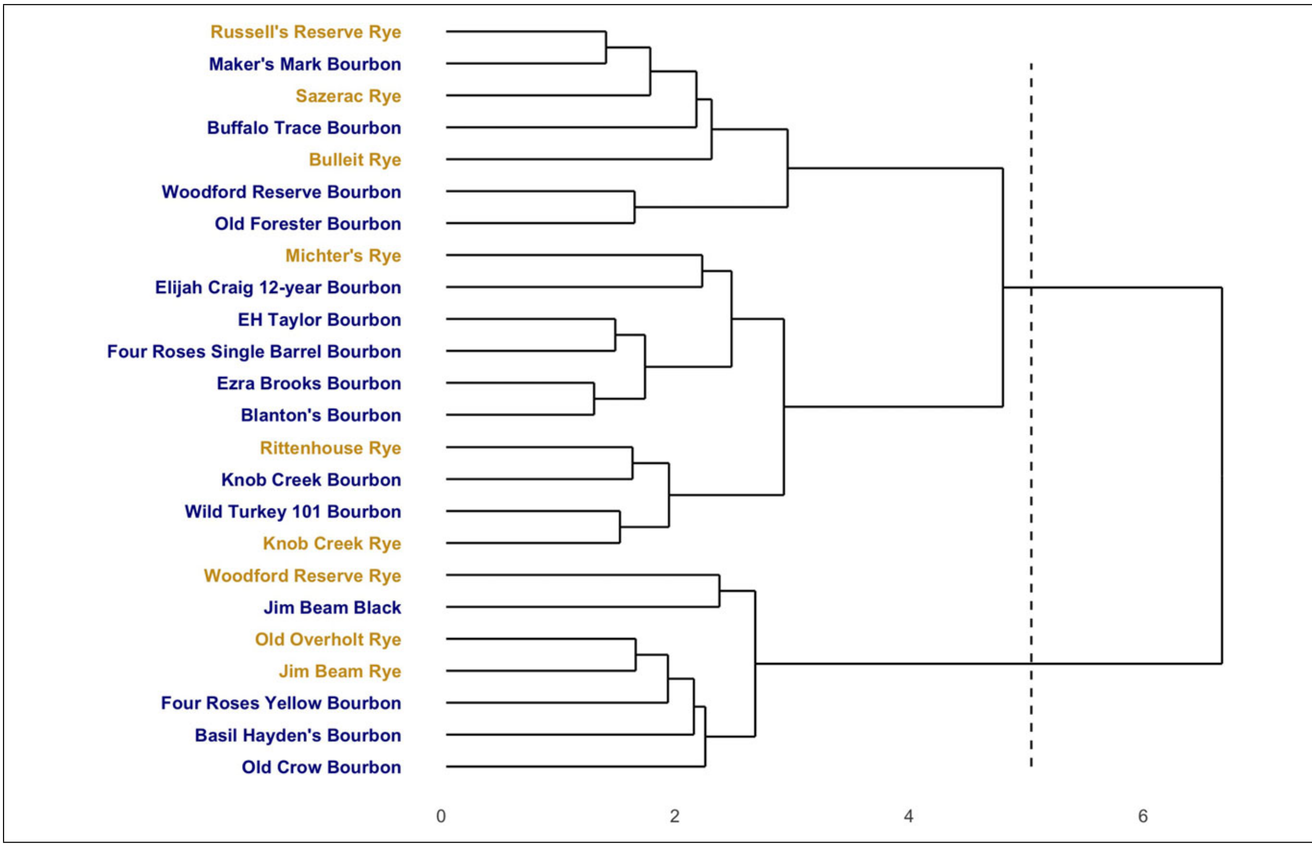

Figure 6–Hierarchical Cluster Analysis (HCA) of whiskey samples based on dissimilarities between mean sensory-attribute scores. Whiskeys are colored as in Figure 3 (bourbon is blue, rye is yellow).

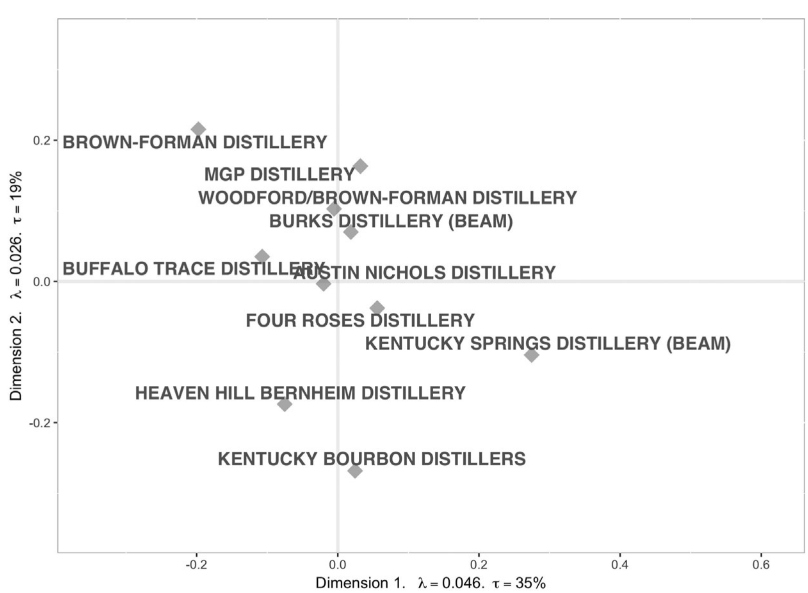

Figure 7–Mean producer scores projected into the BADA space formed by whiskey samples and sensory attributes. Producer significantly predicts sensory attributes.

between rye and corn when used as the bulk of the fermented grain (mashbill). As is apparent from both individual whiskey profiles (Figure 2) and from compromise visualizations of the space defined by all the whiskeys in this study (Figure 3 and 5), mashbill does not predict sensory differences in whiskey. Although there is a legal distinction between rye and bourbon ("Title 27: Alcohol, Tobacco, and Firearms. Part 5: Standards of Identity for Distilled Spirits," 1969), in this study judges perceived some of the rye and bourbon whiskeys to be extremely similar, while there was large intra-category variation. For example, Old Overholt Rye, Four Roses Yellow Label Bourbon, Jim Beam Rye, and Basil Hayden's Bourbon were extremely similar (Figure 2 and 3)—this is especially interesting not only because of the mashbills, but because of the (often large) price differences among these products. On the

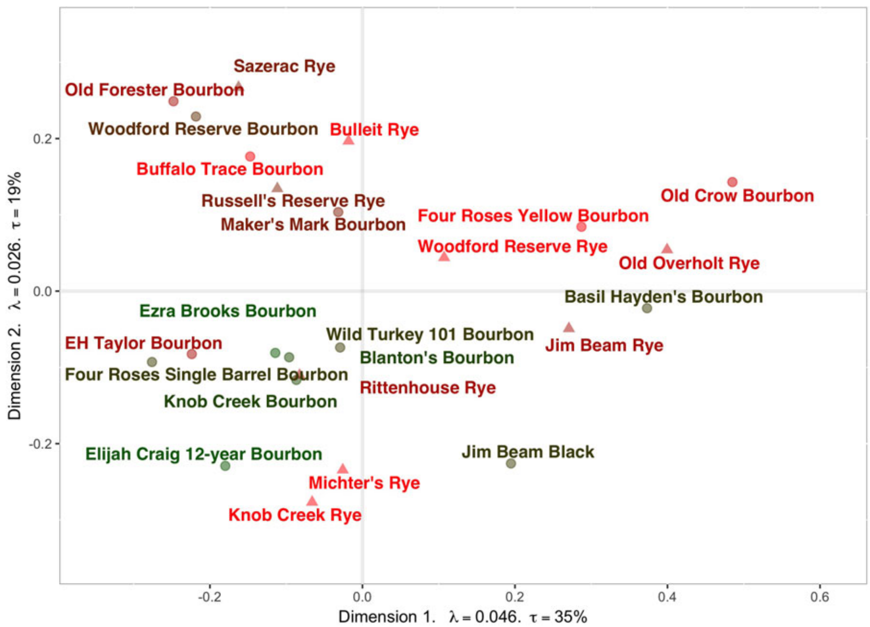

Figure 8–Whiskey score plot from BADA colored according to age (Table 1). Younger whiskeys are more red, older whiskeys are more green.

other end of the spectrum, some bourbons and some ryes were perceived as extremely different: for example, Sazerac Rye and Knob Creek Rye, or Old Forester Bourbon and Jim Beam Black Bourbon (see Figure 2 and 3). This diversity of within-category sensory profiles casts doubt on claims of the intrinsic sensory difference between American bourbon and rye whiskeys (Asimov, 2006a; Bryson, 2014; Jackson, 2017; "Methodology – Bourbon Classification," 2018). No specific sensory attribute was predicted by mashbill.

While the current research did not include alternative hypotheses for the origins of sensory differences in American whiskey, the product set allowed for some rough exploratory analysis. Significant differences in sensory profiles between whiskeys from different producers were found; this effect was quite strong and existed across mashbills (see Figure 7). The exact origin of this effect is unknown: it is possible that different producers use different yeast strains for fermentation, different barrel sources for aging, or just have different preferred "house profiles" that master blenders seek to achieve which are evident to trained tasters (Bryson, 2014). Less surprisingly, age seemed to predict the sensory profile of whiskeys across mashbills (see Figure 8), with age correlating strongly with vanilla/oak ($r = 0.46$), raw wood/cedar ($r = 0.37$), and cooling mouthfeel ($r = 0.42$). These results follow those found in Scotch whiskies by Lee et al. (2001a).

Generalizability of DA results

The sample set of whiskeys in the current study is a superset of those in a consumer sorting study by Lahne et al. (2016). In that study, similar results were found: the five rye and five bourbon whiskeys were not sorted by mashbill, but instead clustered by producer, age, and proof. The overall multidimensional configuration found among the 10 whiskeys can be compared by projecting the sorting configuration from Lahne et al. (2016) into the BADA space defined in the current research. The similarity between the two spatial configurations is much higher than would be expected by chance ($R_v = .79$, $P < 0.001$; Abdi et al., 2013). The R_v coefficient is a multivariate equivalent to the squared-correlation coefficient—ranging between 0 and 1, with higher values indicating a more similar multidimensional configuration between matrices with the same number of rows. This result indicates that the multidimensional configuration of these 10 whiskeys, from two different studies, is very similar. Such a similarity is particularly notable because the Lahne et al. (2016) study used untrained consumers who simply sorted the whiskeys based on similarity, whereas the current study extensively trained judges (see Section 2.3) to describe whiskeys on 24 different sensory "dimensions." Despite this, the 10 whiskeys are ultimately arranged in relation to each other in very similar ways between independent groups of subjects, indicating that the results from this study are likely to be robust and generalizable. Importantly, neither group of subjects found any basis to group whiskeys based on mashbill.

Limitations and future research

A minor limitation of this study is that the panel agreed that several attributes were important during lexicon development—for example, "medicinal," "dried fruit," "earthy," and "leather" (Table 2)—but these attributes did not discriminate samples in testing. Future research could including more extensive panel training (>10 hr), which may result in better discrimination between products on all attributes, and allow for finer resolution.

This study's major limitation is found in the legal standard of identity for "straight" American bourbon and rye whiskeys ("Title 27: Alcohol, Tobacco, and Firearms. Part 5: Standards of Identity for Distilled Spirits," 1969). Whiskey producers, as noted in the introduction, must only declare the whiskey's identity based on the majority of the mashbill: an American whiskey can be made with a mashbill of 51% rye or 95% rye, and still be labeled as "rye whiskey" without further comment. Furthermore, straight whiskeys of the same type and made in the same state can legally be blended and still bottled under the same identity, so two distillates with different mashbills but which are both legally bourbon can be blended prior to bottling, further obscuring the direct effect of mashbill. Finally, the same statements apply to the age-in-barrel of the whiskeys, with the caveat that the declared age is that of the youngest whiskey in the ultimate blend. Therefore, an 8-year whiskey might well contain some distillate that has been aged for 12 years in barrel, and a 2-year whiskey can contain some 24-year-old flavoring whiskey; this is apparently common practice in distillers with established rickhouses (Bryson, 2014), and helps to explain why "microdistillers" often have whiskeys that are so noticeably different from whiskeys of the same age but produced by long-established companies (Collins et al., 2014).

Thus, the most that we know about the sample set in this study is that the rye whiskeys are 51% rye, and the bourbon whiskeys are 51% corn. For future research, working with a licensed distiller to control mashbill—as well as control the aging conditions for the whiskey—would allow for precise quantification of the effect of mashbill on the sensory profile of American whiskeys.

Conclusions

This study disconfirms the widely held belief that American bourbon and rye whiskeys have distinct sensory properties stemming from their respective mashbills. In general, producers, whiskey experts, and connoisseurs believe that bourbon whiskeys—distilled from a mashbill of at least 51% corn—are sweet, smooth, and rich, whereas rye whiskeys—distilled from at least 51% rye—are spicy, harsh, and herbal. The results of a DA with 11 trained panelists and 24 American whiskeys (15 bourbons, nine ryes) does not support these beliefs: while individual whiskeys had significantly different sensory profiles, no overall profile could be found for bourbon or rye whiskeys, and no single sensory attribute was associated with either type of whiskey. However, significant differences could be attributed to the *producer* of the whiskey and to the age of the whiskey at bottling. These results are important because they contradict a widely held but unsubstantiated belief about the origin of flavor in whiskeys, while pointing towards several potential sources of flavor that should be further researched.

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Author Contributions

JL conceptualized, designed, and executed the study, analyzed the data, and drafted the manuscript. HA provided statistical and programming expertise and support, as well as editing the manuscript. TSC contributed to study design and reviewed and edited the manuscript. HGH designed the study, oversaw the data collection, drafted the study conclusions, and edited the manuscript as a whole.

References

Abdi, H., Williams, L., & Béra, M. (2018). Barycentric discriminant analysis (BADA). In R. Alhajj & J. Rokne (Eds.), *Encyclopedia of social networks and mining* (2nd ed.). New York: Springer Verlag.

Abdi, H., Williams, L. J., & Valentin, D. (2013). Multiple factor analysis: Principal component analysis for multitable and multiblock data sets. *Wiley Interdisciplinary Reviews: Computational Statistics*, *5*(2), 149–179. https://doi.org/10.1002/wics.1246

Asimov, E. (2006a). All But Lost, Rye Is Revived as the Next Boutique Find. *The New York Times*.

Asimov, E. (2006b). All but lost, rye is revived as the next boutique find. *The New York Times*.

Bryson, L. (2014). *Tasting whiskey*. North Adams, MA: Storey Publishing.

Chambers, D. H., Allison, A. M. A., & Chambers, E. (2004). Training effects on performance of descriptive panelists. *Journal of Sensory Studies*, *19*(6), 486–499.

Collins, T. S., Zweigenbaum, J., & Ebeler, S. E. (2014). Profiling of nonvolatiles in whiskeys using ultra high pressure liquid chromatography quadrupole time-of-flight mass spectrometry (UHPLC–QTOF MS). *Food Chemistry*, *163*, 186–196.

DISCUS. (2017a). *On America's Whiskey Trail*. Retrieved from https://www.distilledspirits.org/products/bourbon-tennessee-whiskey/

DISCUS. (2017b). *Rye Whiskey - The Return of an American Classic*. Retrieved from https://www.distilledspirits.org/products/rye-whiskey/

Heymann, H., King, E. S., & Hopfer, H. (2014). Classical descriptive analysis. In P. Varela & G. Ares (Eds.), *Novel techniques in sensory characterization and consumer profiling* (pp. 9–40). Boca Raton: CRC Press.

Ickes, C. M., & Cadwallader, K. R. (2017). Effects of ethanol on flavor perception in alcoholic beverages. *Chemosensory Perception*, *10*(4), 119–134.

Ickes, C. M., & Cadwallader, K. R. (2018). Effect of ethanol on flavor perception of rum. *Food Science & Nutrition*, *6*(4), 912–924.

Jack, F. (2003). Development of guidelines for the preparation and handling of sensory samples in the scotch whisky industry. *Journal of the Institute of Brewing*, *109*(2), 114–119. https://doi.org/10.1002/j.2050-0416.2003.tb00139.x

Jackson, M. (2017). *Whisky: The definitive world guide*. New York: Dorling Kindersley Ltd.

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

Kahn, J., Shipley, P., LaRoe, E., & Conner, H. (1969). Whiskey composition: identification of additional components by gas chromatography-mass spectrometry. *Journal of Food Science*, *34*(6), 587–591.

Lahne, J. (2010). *Aroma characterization of American rye whiskey by chemical and sensory assays*. (Master of Science Thesis), Urbana, IL: University of Illinois Urbana-Champaign.

Lahne, J., Collins, T. S., & Heymann, H. (2016). Replication improves sorting-task results analyzed by DISTATIS in a consumer study of American bourbon and rye whiskeys. *Journal of Food Science*, *81*(5), S1263–S1271. https://doi.org/10.1111/1750-3841.13301

Lawless, H. T., & Heymann, H. (2010). *Sensory evaluation of food: Principles and practices* (2nd ed.). New York: Springer.

Lee, K. Y. M., Paterson, A., Piggott, J. R., & Richardson, G. D. (2001a). Origins of flavour in whiskies and a revised flavour wheel: A review. *Journal of the Institute of Brewing*, *107*(5), 287–313.

Lee, K. Y. M., Paterson, A., Piggott, J. R., & Richardson, G. D. (2001b). Sensory discrimination of blended Scotch whiskies of different product categories. *Food Quality and Preference*, *12*(2), 109–117. https://doi.org/10.1016/S0950-3293(00)00037-9

Liebmann, A., & Scherl, B. (1949). Changes in whisky while maturing. *Industrial & Engineering Chemistry*, *41*(3), 534–543.

Methodology – Bourbon Classification. (2018). Retrieved from http://whiskyanalysis.com/index.php/methodology-introduction/methodology-bourbon-classification/

Peltier, C., Visalli, M., & Schlich, P. (2015). Canonical variate analysis of sensory profiling data. *Journal of Sensory Studies*, *30*(2015), 316–328.

Piggott, J. R., & Jardine, S. R. (1979). Descriptive sensory analysis of whiskey flavor. *Journal of the Institute of Brewing*, *85*, 82–85.

Piggott, J. R., Sheen, M. R., & Apostolidou, S. G. (1990). Consumers' perceptions of whiskies and other alcoholic beverages. *Food Quality and Preference*, *2*(3), 177–185. https://doi.org/10.1016/0950-3293(90)90022-M

Poisson, L., & Schieberle, P. (2008a). Characterization of the key aroma compounds in an American bourbon whisky by quantitative measurements, aroma recombination, and omission studies. *Journal of Agricultural and Food Chemistry*, *56*(14), 5820–5826. https://doi.org/10.1021/jf800383v

Poisson, L., & Schieberle, P. (2008b). Characterization of the most odor-active compounds in an American bourbon whisky by application of the aroma extract dilution analysis. *Journal of Agricultural and Food Chemistry*, *56*(14), 5813–5819. https://doi.org/10.1021/jf800382m

Rencher, A. C. (2002). *Methods of multivariate analysis* (2nd ed.). New York: John Wiley & Sons.

Rossini, K., Verdun, S., Cariou, V., Qannari, E. M., & Fogliatto, F. S. (2012). PLS discriminant analysis applied to conventional sensory profiling data. *Food Quality and Preference*, *23*(1)18–24. https://doi.org/10.1016/j.foodqual.2011.01.005

Schoeneman, R. L., Dyer, R. H., & Earl, E. M. (1971). Analytical profile of straight bourbon whiskies. *Ass Offic Anal Chem J*, *54*(6)1247–1261.

Title 27: Alcohol, Tobacco, and Firearms. Part 5: Standards of Identity for Distilled Spirits. 1969 27 CFR §5.22.