Origins of Flavour in Whiskies and a Revised Flavour Wheel: a Review

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The nature and origins of flavour in whiskies are reviewed with the aim of developing a revised and simplified flavour wheel for training of sensory assessors. Scotch whiskies are perceived as having distinctive characters, generally recognised in pattern recognition (perception, macroscopic brain processing), rather than being subjected to a deconstruction process of evaluating attributes (sensation, microscopic brain processing). Although consumers use simple recognition judgements on whisky flavour in categorical assimilation, industry has a requirement for monitoring spirit quality that necessitates a more reductionist approach. Whisky flavour wheels identify attributes, specific components of flavour character, which can be demonstrated to sensory assessors using reference standards. The advent of cyclodextrin bound reference standards has enabled communication of information on flavour character in training of assessors, as exploited in the brewing industry. A revised flavour wheel, with characters illustrated by reference standards, is proposed to assist sensory training on attributes of whisky flavour character.

Key Words: Whisky flavour character, whisky flavour reference standards, flavour perception and sensation, sensory assessor training, quality evaluation.

INTRODUCTION

Improved congener analyses have not yielded greater understanding of whisky flavour51; a dynamic interaction209 between individuals and flavour components268. Perceptions of flavour notes or attributes can be expressed as language291,233 but are more commonly used in Gestalt155,91,107,161,210,249 or holistic pattern recognitions in human brains221, perception of whole over parts (macroscopic brain processing) (Fig. 1)107,242. In contrast, in industrial sensory assessments, quantified sensations are integrated from specific groups of olfactory receptors (microscopic processing). Assessors can also agree on character while differing in quantities of mouth-space volatile flavour components135.

In consumers, causality interactions (slaving effects) exist between perceptual and sensation levels, dictated by cues117 (Fig. 1): the human mind influences the brain242.

Appreciation of whisky character is a synergistic and holistic perceptual process with extrinsic attributes (branding, labelling, marketing and packaging) important in choice decisions (Fig. 1). A drink is more than the sum of its component perceptions. Sensory assessors generate data relevant to consumer judgements, but utilise different forms of mental processing.

On tasting unlabelled whisky, consumers match perceptions against prior experience, using intrinsic attribute patterns. On a mismatch, individuals move to evaluating small numbers of intrinsic attributes, clusters of individual assessments, with sequential creation of further mental images242. Such processing is modelled in sequential assessor evaluations of attributes in appearance, aroma, taste, mouthfeel and after-taste.

Psychophysics suggests humans have physiological limitations in perceptual ability23 and can identify no more than three or four flavours notes in mixtures119,120,122. Only this number are held in short-term memory, more
INTRINSIC ATTRIBUTES

- Appearance
- Aroma
- Taste
- Mouthfeel
- Aftertaste

EXTRINSIC ATTRIBUTES

- Expectation
- Experience
- Brand Image
- Packaging
- Marketing
- Price

Sensation
Microscopic level

Perception
Macroscopic level

FIG. 1. Intrinsic and extrinsic attributes.

in long-term memory\(^{225}\). Spatial response patterns of flavour component mixtures may thus not be summations of individual flavour notes\(^{123}\).

The beer flavour wheels\(^{125,157}\) concentrate assessor attention to specific flavour attributes, including mouthfeel attributes, important in beer. Studies of wood-matured ports\(^{52}\) and whisky\(^{202}\) suggest expert and novice assessors judge flavour character from visual data (slaving effect), a feature common in humans. Manipulating appearance changes perceptions of product character - aroma, taste and flavour\(^{89,126,187,188}\). Processes of odour recognition involve primary visual cortex (BA17) activity, involving comestibility (suitability for drinking) of products\(^{224}\).

Flavour wheel presentations of whisky attributes serve useful functions in directing attention towards specific features of character, forming bases for discussions through definition of vocabularies. Specific reference standards facilitate conceptualisations (knowing an attribute) and development of parallel mental representations of concepts, important in assessor training (ISO 8586-1:1993, 8586-2:1994). Visual representation or symbols could aid recognition or memory\(^{224}\) and assessor training.

WHISKY MATURATION

Ageing new distillates in oak yields mature whisky. This process, central to whisky character development, gives consumer appeal. Maturing can be considered replacement of pungent, soapy, sour and harsh notes in new distillates with smooth, matured and mellowness attributes. Such judgements also employ pattern recognition\(^{224}\) with collections of stimuli from sensory systems (visual, olfactory, gustatory and chemesthesia), integrating in specific brain regions to form macroscopic representations\(^{232}\) of whiskies (Fig. 1).

Research on model and malt whiskies\(^{46-48,51}\) suggests wood maturations change partitioning of key flavour components with less desirable flavour notes\(^{49,50}\), increasing retention in liquid phases, recently simulated\(^{148}\).

Fatty acid ethyl esters, amphiphiles with central polar groups and peripheral hydrophobic aliphatic carbon chains, are important in stabilising whisky headspace compositions\(^{208}\). Structure influences solubility in aqueous ethanol: excess esters form agglomerates\(^{253}\), yielding microemulsions. At 23% (abv), agglomerate diameters increase\(^{190}\) forming hazes\(^{90,195}\). Chill filtration, prior to bottling, removes excess agglomerates - changing congener composition but not sensory quality\(^{208}\). Agglomerates are dominated by ethyl dodecanoate (laurate, C12), tetradecanoate (myristate, C14) and hexadecanoate (palmitate, C16), contributions determined by aliphatic chain length\(^{46,48}\). Other congeners - alcohols, aldehydes and acids - also contribute to agglomerates\(^{49}\), influencing sensory character.

In wood maturations, non-volatile components, including sterols and tannic acids, stabilise ester agglomerates\(^{46,190}\). Temperature influences both agglomerate behaviour and distribution of flavour-active congeners between solution and headspace phases\(^{50}\). At oral temperatures, agglomerates suppress volatile congeners more efficiently\(^{50}\), but differences between nosing and tasting are thought generally small\(^{202}\). In summary, in agglomerate formation congener activity coefficients are increased by extracted wood components.

Alcohol strength influences congener distribution\(^{45}\) and spirit matrix structures. Below 20% abv, ethanol
molecules are mono-dispersed in water; between 20 and 57% abv, ethanol molecules progressive aggregate to reduce alkyl chain hydrophobic hydration and above 57% abv, solutions are ethanolic with loss of water hydrogen-bonded networks. Increasing ethanol concentration lowers interfacial tension between aqueous phases and ethyl esters, increasing aroma thresholds\textsuperscript{45}. Reducing bottling strength (40% to 30–35% abv) increases headspace partition coefficients, decreasing aroma thresholds influencing longer-chain soap-like esters. Bottling strength thus influences perceived spirit quality\textsuperscript{45}. Dilution of a whisky to 23% abv maximises volatile release from distillates, optimising sensory assessment.

WHISKY PRODUCTION

Malt, grain and blended Scotch whiskies differ in production process (Fig. 2). In malt whiskies (4% market sale by volume – UK Food & Drinks Report, 1999) parameters in batch (pot) distillations of washes from barley malts influence final character\textsuperscript{182,173,273}. Grain whisky is a product of continuous fractional distillation\textsuperscript{186} of fermented wheat and maize\textsuperscript{169}, saccharified by lightly-kilned barley malts\textsuperscript{200}. Dominant (90% market) are blends of grain (60–80%) and malt (20–40%) whiskies with lighter grain (2–3) providing a flavour background, and single malts (up to 40) the majority of character. Selection of primary (top-dressing) and secondary malts has significant impacts\textsuperscript{169}. Maturations influence final flavour in blends or single whiskies with cask management ensuring product consistency\textsuperscript{31,151,165}.

A REVISED WHISKY FLAVOUR WHEEL FOR SENSORY ANALYSIS

The flavour wheel of Shortreed and coworkers\textsuperscript{233} ordered attributes in classifications based on production.
FIG. 3. Revised Scotch whisky flavour wheel for industrial purposes.
### TABLE I. Whisky descriptors and reference compounds.

<table>
<thead>
<tr>
<th>Code</th>
<th>Flavour Wheel term</th>
<th>Reference compounds for assessor training</th>
<th>Concentration (mg litre⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N.1</td>
<td><em>Pungent</em></td>
<td>Formic acid¹⁹⁰</td>
<td>10 x 10⁻¹</td>
</tr>
<tr>
<td>A.1, 2</td>
<td><em>Burnt smoky</em></td>
<td>Guaiacol¹²⁹</td>
<td>27</td>
</tr>
<tr>
<td>A.3</td>
<td><em>Medicinal</em></td>
<td>α-Cresol¹³¹</td>
<td>1.75</td>
</tr>
<tr>
<td>B.2</td>
<td><em>Malty</em></td>
<td>Malted barley¹⁹⁷</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2- and 3-Methyl butanal¹³⁵,¹³⁶,¹³⁷¹³⁸,¹³⁹⁴,¹⁴⁰⁴</td>
<td>0.6 (2-methyl butanal)¹⁴⁵</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4-Hydroxy-2-(or 5)-ethyl-2-(or 5)-methyl-3(2H) furanone¹⁴¹,¹⁴²</td>
<td>1.25 (3-methyl furanone)¹⁴³</td>
</tr>
<tr>
<td>C.1</td>
<td><em>Grassy</em></td>
<td>Hexanal¹²⁹</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cis-3-Hexene-1-ol¹⁹⁰</td>
<td>1.00 x 10⁻¹</td>
</tr>
<tr>
<td>D.1</td>
<td><em>Solventy</em></td>
<td>Ethyl acetate¹³⁰</td>
<td>1.12 x 10⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-Methyl propan-1-ol¹⁹⁰</td>
<td>1.00 x 10⁻¹</td>
</tr>
<tr>
<td>D.2</td>
<td><em>Fruity (appley)</em></td>
<td>Ethyl hexanoate¹²⁹</td>
<td>2</td>
</tr>
<tr>
<td>D.3</td>
<td><em>Fruity (banana, pear-drop)</em></td>
<td>isoAmyl acetate¹²⁹</td>
<td>7</td>
</tr>
<tr>
<td>D.5</td>
<td><em>Berry</em></td>
<td>Thiomenthone¹³⁰</td>
<td>3 x 10⁻¹</td>
</tr>
<tr>
<td></td>
<td><em>Catty</em></td>
<td>Thiomenthone¹³⁰</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sodium sulfide·mesityl oxide¹⁹⁰</td>
<td>100 each</td>
</tr>
<tr>
<td>E.1</td>
<td><em>Floral (Natural - rose) - violet</em></td>
<td>Phenyl ethanol¹²⁹</td>
<td>1.52 x 10⁻³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>α-, β-Ionone¹⁹ⁱ</td>
<td>&gt;3 x 10⁻³</td>
</tr>
<tr>
<td></td>
<td><em>Floral (Artificial - scented, perfumed)</em></td>
<td>Geraniol¹²⁹</td>
<td>19</td>
</tr>
<tr>
<td>G.5</td>
<td><em>Nutty (coconut)</em></td>
<td>Whisky lactone¹²⁹</td>
<td>266</td>
</tr>
<tr>
<td></td>
<td><em>marzipan</em></td>
<td>Furufural¹²⁹</td>
<td>839</td>
</tr>
<tr>
<td>G.6</td>
<td><em>Vanilla</em></td>
<td>Vanillin¹²⁹</td>
<td>43</td>
</tr>
<tr>
<td>G.7</td>
<td><em>Spicy</em></td>
<td>4-Vinyl guaiacol¹²⁹</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td><em>Spicy (clove)</em></td>
<td>Eugenol¹²⁹,¹⁹⁹</td>
<td>1 - 55</td>
</tr>
<tr>
<td>G.8</td>
<td><em>Caramel (candy floss)</em></td>
<td>Maltol¹²⁹</td>
<td>1.14 x 10⁻³</td>
</tr>
<tr>
<td>G.10</td>
<td><em>Mothball</em></td>
<td>Naphthalene</td>
<td>&gt;8 x 10⁻³</td>
</tr>
</tbody>
</table>
### Hybrid structures considering production and flavour perception are more likely to be of industrial value. The revised whisky flavour wheel (Fig. 3), similar to other alcoholic drinks, has a hierarchy of three tiers: primary - production origin or generality of nature; secondary - specific sensory or conceptual descriptors; and tertiary - highly specific terms, certain of technical importance. Attributes, in clockwise order, are on the right arising in normal production suitable for promotional and marketing purposes. On the left, off-notes, for technical functions, form four groups.

In the revision, primary tier chemical terms (phenolic, aldehydic, estery) were substituted with common industrial terms (peaty/smoky, grassy, fruity and floral, respectively). The generic feints was not replaced as of industrial value. Blenders and sensory assessors in Scotch whisky more often use subtier terms. For assessor training, reference compounds are recommended (Table 1): formulations with cyclodextrins achieve consistency and parallel conceptualisations.

### Nasal effects

N.1. pungency - ethanolic, peppery, prickle

N.2. drying

Pungency, a primary common chemical sense (irritation, chemesthesia), originates in delocalised stimulation of trigeminal nerve endings - a sharp, stinging or partial sensation of flavour or odour. Individuals are generally more sensitive to aroma notes than pungency.

In maturations, pungency is generally replaced by smoothness. Ethanolic-pungency, often ascribed to ethanol content, is not solely from spirit strength: activity of headspace ethyl esters also contributes. The off-note peppery-pungency originates in bacterial, Lactobacillus spp., fermentations producing acrolein, at elevated temperatures or in extended fermentations, from glycerol from yeast catabolism. The product, \( \beta \)-hydroxy propionaldehyde, is in distillation degraded to lachrymatory acrolein - inducing pungent, burnt and peppery notes.

Wooden washbacks
FIG. 4. Lignin-derived aromatic aldehyde transformations in whisky.
are sources of bacterial contamination but pH, oxygen
tension, agitation, presence of yeast cells and/or mash
residue, fermentable sugars and glycerol influence
acrolein production160. After 2-3 maturation years,
these off-flavours disappear: acrolein reacts with
ethanol yielding 1,1-dioxothio-2-propane38,138, 1,1,3
triethoxypropane, 3-ethoxypropionaldehyde and
propene157. None possesses unpleasant notes or
lachrymatory effects. Pepperpiness attributes should be
discriminated from spicy-peppery character from certain
casks.

Phenolic characters

A. Peaty character

A.1. burnt - tarry, sooty, ash
A.2. smoky - wood smoke, kippery, 
smoked bacon/cheese
A.3. medicinal - TCP, antiseptic, germoline, hospital

Smoky is linked to degraded wood carbohydrates -
cellulose, hemicelluloses and lignins37. Peaty attributes
originate in smoke, introduced into the airflow during
the kilning processes11, from phenolic compounds280
and also sulphur- and nitrogen congeners, pyridines
and thiazoles. Quantitatively important are phenol,
cresols (m-, o-, p-), xyleneols, and p- and m-ethylphenol.
Guaiacol has low flavour thresholds (3 µg litre-1 in 10%
spirit66); detection, 0.09 µg litre-1 and recognition
thresholds of 31 mg litre-' in 10% spirit66 and 30 and
120 µg litre-' (detection and recognition) in 23% grain
whisky127. Phenol contributes only circa 7% odour
units67,225, but related attributes are important, especially
in Scotch whisky280 with characters often described as
medicinal and iodine25. In Speyside malts this is more
often peaty. Strong phenolic characters such as medicinal
relate to kilning o- and m-cresols, peaty may be linked to
eugenol250. In Bourbon and Canadian whiskies
unpeated, green malts from barley, corn or rye, and
phenol and cresols have lesser impacts on character and
smoky attributes originate in lignin breakdown
components. These included eugenol, 4-ethyl phenol
and 4-ethyl guaiacol, from new staves after charring and
ethanolic extractions131 (Fig. 4) or cereal cell walls.
Eugenol with low thresholds of 1166, and detection at
0.5 and recognition of 5 µg litre-'127, influences Bourbon
flavour66. Adding phenol mixtures to Bourbon mimicked
Scotch whisky characters of woody with additional oily,
but not estery and sweet attributes66.

Humic and fulvic acids in mashing waters172,272
influence peaty characters. Congeners including
halogenos of marine origins172 and microbial activity also
generates highly flavour-active compounds such as
chloroguaiacols that at extreme dilutions yield
distinctive off-notes, e.g. Rio character in coffee86,146,240.

In the original flavour wheel233, discrimination of
phenolic attributes was contentious with secondary tier
clustering of medicinal, peaty and kippery. Relationships
between the stronger medicinal, and peaty are unclear12,250
as are those between peaty and dry attributes in
whiskies171. No relationship between dryness of Scotch
and total phenol content has been demonstrated11,251.
Interestingly, a specific volatile phenol anosmia - partial
odour blindness - is reported in 15% of the UK population
for suggesting inconsistent flavour influences88.

Fermentation characters

B. Grainy characters

B.1. cereal - (digestive) biscuity, husky, bran, leathery,
tobacco, mousy
B.2. malt - malt extract, malted barley
B.3. mash - porridge, draff, wort, cooked maize

Grainy characters, unlinked to any specific congener,
are regarded by distillers as important. Raw materials,
grains or cooked grain (mash) form reference standard.
Green malts confer fruity, hay-like, and damp-straw notes,
replaced by burnt, bready, malty and chocolate-like notes14
with increased kilning temperatures. Maillard browning
intermediates interact with cereal lipid oxidation
products (Fig. 5).
Furfural, *grainy* at 20–30 mg/litre in Scotch whisky\(^{138}\), may contribute to *hotness* in spirits\(^{86,238}\). At 90% recognition threshold (839 mg/litre)\(^{129}\) furfural was described by few distillers (<10%) as *grainy*, more used was *marzipan* (coconut, cake mix, almond, nutty, walnut oil and coumarin-like – 54%), *sweet* (26%) and *oily* (15%)\(^{129}\). Pentose sugars, from breakdown of cereal cell walls, yield furfural during pyrolysis in malting and distillation\(^{12,17,176,338}\) (Fig. 5): concentrations are functions of wash pH especially with high numbers of lactic bacteria\(^{17}\).

In whole and ground cereals\(^{220}\), aldehydes, enals, 2,3-butanediols, acetic acid, and chloro- and bromomethoxybenzenes dominate volatiles. The last is associated with *musty* in sorghums. In malts\(^{13}\) *malty* is associated with 2- and 3-methylbutanal, linked to *woody* in alcohol-free beer\(^{193,194}\). Perpète and Collin\(^{193,194}\) associated *woody* primarily with 3-methylthio-propionaldehyde but other compounds influencing *malty* or cereal-like character include ethylmethylpyrazines, maltol\(^{13}\) and hydroxymethylfurane from 2-methylpropanol\(^{71}\). Fermented malt extracts typically contain 4-hydroxy-5(or 2)-ethyl-2(or 5)-methyl-3(2H)-furanone (HMF) and 4-hydroxy-2,5-dimethyl-3(2H)-furanone (HDMF). All produced in beer by *Saccharomyces cerevisiae*\(^{84}\) have sweet, *malty* and *caramel* notes.

**Aldehydic characters**

C. **Grassy character**

C.1. *fresh* – *leafy*, *wet/cut grass*, *flower stem*, *green apple/banana*

C.2. *dried* – *hay*, *straw*, *tea*, *mint*, *herbal*

*Grassy* is often synonymous with *aldehydic*, *green* and *leafy* attributes\(^{233}\) but the technical – *aldehydic* – is better understood as *fresh* and *dried grassy*\(^{129}\). *Grassy* is better defined than *green*, widely used for immaturity in wines (young), from green malt usage\(^{233}\) and multifaceted in perfumery\(^{102}\). *Grassy* notes from hexanal are perceived *almond* by a minority (12%) of assessors\(^{129}\).

Many compounds relate to *grassy* characters in whisky\(^{26,106,216,247,251,278}\) including low molecular weight aldehydes e.g. hexanal, trans-2-hexenal, 2- and 3-hexenol. These confer *green leaves*, *grassy* and even *fruity* notes. Increasing aliphatic chain length yields less pleasant *cardboard*-like and *bitter* notes\(^{156}\). Aldehydes originate in barley lipids, dominated by 9,12-octadecadienoic (linoleic), 9,12,15-octadecatrienoic (linolenic) and 9-octadecenoic (oleic) acids. Malt lipoxigenases oxidise linolenic and 6,10,14,18-eicosatetraenoic (arachidonic) acids (Fig. 5), yielding 9- and 13-hydroperoxides and further aldehydes: hexanal, trans-2-hexenal\(^{189}\), 2- and 3-hexenol (leaf alcohol)\(^{34,102}\) and unsaturated methyl ketones (6-tridecen-2-one, 6-pentadecen-2-one and 6-heptadecen-2-one)\(^{75}\).

**Estery characters**

Estery characters are ordered as in the original wheel\(^{233}\), and include *solvent*, *fruity*, *floral*, and *feinty*, functions of aliphatic chain length\(^{219}\). In distillations, *solvent* and *fruity*, are related to heads (foreshot), passing to *floral* and *feints* (tails) as distillation proceeds\(^{86,189}\).
Cl 6) and 9,12,15-octadecatrienoate (linoleate: C18) - show ethyl decanoate (caprate, C10), hexadecanoate (palmitate, C16) largely retained within yeast cells.180 Fermentation ester formation is influenced by wort gravity215, yeast strain183 and pitching rate116,214, wort unsaturated fatty acid concentration18,136,299, aeration18,299 and temperature159. Mass transfer of substrates, and yeast growth, are key factors for wort levels of medium-chain fatty acids18.

In maturation, further esterification of fatty acids216 occurs, and ethyl acetate127 becomes abundant originating in acetic acid from hydrolysis of hemicellulose acetyl groups176, oxidation of ethanol, and wood charring157. Equilibria exist between acetaldehyde and ethyl acetate; between ester and acetic acid and ethanol. Certain acids, notably hexanoic (caproic, C6) and tetradecanoic (myristic, C14), react slowly in maturations and others - ethyl decanoate (caprate, C10), hexadecanoate (palmitate, C16) and 9,12,15-octadecatrienoate (linolate: C18) - show significant reverse reactions177,216.

The first-light fraction (foreshots)

D. Fruity characters

D.1. solvency - nail vanish remover, paint thinner, fusel oil
D.2. orchard - apple, peaches, pear
D.3. tropical - pineapple, melon, banana (pear-drop)
D.4. citrus - orange, lemon, grapefruit, zest
D.5. berries - blackcurrant, tomato plant, catty
D.6. dried - raisins, figs, prunes

Ester characters - e.g. from ethyl acetate the most abundant at (typically) 175 mg litre\(^{-1}\) in whisky18 - are often perceived solvent-like. Ethyl acetate has high thresholds of between 33156 and 74 mg litre\(^{-1}\)195 with detection and recognition thresholds in 23% (abv)195. This p-damascenone has a high odour unit value (2500) in whisky, but low intensity index limits detection195. Autoxidation of vitamin A or lipids, from yeast or barley54, and breakdown of oak norisoprenoids yields \(\alpha\) and \(\beta\)-ionones with violet-like notes.

Dried-fruity notes in dried bell peppers137 are linked with 2-methylpropanal, and 2- and 3-methylbutanal, also linked to malty and worty notes13,193,194 in malts.

The middle fraction (spirit)

Hexanoic (caproic, C6), octanoic (caprylic, C8), decanoic (capric, C10) and dodecanoic (lauric, C12) acids and esters of dodecanoic (lauric, C12), tetradecanoic (myristic, C14), hexadecanoic (palmitic, C16) and hexadecenoic (palmitoleic, C18) acids.

The tail fraction (feints)

In feints phenylethyl ethanol confers floral, rose-water and fragrant notes; \(\beta\)-damascenone, an impact compound in Damascus rose oil57,58, imparts fragrant dilution to 23% (abv)195. This \(\beta\)-damascenone has a high odour unit value (2500) in whisky, but low intensity index limits detection195. Autoxidation of vitamin A or lipids, from yeast or barley54, and breakdown of oak norisoprenoids yields \(\alpha\) and \(\beta\)-ionones with violet-like notes.

F. Feints characters

F.1. grainy: see section B
F.2. cheesy: see section K
F.3. oily: see section L
F.4. sulphury: see section J

Excess feints notes influence distillate quality172. Notes include leathery or cereal-like (cooked mash, biscuity) passing
to sweaty (piggery) and into stale fish characters. Sweaty is related to isovaleric acid content. Feints, with distinctive stale notes and metallic aftertaste, have abundant malt-derived phenols and DMTS.

**Maturation characters**

**G. Woody character**

White oak wood (e.g. Quercus alba) varies in contents of cellulose (49–52%), lignin (31–33%), hemicellulose (22%) and extractable compounds: volatile lipids, volatile and non-volatile acids, sugars, sterols, tannic substances, pigments and inorganic compounds. Heartwood contains more lipids: triglycerides of C18 unsaturated and C16 saturated fatty acids, sterols and a ferulic acid ester with a C4o wax alcohol. All have **gradual impacts** with cask ageing and staves producing hazes during spirit reduction for bottling.

Cellulose (a glucose homopolymer) is central to oakwood structure with hemicelluloses (heterogeneric polymers) forming matrices and lignin an adhesive encrustant. Cell wall lignin (70%) is linked to hemicelluloses in a three-dimensional complex dominated by phenylpropane derivatives of guaiacyl (2-methoxyphenol) and syringyl (2,6-dimethoxyphenol) units with aliphatic and aromatic intermonomer covalent bonds. Linkages between lignin, tannins and the carbohydrates make fractionation difficult and insolubility reduces flavour impact. However, breakdown products and related extractives influence flavour conferring smoky and woody characters. In charring lignins are more stable than polysaccharides. In acidic (-pH 4.5) wood maturation insoluble hemicelluloses slowly depolymerise and are extracted.

Woody characters are complex in both whisky and wines. Important contributors include lipid-derived whisky lactones, and lignin breakdown compounds - vanillin, and related aromatic aldehydes, and derived acids, esters, tannins and sugars. Perez-Coello and coworkers regarded cis- and trans-lactones, eugenol, vanillin and syringaldehyde as the volatiles with greatest sensory impact with optima for extractions of vanillin and syringaldehyde of 165–215 °C. A greatest sensory impact with optima for extractions of vanillin, and related aromatic aldehydes, and derived whisky lactones, and lignin breakdown compounds - wines.

Higher alcoholic strength fillings reduce extraction of wood-derived components and associated notes. In an 8-year old whisky, filled at 59% abv, character was flavoured, at 63% less matured and weaker and at 77% green oak.

Fresh sawdust or sap notes originating in new barrels, are related to wood origin, and eliminated with second usage. In wines, unpleasant sawdust notes are linked to (E)-2-nonenal (rancid in beer), 3-octen-1-one, (E)-2-octenal and 1-decanal. These compounds, associated with cardboard in whiskies and other products, originate in linoleic acid oxidation in unsaturated barley lipids. Cask toasting processes reduce (E)-2-octenal, and associated notes, in matured wines.

**New wood characters**

**G.1. sap - green bark, wet wood**

**G.2. cedar - sawdust, cardboard, sharpened pencil**

**G.3. oak - resin, polish**

**G.4. pine - turpentine, resina**

Fresh sawdust or sap notes originating in new barrels, are related to wood origin, and eliminated with second usage. In wines, unpleasant sawdust notes are linked to (E)-2-nonenal (rancid in beer), 3-octen-1-one, (E)-2-octenal and 1-decanal. These compounds, associated with cardboard in whiskies and other products, originate in linoleic acid oxidation in unsaturated barley lipids. Cask toasting processes reduce (E)-2-octenal, and associated notes, in matured wines.

**Wood extractive characters**

**G.5. nutty - coconut, hazel nut, almond/marzipan, walnut**

Nutty is associated with a product of oak lipid oxidation, described as "whisky lactone", "3-methyl-4-octanolides", "β-methyl-γ-octalactone", "5-buty1-4-methyl-dihydro-2(3H)-furanone", or "Quercus lactone". Associated flavour character is coconut at high concentrations (>5.3 mg litre⁻¹) and oak wood-like at lower (0.1 mg litre⁻¹). This lactone, together with 4-nonalolide and eugenol, are major volatile congeners derived solely from oak. A possible lactone precursor is 2-methyl-3-(3,4-dihydroxy-5-methoxybenzoy)-octanionic acid.

Four lactone isomers are, cis-(3R,4R), cis-(3S,4S), trans-(3S,4R) and trans-(3R,4S). Differing in flavour character (Table II), Oak contains only cis-(3S,4S) and trans-(3S,4R). Other isomers indicate synthetic lactones in flavouring/ageing agents. Misidentification of isomers has produced contradictory cis/trans ratios, and threshold values.
For racemic mixture of lactones, detection and recognition thresholds were: 0.5 and 1 mg litre\(^{-1}\), respectively in 23\% grain whisky\(^{127}\) but 0.05 mg litre\(^{-1}\)\(^{125}\) in 34\% abv grain spirit; in white and red wines 120 and 125 mg litre\(^{-1}\)\(^{31}\). Reported detection thresholds are 241 mg litre\(^{-1}\) in white, 853 in red wine and 75 in 12\% abv ethanol\(^{234}\). In white wine lactone confers musty notes, in red harsh and in 12\% ethanol coconut, woody and oily\(^{234}\) linked to the more abundant cis isomer (Table II) with a threshold of 0.092 mg litre\(^{-1}\), 2.5–20 times lower than trans\(^{164}\). Wood origins can be related to lactone ratio\(^{192}\), reported\(^{77}\): 77:23 (cis:trans) in wood but dependent on cask history and treatment. The cis lactone is more abundant in American white oaks than Pedunculate or Sessile\(^{152}\). Ratios (cis:trans) also vary through single staves, with cis maximal (250 mg kg\(^{-1}\) of wood), and more extractable\(^{143}\), at 5 mm below stave surface and trans maximal (48 mg kg\(^{-1}\)) at 15 mm depth\(^{44}\).

Lactones have been studied extensively as important in wine characters\(^{142,217}\). Waterhouse and coworkers\(^{271}\) have controversially claimed ratios in wine maturation oaks (European versus American oak) suggest white oaks showed fixed ratios of cis to trans oak lactone, determined genetically\(^{143}\). American white oak (Quercus alba) heartwood contains five-fold more lactone and precursor lipids\(^{142}\) than sapwood: two 3-oxo-retro-a-ionol isomers serve as markers. However, euugenol and vanillin concentrations are similar in American and European oaks\(^{31}\). European pedunculate oak (Quercus robur), low in aromatics and high in ellagittannin, is best suited to ageing spirits; European sessile (Quercus petraea) and American white oak to maturing wine\(^{31}\). New Bourbon casks have ten-fold higher extractable lactones than Scotch casks at 0.047–0.254 mg kg\(^{-1}\); flavour impact is reduced by cask usage\(^{44}\). “Standard” Scotch whisky have been reported containing 0.96, “premium” 1.16, and a “high” had 2.17 mg litre\(^{-1}\) total lactone\(^{184}\). Similar correlations between lactone concentrations and quality grade exist in cognacs\(^{184}\). There is conversion of trans to more stable, flavour-active cis form in bottle maturation of wine\(^{35}\).
of syringaldehyde (50% of total aldehydes) and vanillin (24%) is thought greater. Increased dissolved oxygen yields higher concentrations of vanillin, syringaldehyde, coniferaldehyde, vanillic and syringic acids. Extraction rate is high immediately after filling and slower during subsequent maturation promoted by hydrolysis, ethanolysis and also oxidations, at rates determined by filling strength.

Thresholds for vanillin have been defined as 2 mg litre⁻¹ in water, 0.5 and 0.1 mg litre⁻¹ in 10 and 40% ethanol solutions. These sensorially-important phenols are maximal at 5 mm below the char in new wood with syringaldehyde and syringic acid more abundant than vanillin and vanillic acid. Oak wood drying (air or kiln) also influences vanillin, coniferaldehyde and syringaldehyde contents. Air seasoning may increase mycoflora attacking cell wall lignins and polysaccharides, yielding compounds associated with positive maturation characters.

**G.7. spicy – clove, cinnamon, ginger, 'aromatic', nutmeg**

Woody spicy attributes originate in wood extracts, particularly eugenol, derived from lipid oxidation. This congener has a thresholds 2-34 µg litre⁻¹ in beers and 50 µg litre⁻¹ in 10 and 20% ethanol respectively and detection and recognition thresholds of 0.5 and 4.9 mg litre⁻¹ respectively in 23% abv grain spirit. Lignin thermal degradation products such as vinyl-, allyl- and ethyl guaiacols, guaiacol (2-methoxyphenol), cinnamaldehyde and related phenolic acids contribute sweet, smoky and spicy notes. The yeast enzyme ferulic acid decarboxylase converts cell wall ferulic acid to 4-vinyl guaiacol. The related clove has a character linked to oakiness. However spicy notes are common to clove, cinnamon bark oils, and other spices and distinctions may be difficult necessitating specialised sensory training.

**G.8. caramel – candy floss, treacle, coffee, toast, liquorice**

Caramel – sweet, burnt and notably smoky notes originate in thermal breakdown of lignins, dominated by phenols such as guaiacol (2-methoxyphenol), 4-acetyl-guaiacol and syringol (2,6-dimethoxy phenol), homologues and derivatives. The stability of lignin polymers limits their contributions to maturing spirit but lower molecular weight guaiacyl and syringyl products are extracted in concentrations decreasing with repeated use. Certain flavour notes originate in 5-hydroxymethyl-2-furfuraldehyde and hydroxymethyl-pyranoles from ageing in freshly charred casks. Caramel added to enhance colour in blended whiskies also contains 5-hydroxymethyl-2-furfuraldehyde. In Bourbon whiskey, 2-hydroxy-3-methyl-2-cyclopentenone and 3-hydroxy-2-methyl-4-pyrrone (maltol), with sweet and burnt notes, are important.
Other stave pyrolysis-derived congeners, from Maillard reactions (Fig. 5), are furans: furfural, 2-methyl furfural and 5-hydroxymethylfurfural, and heterocyclic nitrogen compounds including pyrazines, pyridines, thiazoles, aliphatic amines, quinolines and pyrroles\textsuperscript{40,41,142,177,210}. Abundant nitrogen compounds, e.g. methylpyrazine and 4-methyl-5-vinylthiazole, impart burnt, roasted and nutty notes to malts and also contribute to flavour in whiskies. Such compounds are more abundant in char layers than in plain wood shavings or deeper layers\textsuperscript{210}. Concentrations in whiskies are significantly higher than odour thresholds\textsuperscript{185}. Pyrazines are regarded as having pleasant flavour notes: burnt, toasted, medicinal, nutty, fruity, woody and earthy\textsuperscript{210,263}, but also phenolic, nutty and green. Flavour notes are enhanced when methoxyl groups are present on pyrazine derivatives\textsuperscript{145}. Unlike pyrazines, pyridines are perceived as less pleasant: astringent, bitter, buttery, caramel, roasted, green, earthy, rubbery, and fatty\textsuperscript{144}, and pungent, solvent and fishy\textsuperscript{60}. Viro\textsuperscript{266} showed reducing pyridines in Finnish whiskies improved flavour. Such pyridines are ionized at low pH (4.0–4.5) in matured whisky, and therefore flavour impacts are low\textsuperscript{56,210}.

G.9. Previous use—sherry, Bourbon, port, rum, brandy, wine

Scotch whisky has traditionally been matured in reused sherry, Madeira and port casks that flavour spirit. Shortage of ex-sherry, replaced by ex-Bourbon, barrels\textsuperscript{31,164} has promoted pressure pre-treatments with white wine or sweet, dark sherry that increase final ester and sugar contents yielding mildly flavoured whiskies\textsuperscript{164}.

Other wood extractive characters

**Mellowness, roundness & smoothness**

Mellowness and lingering aftertastes are related to changes in hydrogen bonding in spirit during maturation, with formation of ethanol cluster structures\textsuperscript{23,177}. Such clusters can be deduced from differential scanning calorimetry (Fig. 7)\textsuperscript{112} and adiabatic expansion studies under vacuum\textsuperscript{79,174} of immature and mature whiskies. Non-volatile oakwood extracts (Fig. 7)\textsuperscript{114,177} stabilise clusters, increasing mellowness and roundness with accumulation\textsuperscript{40,205,206}. Such non-volatiles are monosaccharides (pentoses and hexoses) and aromatics from cask cell walls and glycerol\textsuperscript{216} from thermal breakdown of wood triglycerides.

**Defective wood characters**

G.10. mothball—paraffin, naphtha, camphor

G.11. musty—mouldy, earthy, fusty, corked

G.12. vinegar—acetic, sour

Mouldy and earthy notes appear to originate in fungi and actinomycetes on malts\textsuperscript{272}, defective casks\textsuperscript{198} and cork closures, notably Armillaria mellea\textsuperscript{222,228,236,237} on corks. In wines such aroma notes are linked to methyl thiopyrazine, 2-acetyl piperidine and its isomer 2-acetyl tetrahydro pyridine, 1-octen-3-one (mushroom), 3-octen-1-one (musty, mouldy, earthy, mushroom)\textsuperscript{32}. Musty, or cork taint notes are associated with 2-methyl-isoborneol (2-MIB (earthy), geosmin (mildew) and 2,4,6-trichloroanisole (2,4,6-TCA)\textsuperscript{69,237}. Other contributors include 2,3-diethyl-5-methylpyrazine and 2-isopropyl-3-methoxy pyrazine (musty/mouldy)\textsuperscript{101,124}. Corks contaminated with moulds and pesticide chlorophenols 6-chlorovanillin, 4-chloroguaiacol, 4,5-dichloroguaiacol and veratrole yield chloroanisoles (e.g. 2,4,6-TCA) with corked taint and musty. These are important in tainted wines\textsuperscript{28,29,77,118} and other drinks\textsuperscript{63}, originating in woods, including shavings\textsuperscript{124}. In wine, the low thresholds\textsuperscript{248} show a bimodal distribution, at 1.461 and 17.4–210 ng litre\textsuperscript{-1}. Certain individuals are particularly sensitive to such flavour notes\textsuperscript{236}. Before surface treatments, corks yield woody and green cork notes and after less woody and more oily from coating materials\textsuperscript{236}. Off notes of microbial origin are reduced by autoclaving\textsuperscript{222}.
Sweet characters are important in whisky flavour but their origins are not clear. In 23% abv grain whisky, sweetness can be evoked by diacetyl (47% respondents), maltol (38%), vanillin (28%), furfural (26%), ethyl hexanoate (24%), iso-amyl acetate (15%), whisky lactone (10%)129. Certain assessors used only the generic description sweet and did not specify between them which reflects either lack of verbal ability or physical properties of congeners. Vanillin is linked to woody-sweet, also vanilla (58%), toffee (35% - toffee, caramel, fudge and chocolate) and sweet (28%). Whisky lactone was described as coconut (84% of respondents), but has also a sweet almond character (nutty, 11%, marzipan, 7% and almond, 4%)129. Nutty is related to sweet taste character102. 4-Vinyl guaiacol contributes sweet-woody character to whiskies. Sweet-smoky (32%) is linked to wood-derived phenols: spicy (17% - spicy, nutmeg, ginger, clove and aromatic), vanilla (13%) and woody (7%). Maltol evoked candy floss in 44% respondents, with frequent usage of related terms - sweet (39% - sweet and sugary) and caramel (35% - caramel, burnt sugar, toffee).

As for floral-sweet, geraniol was described as floral (36%), lemony (citrus and washing-up liquid, 25%), scented soap (21%), but also sweet (17%)129. As for fruity-sweet, iso-amyl acetate was described as pear-drop (67%). Other fruity-sweet terms in 23% abv grain whisky, were banana and pear (22%)129 and buttery-sweet: discrimination of ginger, clove and aromatic), vanilla (13%) and woody (7%).

I. Stale characters

1. cardboard - papery, filter sheet
2. metallic - inky, tinny, wet iron, rusty: see the section F (feints)

Cardboard-like notes generally originate in lipid oxidations of unsaturated fatty acids from cereals or yeast metabolism18.2. Lipoygenase oxidation of 9,12-octadecadienoic (linoleic) and 9,12,15-octadecatrienoic (linolenic) acids yields pentanal, hexanal, nonanal, (E)-octenal, 2,4-heptadienal, (E)-2-nonenal, (E,E)-2,4-nonenal and 2,4-decadienal responsible for cardboard in boiled potato. Hexadecenoic (palmitoleic) acid autoxidation yields (E)- and (Z)-2-nonenal and (E)-2-octanal with cardboard notes in butter oil27. (E)-2-nonenal in 23% abv grain whisky was described as cardboard with detection and recognition thresholds of 3 and 8 µg litre-1, respectively130.

J. Sulphury characters

1. stagnant - sewer, drains, foul water, rotten vegetable
2. meaty - yeasty, Marmite, rotten egg
3. vegetable - turnip, potato, cooked vegetable (sweetcorn, boiled cabbage)
4. sour - pickled onion, garlic
5. gasgy - town gas, burnt match, acrid
6. rubbery - tyre/tubes, pencil eraser, plastic

Sulphur compounds are important sources of off-flavours reducing spirit quality26,133,133, although low concentrations in beers enhance acceptability18. Water dilutions enhanced flavour impact through hydrophobicity, although such volatility is suppressed by wood-derived congeners207. In lagers, dimethyl (DMS) and diethyl sulphide have low thresholds at 30-50 and 0.4 µg litre-1, respectively, and thiols at <2 µg litre-17,19,19. In beer DMS above 100 µg litre-1 imparts cooked sweet-corn, spicy and malty128 or blackcurrant-like7 notes; at lower concentrations flavour impacts are not significant7. In lagers, ethanethiol evokes stronger gunpowder and acrid notes128. In 23% grain whisky detection and recognition thresholds of dimethyl trisulphide (DMTS) were 4 and 20 µg litre-1, respectively130, and 3-6 µg litre-1133. In beer associated flavour notes are garlic (onion, cabbage), drains and (struck) match128 and thresholds for H2S are 6 µg litre-192. In grain whisky perceptions were rubbery (21% respondent), sour (21%) and gassy (15%)129. Low molecular weight sulphur congeners confer light and neutral133 characters, medium as lightly bitter and roasted tinge and higher as heavy. Meaty, burnt and thiamine-like attributes are associated with methyl-(2-methyl-3-furyl)-disulphides (MMFD), bis(2-methyl-3-furyl)-disulphides, and methyl-(2-methyl-3-furyl)-sulphides and 2,5-dimethyl-3-methylthiobutan-1-one. The important congener MMFD, present in grain and malt whiskies, has low thresholds of 0.005 µg litre-1 in rectified and 0.10 µg litre-1 in grain spirit7. Other compounds derived from thiamine and amino acids also have low thresholds, <1 µg litre-1, and are important in roasted coffee260 and yeast extracts5.
although DMTS concentration can be modulated in still operation\textsuperscript{26,211}. Malathion used for pest control on barley might influence sulphur congener concentrations, but was reported to have no influence on final spirit\textsuperscript{256}. Additon of rock sulphur or gaseous sulphur dioxide (SO\textsubscript{2}) during malt kilning reduces nitrosodimethylamine (NDMA) level through reactions between barley amines (especially hordeins in the rootlet) and fuel NO\textsubscript{2}. Most nitrosamines are unstable, evaporating before the kilning 'break point'. Formation of NDMA is reduced by prior rootlet removal but influenced by hordein content\textsuperscript{239}. Sulphur dioxide at 10–30 mg litre\textsuperscript{-1} also reduces malt microbial loads\textsuperscript{21,22,235} and lightens colour. Wort pH is influenced by concentrations of SO\textsubscript{2} and sulphuric acid with effects on polysaccharide, glyco-proteins and glycolipid hydrolysis and wort concentrations of protein, α-amino nitrogen, lipids and fatty acids\textsuperscript{231}.

Malt yields DMS from S-methyl-methionine (SMM), absent from barley grain but increasing during germination\textsuperscript{224}. Temperature and moisture levels in barley at kilning influence conversion of SMM to DMS, with a boiling point of 38°C. Although evaporating during kilning and mashing, DMS is oxidised to dimethyl sulfoxide (DMSO) and dimethyl sulphur dioxide (DMSO\textsubscript{2})\textsuperscript{7,26}. Other sulphur congeners formed in mashing include carbonyl and hydrogen sulphides, methanethiol, carbon disulphide, sulphur dioxide and dimethyl sulphoxide (DMSO)\textsuperscript{78}. In fermentation, DMSO is reduced to DMS by sulphur hydrol compounds during the fermentation. Anaerobic bacteria (\textit{Enterobacteriaceae}) in certain washes also produce DMS from DMSO\textsuperscript{282}. Yeast autolysis yields DMDMS, DMTS and certain other sulphur congeners\textsuperscript{10,21,244} at concentrations related to duration and intensity of wort heating. Yeast malic and citric acids\textsuperscript{238} promote hydrogen sulphide and sulphur-containing compounds secretion by lactic acid bacteria (\textit{Lactobacillus brevis}, and \textit{L. fermentum})\textsuperscript{138}. Yeast metabolism also has a role, with storage at 5°C yielding less sulphur congeners than 20°C\textsuperscript{192}. Whisky mashes are susceptible to yeast infections, producing sulphides and further metabolic products (e.g. ethanethiol) through hydrogen sulphide reactions with ethanol\textsuperscript{16}. Strecker degradations (Fig. 5) of cysteine with diketone yield hydrogen sulphide (H\textsubscript{2}S) during fermentation, converted to ethanethiol and diethyl sulphide during distillation\textsuperscript{244}. Such H\textsubscript{2}S (typically at 9 mg litre\textsuperscript{-1}) interacts with residual maltotriose (0.8–1.4 mM) during distillation, yielding DMDMS from methionine independent of the presence of copper ions\textsuperscript{278}. Notes from H\textsubscript{2}S were rotten-egg at high concentrations (ca 140 μg litre\textsuperscript{-1})\textsuperscript{128} and yeasty at 50 μg litre\textsuperscript{-1}\textsuperscript{258}. Supply of oxygen at distillation has little influence on sulphur compound formation as foam and carbon dioxide replace air in wash headspaces\textsuperscript{78}.

Copper interacts with sulphur compounds\textsuperscript{133} and reaction with copper ions is regarded as essential for producing clean spirit\textsuperscript{173,273}. Copper ions accumulate during wash distillation reaching 15 mg litre\textsuperscript{-1} Is,\textsuperscript{213}. Cupric ions react with methinhol to produce DMDMS, converted to other compounds as distillation progresses\textsuperscript{76}. As conversion is faster than formation\textsuperscript{26}, total DMDMS concentrations in spirit are reduced.

Copper sulphate removes volatile sulphur congeners as non-volatile copper sulphides and mercaptides\textsuperscript{82}. Still deposits contain copper cyanides, thiocyanates, oxides and sulphides\textsuperscript{140}. This behaviour may be important for understanding spirit quality\textsuperscript{82}. Thiol reacts with surface copper oxide to form copper thiolates that in excess form complexes becoming self-assembled layers, with chemisorption\textsuperscript{109}. Thiolate layers react with congeners (e.g. thiophene) influencing sensory quality\textsuperscript{82}. However, chemisorbed thiol is limited (<4% of offered thiol concentration)\textsuperscript{109}. Distilling removes most sulphur compounds especially in predistillate (heads) and feint (tail) fractions: a copper still removed 70% dimethyl sulphide (DMDMS) more than glass\textsuperscript{16,229} with similar findings reported for rum\textsuperscript{174}. For DMDMS\textsuperscript{153}, however, glass distillation has been reported to show a ten-fold reduction over copper. Copper distillation also increases concentrations of other congeners: aldehydes, higher alcohols and esters but not carboxylic acids\textsuperscript{179}. The consensus is that copper distillation reduces sulphur congeners and positively influences sensory quality.

During maturation, oxidation of DMS to dimethyl-sulphoxide (DMSO) and dimethyl sulphur dioxide (DMSO\textsubscript{2}) continues: 50% of DMS was oxidized to DMSO and DMSO\textsubscript{2} after 96 h in a new cask\textsuperscript{276}. This was largely affected by the charcoal, and gallic acid was less effective. After 12 months, whisky DMS contents were low and a function of maturation parameters\textsuperscript{76} and DMTS contents decreased more slowly\textsuperscript{133,153}. Ratios of DMDMS/DMTS form maturity indicators (30 for new-filling, 15 after 3 years\textsuperscript{133}. Either DMDMS evaporates\textsuperscript{256} or is converted to DMTS until concentrations fall below flavour thresholds\textsuperscript{133}). Sulphur compounds – particularly, thiophenes and polysulphides – can also differentiate aromatic sulphur compounds such as thiophene and thiazole\textsuperscript{153}. Addition of oak wood (chips) and air reduces sulphur congeners notably methionyl acetate and ethyl methionate\textsuperscript{272}.

K. Cheesy characters

K.1. rancid – 'sickly sour', baby vomit, oxidized fat
K.2. sweaty – old trainer/sock, musky, piggery

Bacterial action (\textit{Clostridia}) yields n-butyric acid and ethyl butyrate\textsuperscript{26} with rancid (sickly) sour notes at low
mashing temperatures or if wash stands in cast iron vessels. Propionic, iso-butyric and iso-valeric acids have similar characters in whisky and are abundant in rum and brandy. In whisky iso-valeric acid, present in concentrations related to yeast and fermentation conditions, dominates.

Rancio, a Cognac character reminiscent of musty walnuts, can be confused with rancid in whiskies. This rancio character, indicating an old, well-stored cognac increasing with age in parallel with fineness and mellowness. The gradually acquired rancio is from hydrolysis of fatty acid esters with oxidation to the ketones: 2-heptanone, 2-nonanone, 2-undecanone and 2-tridecanone. Concentrations are functions of peroxidases and cask volume. Long chain aldehydes, methyl ketones (C7, C9 and C11), glyoxal and methyl glyoxal are related to rancio characters in old wine-spirits (e.g. Armagnac, Cognac). Glyoxal is present in whisky, but at concentrations too low to be quantified and Rancio character has not been explicitly identified. Butter/ rancio notes in wine are related to N-(3-methylthiopropyl) acetamide and 3-methylthiopropionic acid from methionol.

L. Oily characters
L.1. soapy - waxy, unscented soap, detergent, damp laundry; see section F (feints)
L.2. buttery - creamy, toffee, butterscotch
L.3. lubricant - mineral oil
L.4. fat - fatty, greasy, fish oil, castor oil

Buttery characters are related to diacetyl (2,3-butanediol), an off-note in lagers. Diacetyl and 3-hydroxy butanone are also important in wines, especially sweet Sherries. Diacetyl is produced by citrate-metabolising lactic acid bacteria and in yeast fermentations formed from α-acetolactate and metabolised to acetoin. Yeast metabolism can be manipulated to produce acetoin directly from α-acetolactate. In whisky nosing, diacetyl has a detection threshold of 0.02 mg litre⁻¹, a recognition of 0.04, and in tasting is 0.2 mg litre⁻¹. Fermentation oxygen influences spirit diacetyl content.

T. Primary taste
T.1. sweet

Oak maturation influences time intensity factors (maximum intensity and duration) of sweet taste in sugar cane spirit (cachaca). After 2 years there was little increase in peak intensity but a substantial increase in duration. Spirit changes can therefore influence perception of sweet character. In whisky, congeners conferring sweet are extracted from wood largely within 3 years. Glycerol primarily from wood triglycerides may also be generated by trans-esterification of triglycerides and ethanol, yielding fatty acid ethyl esters and free glycerol. In Bourbon whiskies stave hemicelluloses and acid-catalysed hydrolysis yield monosaccharides (arabinose, glucose, xylose, galactose and rhamnose). Concentrations of most sugars increase in the early stages of wood maturation, but fructose and glycerol are still formed late in maturation (Fig. 8). Glucose, fructose, proto-quercol and arabinose are reported the most abundant in whiskies with similarities in saccharide compositions in 12-month Scotch and Irish whisky distillates: Bourbons contained less arabinose and more xylose through new wood extractions. Bourbon spirit had greater total sugar contents than Scotch and Irish (Table IV), and quantitative differences may increase with age. Such concentrations of sugar in retired whiskies are thought too low (Table IV) to induce sweet characters – detection threshold is approximately 5 g litre⁻¹ in water. Ethanol, enhancing water structures through hydrophobic effects, decreased sweetness intensity and persistence in sugars. In summary it is believed that sugars make lesser contributions to flavour than other congeners such as vanillin, whisky lactone and maltol. Fruity, woody, floral and buttery characters enhance sweet characters in whisky. However, Swan has suggested products of hemicellulose degradations add fudgey and caramel notes and colour to whisky, those of cellulose have little impact (Swan, unpublished).

T.2. sour

Wood-derived acids and esters in whiskies are thought to influence flavour little. Wood-derived non-volatile congeners in matured whiskies include: oxalic, fumaric, succinic, methyl- and methoxy succinic, mesaconnic, adipic, phthalic, azelaic, sebacic and trimethylbenzoin acids. New distillate has a fixed acidity of zero but over 12 months the extraction of acids, oxidations of ethanol and other congeners and other reactions produce an acidic environment. A typical matured whisky is pH <4.5. Ethanol, enhancing water structures through hydrophobic effects, decreased sweetness intensity and persistence in sugars. In summary it is believed that sugars make lesser contributions to flavour than other congeners such as vanillin, whisky lactone and maltol. Fruity, woody, floral and buttery characters enhance sweet characters in whisky. However, Swan has suggested products of hemicellulose degradations add fudgey and caramel notes and colour to whisky, those of cellulose have little impact (Swan, unpublished).

T.3. salty

This character, often adopted in whisky flavour evaluations, is of uncertain origin. It is possibly associated with peat bogs close to a sea, saturated with marine spray and seaweed relics. Coastal warehousing with permeation of cellulose have little impact (Swan, unpublished).

T.4. bitter: see section M (mouthfeel) - astringent

M. Mouth effect (mouthfeel)
M.1. warming - alcoholic, burn, fiery
M.2. coating - oily, creamy feeling

A highly intense biting sensation, described as burning, can increase to a pain sensation. Burning also includes a warm sensation.

**TABLE IV.** Contents (mg litre⁻¹) of sugars in some whiskies.

<table>
<thead>
<tr>
<th>Sugar</th>
<th>Scotch (6 y)</th>
<th>Scotch (12 y)</th>
<th>Irish</th>
<th>Bourbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose</td>
<td>106.0 - 248.3</td>
<td>170.5 - 181.6</td>
<td>114.1</td>
<td>85.1</td>
</tr>
<tr>
<td>Proto-quercitol</td>
<td>10.4 - 16.5</td>
<td>28.9 - 34.4</td>
<td>8.6</td>
<td>90.9</td>
</tr>
<tr>
<td>Arabinose</td>
<td>14.4 - 21.1</td>
<td>35.6 - 42.9</td>
<td>12.4</td>
<td>82.5</td>
</tr>
<tr>
<td>Xylose</td>
<td>6.2 - 8.2</td>
<td>18.4 - 20.1</td>
<td>5.3</td>
<td>82.1</td>
</tr>
<tr>
<td>Mannose</td>
<td>31.3 - 69.6</td>
<td>35.3 - 35.5</td>
<td>6.8</td>
<td>19.2</td>
</tr>
<tr>
<td>Galactose</td>
<td>1.5 - 3.0</td>
<td>5.4 - 6.2</td>
<td>0.7</td>
<td>16.2</td>
</tr>
<tr>
<td>Rhamnose</td>
<td>1.5 - 2.2</td>
<td>4.0 - 4.5</td>
<td>1.5</td>
<td>10.6</td>
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<tr>
<td>Inositol</td>
<td>1.2 - 2.2</td>
<td>4.4 - 5.6</td>
<td>1.2</td>
<td>13.1</td>
</tr>
</tbody>
</table>

(Nykänen et al., 1984; reproduced with permission from Helsinki Foundation for Biotechnical & Industrial Fermentation Research, 1984, 141)
In many products the term creaminess is important for appearance, flavour or texture. In whisky, understanding of the character is limited but related to mouthfeel and also described as 'length in mouth'. Perception could be related to thickness, smoothness and fatty mouthfeel and is closely related to buttery (diacetyl) in many foods and whisky. In whisky, consumers to represent maturity may use this character associated with: smoothness, roundness, body, richness and mellowness.

Ethyl lactate, from esterification of lactic acid of bacterial origins, is reported linked to creamy character. In spirit, ethyl lactate yield is related to length of fermentation. However, relationships between creamy and smoothness appear to differ.

M.3. Astringent — drying, furry, powdery

Astringent is a trigeminal tactile sensation related to behaviour of the epithelium on exposure to tannins yielding on ingestion drying, roughing, puckering or drawing sensations. Such sensations, from binding of tannin to salivary proteins, mucopolysaccharides or directly to oral epithelia, reduce the lubricating effects of saliva, promoting roughness, particularly following repeated exposure.

Such flavour components, absent from new spirit, accumulate through extraction of wood and by oxidation processes. Wood-derived tannic substances contribute bitter and astringent character, but add colour and delicate fragrance to whiskies.

These water-soluble plant polyphenols, are commonly divided into the condensed - derivatives of flavonols - and hydrolysable tannins (gallotannins and ellagitannins). Ellagitannins, monosaccharide polyols (normally D-glucose) with hydroxyl groups esterified by either gallic or hexahydroxydiphenic (HHDP) acids, are hydrolysed enzymically or in acid or base conditions, to free gallic or HHDP acid, the latter lactonizing to ellagic acid. Polyphenols from white oak heartwood include gallic and ellagic acids, gallo- and ellagi-tannins. Such tannins oxidise slowly and polymerise as heart wood ages, reducing solubility and perceptions of astringency in ripening fruit. The effect is thought to be: promotion of ethanol oxidation to acetaldehyde and diethyl acetal; and formation of esters from acids (e.g. acetic acid) and alcohols. Tannic substances assist the reaction of salivary proteins, mucopolysaccharides or directly to oral epithelia, reduce the lubricating effects of saliva, promoting roughness, particularly following repeated exposure.

Understanding of the fundamental nature of whisky maturation is also required. Little is known about detailed physical structures of the aqueous ethanol liquid phases of new distillates and matured whiskies. High-resolution analysis strategies, such as neutron scatter, combined with headspace congener studies will contribute to an understanding of sensory quality that will benefit whisky distillers.

However, perhaps greatest priority should be given to understanding perceptions of flavour character in whiskies. Products are perceived holistically by consumers but analysed by sensory assessors through quantifications of deconstructed attributes. Study of relationships between these two, fundamentally different, forms of mental processing is an urgent requirement for understanding whisky quality.

REFERENCES


FUTURE RESEARCH

This review treats flavour attributes of whiskies, defined in a revised flavour wheel, as if perceived at a unified time point. However perceptions on ingestion of whisky form a temporal progression and the limited understanding of time intensity features suggest a fertile area for research.

Conclusions

On drinking a glass of whisky, consumers employ pattern recognition processes, using sensory data to develop a holistic mental image in specific regions of the brain. Flavour recognition involves matching of information from long-term, short-term and sensory memories. Whisky maturation influences volatile congener release into headspaces through modifications of spirit liquid phases, and agglomerates. Complex changes in congener partitioning replace immature notes in new distillates with matured whisky characters.

The revised flavour wheel specifies a vocabulary that defines consensus deconstructed attributes of whiskies to meet industrial needs. Each attribute is demonstrable by a flavour standard and terms suitable for training of sensory assessors for quality assurance, new product development and similar purposes.
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107. Kanizsa, G., Philosophical Psychology, 1994, 7(2), 149.
120. Laing, D. G. and Glenmarch, A., Psychology and Behaviour, 1992a, 52, 1047.


