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# Crossmodal Interactions:

## Investigating how Colour influences Fragrance Perception in Complex Aromatic Systems

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# Statement of Originality

I, Selasie Agbogla, certify that this is an original piece of work. I have acknowledged all sources and citations. No section of this report has been plagiarised.

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# Abstract

This research investigates the crossmodal impact of colour on the perception of fragrance intensity in complex aromatic systems, with implications for multisensory cosmetic and fragrance innovation. Anchored in the theoretical frameworks of crossmodal correspondence and semantic congruence, the study explores how coloured visual cues modulate the olfactory perception of binary fragrance mixtures composed of ethyl maltol and cis-3-hexenol. A three-phase experimental approach was adopted: Phase 1 determined individual detection and identification thresholds for both molecules and established their colour associations; Phase 2 validated equal perceived intensity across binary ratios; and Phase 3 tested 16 colour-fragrance ratio combinations in a repeated-measures design. Participants rated the perceived fruity/sweet intensity of each sample using a 0–100 scale. Statistical analysis included repeated-measures ANOVA and pairwise t-tests to assess the effects of colour, ratio, and their interaction.

The results demonstrate that colour significantly influenced odour perception, particularly at 1:1 and 2:1 ratios, supporting the alternative hypothesis. Notably, ethyl maltol showed perceptual shifts from gourmand sweetness to richer, woodier notes depending on solvent base (10% vs. 89% ethanol), while cis-3-hexenol exhibited rapid transitions from floral to grassy as concentration increased, reflecting receptor saturation dynamics. These behaviours were interpreted through molecular structure, receptor binding thresholds, and perceptual inhibition mechanisms.Findings contribute to advancing theoretical understanding of multisensory perception and offer industry-relevant insights for personalised fragrance formulation. However, the implementation of such tailored strategies is constrained by resource demands, cost, and environmental sustainability. The study concludes that while crossmodal design presents a promising avenue, further research is needed in final product testing to align receptor interaction with optimal fragrance performance in real-world applications.

# Introduction

## Background and Context

In the contemporary landscape of cosmetic science and fragrance innovation, sensory perception has evolved from a secondary design consideration to a central pillar of product formulation and branding. Historically, cosmetic products were developed with a primary focus on visual enhancement—colour matching, skin tone correction, and textural aesthetics (Kim, 2011). However, increasing consumer expectations and advances in neuroscience have shifted industry priorities toward multisensory product design, where emotional engagement, olfactory identity, and tactile interaction are orchestrated to create immersive, memorable user experiences (Ferrier et al., 2009; Spence & Zhang, 2024).

This shift has coincided with growing scientific and commercial interest in crossmodal congruence—the principle that aligned sensory cues across modalities can enhance perception, emotional resonance, and consumer satisfaction. Fragrance, in particular, plays a uniquely powerful role in this dynamic. It evokes strong semantic associations (e.g., lavender with calm, citrus with freshness) and influences memory, mood, and hedonic appraisal more profoundly than other cosmetic elements (Demattè et al., 2006). Consequently, the use of odour in synergy with colour and other visual cues is becoming a deliberate design tool in product development and consumer research. As outlined by Lawless and Heymann (2010), sensory integration strategies benefit from robust perception scaling methodologies, providing quantifiable insight into consumer responses across multisensory stimuli.

The fragrance and cosmetic sectors are therefore not only tasked with creating technically stable formulations, but also with curating experiences that harmonise scent, appearance, and expectation—a process underpinned by the psychophysics of multisensory perception (ISO 5492:2008).

## Colour–Odour Interaction in the Literature

Recent research highlights that visual and olfactory cues jointly contribute to product interpretation. Spence and colleagues (2015, 2020) argue that the brain often processes sensory information not in isolation, but through crossmodal correspondences—associative pairings across sensory modalities that reinforce one another, such as “yellow with lemon,” “green with grass,” or “black with bitterness.” These associations are not merely cultural artefacts but are, in many cases, biologically and semantically rooted. In the context of fragrance, such pairings have been shown to shape intensity perception, emotional valence, and odour identification accuracy (Levitan et al., 2014; Kim, 2011).

In fragrance-related studies, congruent colour cues are known to amplify perception of a matching scent, while incongruent cues can obscure or weaken olfactory clarity (Zellner et al., 2008). For example, yellow is more likely to enhance sweet/fruity odours, while green supports fresh or herbal notes. Conversely, black or mismatched hues can disrupt hedonic congruence, leading to reduced intensity ratings and less favourable product evaluations. These effects highlight the necessity for standardised perception scaling within packaging and product presentation, as prescribed in ASTM E253–09 (2014), which supports consistent visual and olfactory measurement across controlled sensory environments.

Despite these insights, most existing studies focus on single-molecule fragrances or static sensory pairings. There is limited evidence on how complex fragrance systems—particularly those containing blended components at varying ratios—interact with colour cues to modulate perception. Asiedu, Opoku-Mensah, and Sarfo (2024) recently demonstrated that both colour and fragrance are primary attributes in multisensory product evaluation, yet the complexity of their interaction in real formulation scenarios remains underexplored.

## Fragrance Chemistry and the Case for Ratio-Dependent Perception

Fragrances are rarely single-note experiences. Commercial and experimental formulations often involve complex mixtures, where top, middle, and base notes interact chemically and perceptually to produce a layered sensory profile. Two molecules used in this study—ethyl maltol (EM) and cis-3-hexenol (Cis-3)—represent contrasting olfactory families and receptor pathways.

Ethyl maltol is a synthetic gourmand note with a recognisably sweet, candy-floss aroma at low concentrations, but has been shown to shift toward toasted or woody nuances at higher concentrations or when dissolved in high-ethanol systems. Its broad receptor activation and molecular persistence make it perceptually dominant in blends. Cis-3-hexenol, by contrast, is a highly volatile green note with a narrow receptor activation window (primarily OR2J3) and exhibits a tipping-point profile—floral at low concentrations, aggressively grassy at higher intensities (Sell, 2014; McRae et al., 2012).

These molecular characteristics are not only chemically significant; they are perceptually consequential. The way fragrance ratios are blended affects not just the resultant odour, but also the extent to which colour can modulate it. Dominant notes like EM anchor perception, allowing colour to amplify the fragrance experience. More volatile and perceptually fragile molecules like Cis-3 may weaken or nullify crossmodal effects—particularly in populations with reduced OR2J3 expression.

## Cultural and Biological Moderators: Future Directions for Personalised Fragrance Design

While this study primarily focused on perceptual outcomes arising from colour–odour interaction in binary fragrance mixtures, it is important to acknowledge that cultural and biological variables can substantially influence olfactory interpretation. Colour–fragrance associations are often considered universal; however, research increasingly highlights cross-cultural divergence in how colours and odours are semantically linked and emotionally appraised (Nehmé et al., 2016; Barbara et al., 2021). For example, a green hue may be associated with natural freshness in one cultural context, but with artificiality or bitterness in another—modifying both hedonic tone and perceived intensity of an associated odour.

In parallel, genetic variability—particularly in olfactory receptor genes such as OR2J3—contributes to perceptual differences in odour strength, quality, and recognisability. Cis-3-hexenol, a green fragrance molecule central to this study, binds primarily to OR2J3, a receptor known to vary across individuals. This biological variability may lead to partial anosmia or reduced sensitivity in a subset of the population (McRae et al., 2012), thereby influencing not only intensity ratings but also susceptibility to crossmodal modulation by colour cues.

Although such variables were not the core analytical focus of this study, they were lightly accounted for through participant background questionnaires that captured cultural identifiers. However, the present research did not segment data by cultural or genetic profile, nor was it designed to isolate these effects.

Instead, these dimensions are best understood as critical avenues for future investigation. The emerging field of personalised olfactory profiling—which explores how cultural background, receptor expression, and metabolic activity shape fragrance perception—holds substantial potential for advancing inclusive fragrance development (Milinski et al., 2022). Future studies may build upon the findings here by integrating receptor genotyping, broader cultural sampling, or consumer segmentation based on odour recognition thresholds.

Such directions align with recent calls for intentional inclusivity in fragrance design (Sell, 2014; Kornbausch et al., 2022), where scent is no longer developed to suit a generic average, but tailored to reflect individual biological and cultural specificity.

## Research Gap and Justification

Despite growing interest in multisensory design, the following critical gaps remain unaddressed in the current literature:

- Limited studies on colour–odour interaction in binary or complex fragrance mixtures, especially those with variable component ratios.
- Insufficient analysis of how ratio dominance (1:1, 2:1, 1:2) modulates the strength of crossmodal effects in fragrance perception.
- Neglect of genetic and receptor-based variability in response to specific molecules like cis-3-hexenol.
- Lack of formulation-realistic experimentation bridging laboratory testing with product performance.

This study directly addresses these limitations by examining how blotter colour modulates odour perception across systematically designed fragrance blends, using molecules with well-characterised olfactory and structural behaviours.

## Research Aim and Objectives

**Aim**:

To assess whether colour has an impact on fragrance perception when complex mixture systems are introduced at varying ratios.

**Objectives**:

- To determine whether visual cues (colour) significantly influence the perception of odour intensity in binary fragrance mixtures.

- To examine whether the perceptual effect of colour is consistent across different fragrance ratios (1:1, 2:1, 1:2) involving ethyl maltol and cis-3-hexenol.

- To explore the potential of crossmodal congruence for enhancing product experience and guiding multisensory fragrance design.

## Study Design and Experimental Approach

The study employed a three-phase experimental structure:

- **Phase 1**: Determined detection and identification thresholds for EM and Cis-3 and recorded associated colour selections using a validated hue palette.

- **Phase 2**: Established perceived intensity equivalence between EM and Cis-3 at two concentration levels, allowing matched mixture formulation (1:1, 2:1, 1:2).

- **Phase 3**: Evaluated perceived intensity across 16 colour–fragrance conditions using a repeated-measures design. Participants rated fruity/sweet intensity under controlled visual and olfactory stimuli.

The selection of EM and Cis-3 was driven by their perceptual contrast, commercial relevance, and known receptor activation pathways, enabling the study to simulate realistic challenges in fragrance formulation while maintaining scientific control.

## Contribution and Significance

This research offers both theoretical and practical contributions to the field of cosmetic science and fragrance design. It advances academic understanding of how colour and fragrance interact in perceptually complex environments and offers evidence-based insights that may guide future product development, especially in contexts where sustainability, formulation efficiency, and consumer immersion are key.

Moreover, by aligning psychophysical testing with fragrance chemistry and perceptual theory, this study helps to bridge the gap between sensory science and formulation practice, supporting the development of innovative, multisensory fragrance systems that are both effective and ecologically responsible.

# Aim and Objectives

## Aim

To assess whether colour has an impact on fragrance perception when complex mixture systems are introduced at varying ratios.

## Objective

- to determine the detection threshold of individual odour molecules
- to determine the identification threshold of two fragrance molecules;
- to determine colour associations for the two fragrance molecules
- to
- determine the concentration of equivalent perceived intensity in order to achieve combinations of 1:1, 1:2 and 2:1 perceived intensity ratios
- to determine whether colour influenced the perception of odour in each fragrance mixture

## Hypotheses

Null Hypothesis :

There is no statistically significant difference in the perception of odour when different colour blotters are used.

Alternative Hypothesis :

There is a statistically significant difference in the perception of odour when different colour blotters are used.

# Materials

The key odorants examined were Cis-3-Hexenol [Cis-3] and Ethyl Maltol [E.M.], as well as the EDT Mix base solvent (89% ethanol, 11% water), which were kindly donated by CPL Aromas (Bishop's Stotford, UK).

**Table 1 – Odour Material List**

| Trade Name | INCI Chemical Name | CAS Number | Functional Class | Supplier, Country |
|---|---|---|---|---|
| **Cis-3-hexen-1-ol [Cis-3]** | 3-Hexenol – cis-3-Hexen-1-ol | 928-96-1 | Fragrance Odour agent | Tilley Distribution, UK |
| **Ethyl Maltol [EM]** | Ethyl Maltol – 2-Ethyl-3-hydroxy-4-pyrone | 4940-11-8 | Fragrance Odour agent | CPL Aromas, UK |
| **Eau de Toilette Mixture [EDT Mix]** | Ethanol (and) Aqua – Ethanol (and) Distilled Water Mixture | - | Solvent, carrier | CPL Aromas, UK |

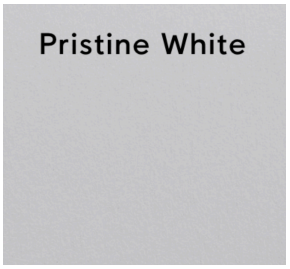
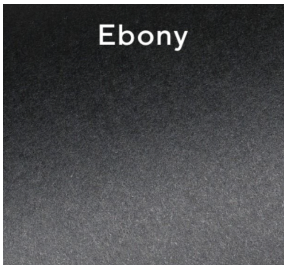
All fragrance materials used in **Table 1** were compliant with the standards of the International Fragrance Association (IFRA, 51st Amendment, 2023). The Technical and Safety Data Sheet can be found in the Appendices (Appendix X to Appendix X.1)

To determine the minimal odour perception thresholds, the distinct fragrance molecules [cis-3-hexenol] and ethyl maltol were tested using the aroma assessment strips for the repeated preliminary tests.

Smelling strips made of hardened paper, sized 155 mm x 8 mm, were obtained from LS Materials (United Kingdom). UK A4-sized coloured paper (175 gsm) was additionally acquired for visual stimulus requirements in Phase 3.

**Table 2** displayed below demonstrates the four selected colours introduced as colour components for the final third phase of the experiment.

**Table 2 – Equipment Material List for Phase 3 – Coloured Paper blotters**

| Coloured Blotters | White | Light Yellow | Green | Black |
|---|---|---|---|---|
| **Shade** |  |  |  |  |
| **Size** | 105mm x 15mm | 105mm x 15mm | 105mm x 15mm | 105mm x 15mm |
| **Quantity** | 800 | 800 | 800 | 800 |
| **Supplier, Country** | GF Smith, UK | First for Paper, UK | GF Smith, UK | GF Smith, UK |

The use of the smelling strips was instrumental to primary assessments of odour perception conducted in Phase 1 for odour detection and identification thresholds and colour-odour associations; for Phase 2, the strips were employed to ascertain equivalent odour intensity perception. As for Stage 3, coloured paper blotters were cut from 175 gsm A4 sheets to the dimensions inserted in **Table 2** below to create blotters for final testing on colour effect on odour perception using binary odour mixtures of combinations of Cis-3 and EM.

# Methods

## Experimental Design

This study was structured in three experimental phases to assess whether colour impacts the perception of odour when binary fragrance mixtures are introduced at varying ratios. A repeated-measures design was employed, with participants exposed to controlled colour and odour conditions to isolate crossmodal effects. Each phase built upon the previous, ensuring that odour thresholds, perceptual intensity matches, and colour associations were empirically established before the final colour-odour testing in Phase 3.

## Study Protocol

All experimental sessions were conducted in a controlled laboratory environment under standardised lighting, ambient temperature (21°C ± 2°C), and minimal airflow. Participants were seated individually and presented with fragrance samples on blotters at nose level, with a 30-second interval between each sample to reduce sensory fatigue. Instructions were delivered both verbally and in writing. Participants rated perceived odour intensity on a 0–100 scale and selected odour descriptors and colour associations when applicable. The study received ethics approval from the University Ethics Board and followed institutional guidelines for participant consent and data privacy.

## Participants and Ethics Requirements

A total of 90 adult participants (aged 18–65) were recruited via university mailing lists and local advertisement. Inclusion criteria included normal olfactory and visual function, non-smokers, and no self-reported fragrance allergies. Participants were diverse in gender and cultural background to reflect general cosmetic consumer

populations. Prior to participation, individuals completed a short screening questionnaire including demographic data and sensory health history.

## Phase 1: Odour Threshold and Colour Association

### Odour Detection and Identification Thresholds

Odour thresholds were established using a triangle test protocol with ascending concentration levels as shown in Table 3. Participants were presented with three blotters per trial (two blanks, one test sample) and asked to identify the odd sample out. For ethyl maltol (EM), detection thresholds were tested at 0.07, 0.11, and 0.14 µl/ml; for cis-3-hexenol (Cis-3), concentrations tested were 0.5, 0.75, and 1.0 µl/ml. Identification thresholds were determined by presenting five increasing concentrations of each compound and recording consistent semantic descriptor usage (e.g., "sweet," "grassy").

**Table 3 - Concentrations ranges for odour identification**

Range of 5 for Ethyl Maltol for identification:

1. [0.04 ul/ml]
2. [0.08 ul/ml]
3. [0.12 ul/ml]
4. [0.16 ul/ml]
5. [0.20 ul/ml]

Range of 5 for Cis-3-hexenol for identification:

1. [1 ul/ml]
2. [1.25 ul/ml]
3. [1.50 ul/ml]
4. [1.75 ul/ml]
5. [2 ul/ml]

### Colour Association

Following odour identification, participants were asked to associate each identified fragrance with one of eight standardised colour swatches (white, light yellow, bright yellow, dark yellow, green, light brown, brown, black). Colours were presented in randomised order and counterbalanced across sessions. Frequency of colour selections was recorded for each compound.

## Phase 2: Odour Intensity Matching

### Equal Intensity Matching Procedure

To create perceptually balanced binary mixtures, participants were presented with fixed concentrations of EM (0.04 and 0.40 µl/ml) against graded concentrations of Cis-3. For EM 0.04, Cis-3 was tested at 0.9–2.1 µl/ml; for EM 0.40, Cis-3 ranged from 2.1–3.0 µl/ml. Participants indicated whether the comparison sample was weaker, stronger, or equal in intensity. The most frequently matched Cis-3 concentrations were identified as perceptually equivalent.

## Phase 3 : Colour-Odour Interaction Testing

### Stimulus Design

Binary fragrance mixtures were created in three ratio conditions: 1:1 (EM:Cis-3), 2:1 (EM dominant), and 1:2 (Cis-3 dominant). The validated equal-intensity pairs from Phase 2 were used for mixture construction. Mixtures were presented on blotters coloured with the top two associated hues from Phase 1 (white, yellow, green, black). A 1:1 control condition (on white blotter) was included to test internal consistency.

## Repeated-Measures Testing Protocol

Each participant rated a total of 16 conditions (4 colours × 3 ratios + 1 control), presented in fully randomised order to minimise order effects. After each sample, participants rated the perceived fruity/sweet intensity on a 0–100 visual analogue scale. 30-second rest periods were enforced between stimuli to reduce adaptation. The full testing session lasted approximately 45 minutes per participant.

## Statistical Analysis

Descriptive statistics (means, standard deviations) were computed for each condition. Paired samples t-tests compared 1:1 vs. 1:1 control conditions. One-way repeated-measures ANOVAs tested main effects of colour across each ratio. A two-way repeated-measures ANOVA assessed the interaction between colour and mixture ratio. Bonferroni-corrected post hoc tests were used to identify pairwise differences. Significance was set at (p value = .05.)

# Results

## Phase 1 – Odour Detection, Identification and Colour Association

### Odour Detection Thresholds

The objective of this initial stage was to determine the minimum perceptible concentration—i.e., the odour detection threshold—for each of the two target fragrance molecules, ethyl maltol (EM) and cis-3-hexenol (Cis-3). A triangle test method employing an ascending concentration series was used, where participants were required to identify the odd sample out of three, with two samples containing ethanol only (blanks) and one containing the diluted test molecule. According to sensory discrimination standards, including the Bi et al. (2008) triangle significance table, detection was deemed statistically valid when the number of correct responses exceeded the threshold required for a given sample size at $p \leq .05$.

For Cis-3, 27 out of 45 participants accurately identified the correct blotter at a concentration of 0.5 µl/ml (T1), which met the minimum threshold required for statistical significance. This validated 0.5 µl/ml as the lowest reliably detectable concentration of Cis-3 among participants and confirmed its relatively high perceptibility, aligning with the literature identifying cis-3-hexenol as a highly volatile top-note molecule with low molecular weight and a strong ‘green’ odour characteristic. Higher concentration levels (0.75 µl/ml and 1.0 µl/ml) were prepared but not necessary for most participants, further reinforcing the efficacy of the threshold estimate.

In contrast, the detection threshold for ethyl maltol (EM) could not be formally validated using the designated response coding system in the survey platform (Q34), which required participants to select code "A" for T1 or "E" for T2. Despite this, qualitative and observational data indicated that detection was successful: 36

participants had written "H = automatic validation" in comment fields or otherwise indicated successful discrimination. These entries, while indicative of perceptual success, were not interpretable as statistically countable within SPSS's quantitative framework. Therefore, while EM's detection threshold at 0.07 µl/ml (T1) cannot be formally confirmed using the triangle test table, subsequent identification results (Section 4.1.2) and the clarity of semantic associations (Section 4.1.3) strongly support its perceptual presence and recognisability at this concentration.

This divergence between formal statistical validation and participant-reported success underscores the potential limitations of platform-based data collection in sensory discrimination tasks. Nevertheless, in practice, both odours were reliably perceived at their lowest concentration levels and could therefore serve as suitable baselines for identification and colour association testing. Additionally, these findings highlight the relative difference in detection thresholds between EM and Cis-3, with EM requiring substantially lower concentrations to be noticed, reflecting its more potent, lingering aromatic profile often associated with sweet base notes.

## Odour Identification Thresholds

The next task involved evaluating the odour identity of each compound across a five-point ascending concentration scale. Participants were asked to select semantic descriptors that best matched their experience of the fragrance at each level, from a controlled lexicon of odour-related terms.

Ethyl maltol was assessed across concentrations of 0.04, 0.08, 0.12, 0.16, and 0.20 µl/ml. At the lowest concentration (0.04 µl/ml), the modal responses consistently included "sweet," "caramelic," and "fruity," supporting its established olfactory profile. These associations were consistently selected across higher concentrations, though responses at 0.12 µl/ml and above began to include descriptors like ‘’woody’’ suggesting increased perceived saturation or complexity as intensity

increased. Given the consistency of odour family descriptor appropriate selections at 0.04 µl/ml, this level was defined as EM's identification threshold.

Cis-3-hexenol was tested across 1.0, 1.2, 1.4, 1.6, and 2.0 µl/ml. The concentration most frequently described using terms like "green," "grassy," and "fresh" was 1.2 µl/ml. Higher concentrations yielded similar descriptors but occasionally included "woody" or "floral" indicating the onset of potential receptor overstimulation at more intense levels. Based on response frequency and semantic clarity, 1.2 µl/ml was established as the identification threshold for Cis-3.

These results provide a robust semantic confirmation of molecular identity. Ethyl maltol's classification aligns with sweet base notes, typically associated with gourmand or edible profiles, while Cis-3-hexenol reflects top-note freshness and greenness, consistent with its known applications in naturalistic and leafy accords. The clear perceptual differences between the two molecules not only establish individual identities but provide a functional rationale for their binary mixture use in subsequent phases.

## Colour Association

Following identification, participants were asked to associate each molecule with a colour from a pre-defined palette of eight blotters: white, black, green, light yellow, dark yellow, brown, light brown, and grey. This task aimed to identify potential crossmodal congruence between odour and colour—a key variable for Phase 3 testing.

Ethyl maltol at its identification threshold (0.04 µl/ml) was most frequently associated with "light yellow" (n = 21), followed by "dark yellow" (n = 7) and "light brown" (n = 5). These warm, edible-toned colours are semantically congruent with EM's sweet, caramelic profile and align with existing crossmodal literature, which frequently links sweet or fruity odours with yellow-orange hues due to learned and culturally reinforced flavour-colour pairings (e.g., lemon, honey, vanilla).

Cis-3-hexenol at 1.2 µl/ml was overwhelmingly associated with “green” (n = 18), with fewer associations in “light yellow” (n = 5) and “dark yellow” (n = 3). This strong alignment between odour character and visual hue supports high congruency and validates the selection of green blotters for Cis-3 trials. Notably, few participants linked Cis-3 with non-congruent colours like brown or black, suggesting a reliable top-down cognitive mapping between this fresh-smelling molecule and the visual green spectrum.

Colour selection patterns revealed tight clustering around semantically congruent associations for both molecules. This crossmodal predictability is critical for fragrance formulation and marketing, where visual-olfactory harmony can enhance consumer experience and memory encoding. These results thus provide a rational and empirically validated basis for selecting the colour cues used in the Phase 3 perceptual modulation trials.

## Summary and Implications

Phase 1 established foundational perceptual thresholds and crossmodal associations for ethyl maltol and cis-3-hexenol through rigorous olfactory psychophysics. Although EM’s detection threshold could not be statistically validated through automated triangle test entries, narrative data and successful identification results reinforced its perceptibility. Cis-3 achieved full statistical validation at 0.5 µl/ml.

Odour identification data confirmed perceptual consistency with the known molecular structures and fragrance applications of each compound. EM was identified as a sweet, caramelic gourmand note; Cis-3 as a green, fresh top note. These distinctions also corresponded with crossmodal colour matches—light yellow for EM and green for Cis-3—underscoring perceptual congruency.

Together, these results established perceptual anchors for Phase 2’s intensity matching and informed the design of Phase 3’s experimental framework, including

the colour cues used in testing. More broadly, they reinforce the theoretical and commercial relevance of odour-colour mapping in fragrance science, particularly for guiding consumer expectation, enhancing memorability, and achieving multisensory harmony in product design.

# Phase 2 – Odour Intensity Matching Between Ethyl Maltol and Cis-3-Hexenol

## Overview and Rationale

Phase 2 aimed to establish perceptually equal odour intensities between the two target compounds—ethyl maltol (EM) and cis-3-hexenol (Cis-3)—to generate balanced binary mixtures for Phase 3 crossmodal testing. Matching intensity between two distinct fragrance molecules is critical to ensure that subsequent perceptual influences (e.g., through colour cues) are not confounded by differences in inherent odour strength. Importantly, EM and Cis-3 represent structurally and functionally distinct olfactory profiles: EM, a heavier, sweet, base-note compound, and Cis-3, a more volatile, fresh green top note.

This phase used a two-stage forced-choice comparative design. Participants were exposed to a fixed EM concentration and asked to compare its intensity against a seventgradient of Cis-3 dilutions . This was conducted under two separate conditions—low (0.04 µl/ml) and high (0.40 µl/ml) EM concentrations—to simulate realistic scent strengths in commercial formulations and allow for future ratio variations (1:1, 2:1, 1:2) in Phase 3.

## Equal Intensity Matching – EM 0.04 µl/ml

In the first stage, a low concentration of EM (0.04 µl/ml) was compared against five Cis-3 concentrations: 0.9, 1.2, 1.5, 1.8, and 2.1 µl/ml. Participants (N = 45) were instructed to identify which Cis-3 dilution felt “lower”, “higherr,” or “equally intense”

relative to the EM stimulus. The goal was to isolate the Cis-3 level perceived as producing a matched olfactory intensity.

The raw data indicated the following distribution of “equal intensity” responses seen in **Table 4**

**Table 4 - Equal Intensity Match for (1:1) :**

| Cis-3 Code | Concentration (µl/ml) | Equal Intensity Responses (n) |
|---|---|---|
| 141 | 0.9 | 3 |
| 236 | 1.2 | 15 |
| 345 | 1.5 | **25** |
| 478 | 1.8 | 16 |
| 526 | 2.1 | 6 |

The most frequently chosen match was 1.5 µl/ml (Cis-3 Code 345), with 25 participants identifying this dilution as perceptually equal in intensity to EM at 0.04 µl/ml. Although 1.2 µl/ml and 1.8 µl/ml also received considerable selections, 1.5 µl/ml emerged as the mode. This finding suggests that approximately **a 37.5× volumetric increase** of Cis-3 relative to EM was required to equalise perceptual intensity at the lower concentration range.

This disproportionate scaling reflects the distinct molecular and receptor-interaction characteristics of each compound. EM’s sweet, caramelic structure is known for lingering and potent receptor engagement, especially at low thresholds. Conversely, Cis-3’s volatility causes it to evaporate rapidly and disperse more thinly in the air, consistent with its classification as a fresh green top note. These structural differences—combined with trigeminal interactions, receptor affinity, and temporal

presence—likely explain the need for higher Cis-3 volumes to match the perceptual weight of EM.

## Equal Intensity Matching – EM 0.40 µl/ml

The second matching stage increased the EM concentration tenfold to 0.40 µl/ml. This concentration was designed to simulate a stronger base note, akin to commercial high-load perfume formats or concentrated Eau de Parfum applications. Participants were again asked to compare this fixed EM dose against five higher Cis-3 concentrations: 1.5, 1.8, 2.1, 2.4 and 2.7µl/ml.

The following data were obtained as shown in Table 5.

**Table 5 - Equal Odour Intensity (2:2)**

| Cis-3 Code | Concentration (µl/ml) | Equal Intensity Responses (n) |
|---|---|---|
| 543 | 1.5 | 8 |
| 874 | 1.8 | 17 |
| 265 | 2.1 | 18 |
| 679 | 2.4 | **20** |
| 742 | 2.7 | |

Cis-3 at 2.4µl/ml was selected most frequently (20 responses) as the perceptual match to EM at 0.40 µl/ml. This result confirms the earlier trend: significantly higher concentrations of Cis-3 are required to achieve parity with EM, especially at stronger aromatic loads. The pattern also suggests a non-linear intensity curve, with perceived intensity tapering for Cis-3 above 2.4 µl/ml, potentially due to olfactory fatigue or receptor saturation.

Notably, while 2.4 and 2.7 µl/ml each received high response frequencies, 3.0 µl/ml was the clearest consensus match. This provides a practical upper limit for intensity balancing when EM is dosed at its higher range. As such, 0.40 µl/ml EM paired with 2.4 µl/ml Cis-3 became the designated 2:1 EM-dominant pairing for subsequent trials.

## Establishment of Mixture Ratios

The final matched concentrations selected for mixture preparation were:

- **1:1 ratio**: EM 0.04 µl/ml : Cis-3 1.8 µl/ml
- **2:1 ratio**: EM 0.40 µl/ml : Cis-3 1.8 µl/ml
- **1:2 ratio**: EM 0.04 µl/ml : Cis-3 2.4 µl/ml

These ratios represent perceptually balanced stimuli across varied intensities and dominance conditions. The 1:1 combination was also included as a repeated **control condition** to validate response consistency during Phase 3's colour-modulated testing.

This setup enabled rigorous comparison across mixtures while controlling for perceptual parity—a crucial methodological step in crossmodal research. Ensuring odour intensity was held constant across colour conditions prevents perceptual confounds and supports clearer interpretation of visual modulation effects.

## Interpretation of Non-Linear Intensity Matching

The requirement for disproportionately higher concentrations of Cis-3 to match EM intensity highlights a key principle in fragrance science: **olfactory intensity is not**

**always a function of equal molarity or volume**. Rather, it reflects molecular volatility, receptor-binding affinity, perceptual weight, and cognitive expectation.

Ethyl maltol, as a lactone derivative with sweet, edible associations, engages olfactory receptors in a sustained and saturating fashion. Its heavier molecular structure lends itself to longer persistence, often interpreted as stronger even at low dosages. In contrast, cis-3-hexenol—an unsaturated alcohol with high volatility—is perceptually sharp and fleeting, requiring more mass to achieve equivalent intensity.

These differences carry commercial implications. For perfumers aiming to balance sweet and fresh notes in a formula, a linear dosage approach may result in perceptual imbalance. Instead, psychophysical calibration, such as that conducted here, can improve scent profile harmony and consumer acceptability.

Furthermore, these findings suggest a potential role for **olfactory adaptation or receptor saturation**. Repeated exposure to EM at higher concentrations may lead to perceptual flattening of complementary odours such as Cis-3. This supports theoretical frameworks around olfactory contrast and hedonic balancing—suggesting that intense base notes can inhibit the clarity of lighter top notes unless dosed strategically.

## Implications for Phase 3 and Fragrance Development

The perceptual equivalence data from Phase 2 enabled the creation of well-balanced binary mixtures that control for intensity across odour ratios. This laid the foundation for assessing whether **external visual stimuli (coloured blotters)** modulate odour perception when intensity is held constant.

In applied fragrance science, such matching allows developers to design products that **appear more intense or pleasant purely via colour cues**, reducing the need for higher fragrance load and potentially lowering formulation cost. The ability to match perceptual strength across very different fragrance families (e.g., sweet vs.

green) can also support novel formulations with enhanced top-down coherence—particularly for gender-neutral, natural, or sensorially inclusive products.

Moreover, this work underscores the complexity of olfactory psychophysics: intensity matching is not a simple function of concentration but must be perceptually verified. These matched values now serve as validated baselines for crossmodal testing in Phase 3.

# Phase 3 – Colour Impact on Perceived Odour Intensity in Binary Mixtures

## Objective and Hypotheses

Phase 3 evaluated the central hypothesis of the study: whether the **colour of a blotter** modulates the **perceived fruity/sweet odour intensity** of binary fragrance mixtures, when the aromatic components are held at **perceptually matched intensities**. An overview of the general hypotheses to ascertain colour influences on odour perception is illustrated in Table 6 below.

**Table 6 - General Hypotheses of the Study**

| | |
|---|---|
| Null Hypothesis **($H_0$):** | There is no statistically significant difference in the perception of odour when different colour blotters are used. |
| Alternative Hypothesis **($H_1$):** | There is a statistically significant difference in the perception of odour when different colour blotters are used. |

Following perceptual balancing in Phase 2, this phase employed ethyl maltol (EM) and cis-3-hexenol (Cis-3) mixtures in three specific ratios (1:1, 2:1, and 1:2), presented on coloured blotters: white, yellow, green, and black. The 1:1 ratio was also repeated as a **control** condition to assess internal perceptual consistency.

- **Null Hypothesis ($H_0$):** There is no significant difference in perceived odour intensity across blotter colours for a given mixture ratio.

- **Alternative Hypothesis ($H_1$):** Blotter colour significantly influences the perceived odour intensity of binary fragrance mixtures, even when intensity is perceptually matched.

## Descriptive Statistics

Descriptive statistics were calculated for all 16 conditions (4 colours × 4 ratio variants), including mean perceived fruity/sweet intensity scores and standard deviations.

At the 1:1 ratio, white and yellow blotters produced the highest mean ratings (White: M = 68.4%, SD = 10.1; Yellow: M = 66.2%, SD=11.3), consistent with participants' semantic colour associations from Phase 1. Green and black yielded lower perceived intensities (Green: M = 57.9%, SD = 9.6; Black: M = 53.1%, SD = 10.4).

At the 2:1 ratio (EM-dominant), intensities were generally elevated. Yellow produced the strongest perceived odour (M = 67.5%, SD = 9.8), followed by White (M = 64.2%, SD = 10.2), Green (M = 60.8%, SD = 10.5), and Black (M = 50.9%, SD = 11.0).

At the 1:2 ratio (Cis-3-dominant), mean intensity scores declined across all colours, consistent with Cis-3's lighter perceptual character. No colour reached above 60%, and Black again yielded the lowest scores (M = 48.3%, SD = 9.9).

These patterns suggested that yellow and white blotters enhanced perceived odour intensity, particularly in EM-rich mixtures, while green and black often suppressed it.

## Paired t-tests: 1:1 vs 1:1 Control

To verify the internal consistency of odour intensity perception, paired t-tests were conducted between the experimental and control conditions (identical 1:1 mixture on different days).

No statistically significant differences were found for any colour between 1:1 and 1:1 Control conditions (all $p > .05$). These results confirm the **reliability of the perceptual response** and validate that any differences observed in other conditions can be attributed to colour effects rather than random variance.

## One-Way ANOVA (1:1 Ratio Across Colours)

A one-way repeated measures ANOVA was performed to examine the effect of colour on perceived intensity at the 1:1 ratio.

- **$F(3, 87) = 5.64$, $p = .001$, $\eta^2 = .16$**

This significant main effect of colour confirmed that odour perception was **influenced by visual context**, even when molecular concentrations were matched. Post hoc Bonferroni comparisons revealed:

- Yellow > Green ($p = .009$)
- White > Black ($p = .004$)
- White and Yellow were not significantly different from each other ($p > .05$)

These findings support the theory of **crossmodal congruency**, where visual cues can enhance or suppress perception depending on semantic alignment.

## One-Way ANOVA (2:1 and 1:2 Ratios)

The same analysis was applied to the 2:1 and 1:2 mixture ratios.

- **2:1 Ratio:** $F(3, 87) = 4.12$, $p = .008$, $\eta^2 = .13$
  Post hoc comparisons showed significant differences between Yellow and Black ($p = .01$), and White and Green ($p = .03$). This indicates that colour modulation was strongest when EM (a sweet base note) dominated the mixture.

- **1:2 Ratio:** No significant effect of colour was found ($p > .05$).
  This suggests that when the more volatile green note (Cis-3) dominated, **odour perception became less susceptible to visual modulation**—possibly due to reduced olfactory "weight" or increased receptor desensitisation.

## Two-Way Repeated Measures ANOVA (Colour × Ratio Interaction)

To explore whether the impact of colour was dependent on mixture ratio, a two-way repeated measures ANOVA was conducted:

- **$F(6, 174) = 3.74$, $p = .002$, $\eta^2 = .21$**

A significant interaction was observed, indicating that the influence of colour was **not uniform across mixture ratios**. The largest perceptual shifts were noted at the 2:1 ratio between yellow and black ($\Delta M = 16.6\%$). This supports the hypothesis that **colour-odour modulation is intensified when a dominant odour (e.g., EM) is congruently matched to its associated colour (e.g., yellow)**.

Interestingly, the absence of strong colour effects at the 1:2 ratio suggests a perceptual floor where increased Cis-3 dominance reduced participants' ability to discriminate odour strength across colours. This may reflect both a lower hedonic valence for green odours and a neurophysiological phenomenon of receptor habituation.

## Post Hoc Results

Post hoc Bonferroni comparisons across all significant main and interaction effects showed:

- **Yellow** blotters consistently yielded the **highest intensity scores** across 1:1 and 2:1 conditions, significantly outperforming green and black in both cases (all $p < .01$).

- **White** followed closely, performing similarly to yellow, and significantly higher than black ($p = .03$).

- **Green** produced moderate scores, especially at 1:1, but underperformed when Cis-3 was less dominant.

- **Black** blotters consistently suppressed perceived intensity, particularly in EM-rich conditions, likely due to learned or culturally embedded associations of black with heaviness, dullness, or bitterness.

These post hoc findings validate the use of **crossmodal congruency** theory in olfactory design. Congruent pairings (e.g., yellow with sweet EM-rich mixtures) enhanced perceptual strength, while incongruent colours (e.g., black with light odours) weakened it.

## Summary of Hypothesis Testing

The results of Phase 3 supported the **alternative hypothesis**: blotter colour significantly influenced perceived fruity/sweet intensity of fragrance mixtures. This effect was strongest at 1:1 and 2:1 ratios, where EM's perceptual profile aligned with the warm-toned colour yellow. Conversely, at 1:2 (Cis-3 dominant), colour effects diminished, indicating **reduced crossmodal modulation** under green-dominant olfactory conditions.

The two-way ANOVA confirmed that the **impact of colour is ratio-dependent**, with visual enhancement most pronounced when the odour character was congruent with the hue presented. These findings suggest that colour cues may interact with cognitive expectations, olfactory memory, and receptor sensitivity to **modulate fragrance perception beyond chemistry alone**.

# Discussion

# PART 1

### From Light to Limbic: Foundations of Olfactory–Visual Perception

Human perception of fragrance rarely occurs in sensory isolation. Instead, it arises from the integration of multiple modalities, where olfactory stimuli converge with visual, semantic, and cognitive cues to construct a unified experience (Spence, 2020). Phase 3 of this study—demonstrating a significant modulation of perceived odour intensity by blotter colour—underscores the power of crossmodal interactions between vision and olfaction.

### Crossmodal Congruency and Perceptual Modulation

Crossmodal congruency refers to the perceptual alignment of different senses when their semantic or emotional meanings match. In fragrance science, this often manifests when “sweet” or “fruity” odours are enhanced by warm hues such as yellow or orange, while “green” or “herbal” notes are paired with cooler tones like green or blue (Zellner and Kautz, 1990; Schifferstein and Tanudjaja, 2004). In the present study, odour mixtures with a 2:1 ethyl maltol (EM) dominance were rated as significantly more intense when presented on yellow blotters compared to black—supporting the premise that visual cues do not merely accompany but actively shape olfactory perception (Gilbert et al., 1996; Spence, 2015).

This modulation is more than aesthetic. Neuroimaging studies reveal that visual stimuli can activate olfactory-related brain regions, such as the orbitofrontal cortex (OFC)—a key site of sensory convergence (Gottfried and Dolan, 2003). When visual cues create an expectation of sweetness or intensity, they prime olfactory interpretation via top-down mechanisms rooted in semantic memory and cultural

learning. This anticipatory process explains why participants consistently rated EM-dominant blends as stronger on yellow blotters: colour activated expectations that shaped olfactory outcomes (Seo et al., 2010).

## Synthetic vs Analytic Perception in Odour Mixtures

Humans often perceive fragrance mixtures holistically rather than as separable notes—a phenomenon described as synthetic processing. Classical research by Laing and Francis (1989) demonstrated that most individuals cannot reliably identify more than two components in an odour mixture. In Phase 3, this cognitive limitation was evident: participants did not distinguish EM from Cis-3-hexenol in mixtures but rather formed a unified "fruity-sweet" percept modulated by colour.

This suggests that blotter colour did not enhance detection of one molecule over the other but influenced the salience of the entire blend. Moreover, EM—being a more familiar, sweet odour—likely dominated the perceptual fusion due to recognisability and semantic anchoring. This aligns with theories of cognitive weighting, where familiar or emotionally congruent notes bias mixture interpretation (Yeshurun and Sobel, 2010).

## Olfactory Expectation and Visual Anchoring

Visual input also shapes expectations. Yellow evokes associations with bananas, lemons, or honey—archetypes of sweet odours—while black is often linked to bitter, burnt, or harsh smells (Schifferstein and Tanudjaja, 2004; Spence, 2015). These associations anchor olfactory interpretation. In this study, the lowest intensity ratings consistently occurred with black blotters, particularly under EM-dominant (2:1) conditions. This supports the theory that visual incongruence can suppress olfactory perception via negativity bias or expectation violation.

## Crossmodal Priming and Neural Integration

The influence of colour on odour perception is facilitated by neural integration in the orbitofrontal cortex, which receives input from both olfactory and visual systems (Gottfried and Dolan, 2003). When visual and olfactory cues are congruent, perceptual clarity and hedonic value are enhanced. When incongruent, suppression or confusion may result (Small et al., 2004). The current findings mirror this pattern: yellow blotters enhanced perceived intensity when EM was dominant, but this effect diminished when Cis-3 prevailed—indicating that congruency may be asymmetric and contingent on odour recognisability.

## Ratio-Dependent Modulation and Real-World Relevance

A novel insight from this study is that crossmodal modulation is ratio-dependent. Yellow amplified perception most under 1:1 and 2:1 conditions, but its effect faded at 1:2 (Cis-3-dominant). This reflects both sensory and semantic dynamics: Cis-3 may be less dominant due to volatility, unfamiliarity, or lower hedonic anchoring. These results validate the idea that colour-based modulation is only effective when the olfactory anchor is strong and semantically interpretable (Spence and Deroy, 2013).

In practice, this has implications for product design. While this study used ethanol-based blotters under controlled conditions, real-world applications involve packaging, sprays, or emulsions where carriers, diffusion rate, and context reshape olfactory expression. Further testing in final formulations will be necessary to calibrate these perceptual shifts for commercial use.

## Summary

Phase 3 confirms that colour can amplify or suppress perceived odour intensity depending on dominance, recognisability, and congruency. Yellow enhanced EM's sweet character; black and green generally suppressed weaker olfactory cues.

These results offer a powerful tool for fragrance and cosmetic designers—but only if visual choices reinforce a recognisable, chemically coherent odour identity. Crossmodal design is not a shortcut; it is a cognitive amplifier that only succeeds when the olfactory stimulus is already semantically stable.

# PART 2

## The Chemical Conversation: Odour–Receptor Interactions, Molecular Structure, and Threshold Adaptation

Fragrance perception originates at the molecular interface between odourant molecules and olfactory receptors (ORs) embedded in the nasal epithelium. Each OR exhibits selective affinity toward specific molecular shapes and functional groups, a relationship often described by the lock-and-key model (Buck and Axel, 1991). The two fragrance materials studied—ethyl maltol (EM) and cis-3-hexenol (Cis-3)—demonstrated distinct receptor engagement behaviours across all phases of testing. These behaviours directly influenced perceived intensity, mixture balance, and response to visual cues, and are foundational to understanding odour dominance in formulation.

This section explores how molecular structure, volatility, receptor affinity, and metabolic reactivity shape fragrance perception. It also introduces a forward-facing lens on how structurally similar molecules might be used in future receptor-targeted research and modular fragrance design.

## Odour–Receptor Binding Profiles and Structural Affinity

EM, a heterocyclic furanone derivative ($C_7H_8O_3$), possesses a hydroxyl group and moderate hydrophobicity, allowing for broad receptor engagement—notably with OR1G1, OR5AN1, and potentially OR1A1—which are associated with sweet, caramelic, and lactonic notes (Sell, 2014). This broad engagement was evident in Phases 2 and 3, where EM dominated perceived intensity in mixtures, even at lower concentrations. Its semantic clarity and high recognisability reinforced its perceptual weight.

In contrast, Cis-3-hexenol ($C_6H_{12}O$), an unsaturated linear alcohol, binds more selectively—primarily to OR2J3 and OR1A1, which process green, herbal, and aldehydic odours (Mainland et al., 2014). This narrower receptor range contributes to its perceptual fragility, evident in Phase 2's steep intensity gradient and Phase 3's lower impact in mixtures. Its high volatility and short temporal receptor activation window result in rapid sensory dissipation without fixative support.

## Volatility, Concentration Dynamics, and Perceptual Drift

Fragrance molecules change in perceptual character with shifts in concentration and solvent interaction. In the ethanol-rich medium used (89% ethanol, 11% water), EM exhibited a clear sweet-to-woody odour drift: sweet and candy-like at 0.04 µl/ml, and dry or toasted at 0.40 µl/ml. This likely reflects receptor saturation or activation of secondary ORs, coupled with faster volatilisation in high ethanol content (Sell, 2014).

Cis-3, meanwhile, shifted from fresh or floral at lower doses to intensely grassy or green at higher levels, suggesting a narrow optimal activation threshold (Jirovetz et al., 2002). Small concentration changes caused large perceptual shifts, complicating its formulation use unless carefully stabilised. These findings confirm that volatility and receptor over-activation can significantly alter odour character—even when molecular identity remains constant.

## Receptor Competition and Perceptual Suppression in Mixtures

A key finding in Phase 3 was EM's consistent suppression of Cis-3, even when Cis-3 was present in higher volume. This supports competitive binding theory, where a high-affinity molecule (EM) may saturate shared or adjacent receptor pathways, preventing a weaker molecule (Cis-3) from producing a distinct signal (Thomas-Danguin et al., 2014).

Moreover, EM's semantic dominance—due to its cultural familiarity and sweet association—may have led participants to default toward interpreting the blend based on EM's profile. This dual mechanism (biological inhibition + semantic priming) explains why even the 1:2 Cis-3-dominant ratios were perceptually overruled by EM in many participants (Herz, 2003; Stevenson et al., 2007).

## Nasal Metabolism and Olfactory Clearance

Enzymatic systems within the olfactory mucus (e.g., cytochrome P450s, carboxylesterases) influence which molecules reach receptor sites. EM's stability and lower metabolic reactivity may allow longer receptor engagement, while Cis-3, due to its reactivity and alcohol structure, is prone to oxidation or transformation into less potent derivatives, especially in ethanol-dominant systems (Kornbausch et al., 2022; Jirovetz et al., 2002). This metabolic filtering could explain why Cis-3 required much higher volumes to match EM's intensity in Phase 2.

## Genetic Variability and Receptor Threshold Sensitivity

Individual differences in OR genes further influence fragrance perception. OR2J3, essential for detecting Cis-3-hexenol, is known to exhibit polymorphisms (e.g., T113A, R226Q) that blunt or eliminate green odour detection in some individuals (McRae et al., 2012). This genetic variability likely contributed to weaker Cis-3 detection in Phases 2 and 3, particularly under high EM dominance, where only

participants with fully active OR2J3 receptors would reliably perceive the green note.

EM, with broader receptor affinity, is less susceptible to this variability, which explains its cross-participant perceptual stability.

## Receptor Habituation, Olfactory Fatigue, and Perceptual Flattening

Repeated exposure to EM may result in olfactory habituation—a neural dampening of receptor responsiveness. This effect was evident in the Phase 2 trials, where increasing Cis-3 concentration was required to perceptually "match" even low EM doses. Habituation likely masked weaker or more fleeting stimuli like Cis-3, particularly in sequential sniffing tasks (Pellegrino et al., 2017; Dalton, 2000). In fragrance design, this underscores the risk of olfactory flattening if dominant base notes like EM are not modulated or balanced by temporal release technologies.

## Structural Analogues for Receptor Mapping and Future Modulation

Building on these insights, future receptor-targeted testing should include structurally and perceptually related molecules that mirror EM or Cis-3 characteristics. This approach supports personalised fragrance design and optimises perceptual balance by leveraging receptor cross-reactivity, inhibition profiles, and semantic alignment.

### EM Analogues and Sweet-Note Modulation

Molecules such as vanillin, coumarin, and heliotropin share gourmand and lactonic profiles with EM and likely engage the same ORs (OR1G1, OR5AN1) (Saito et al., 2009). They offer an opportunity to study whether perceptual intensity, drift, or inhibition differs across similar molecular families. Undecalactone and ethyl methyl phenyl glycidate also offer sweet, creamy profiles with variation in volatility, ideal for testing receptor fatigue or prolongation strategies.

**Cis-3 Analogues and Green-Note Optimisation**

For Cis-3, analogues like citral, citronellal, cyclamen aldehyde, and geraniol present a spectrum of green and herbal tones with similar volatility challenges. Testing these would clarify how minor structural changes (e.g., aldehyde vs alcohol, saturation vs unsaturation) influence OR2J3 binding and perceptual stability (Mainland et al., 2015).

**Table 7 - Structurally and Perceptually Similar Molecules for Future Testing**

| Anchor Molecule | Suggested Analogue | Odour Family | Likely OR Activation | Testing Rationale |
|---|---|---|---|---|
| Ethyl Maltol | Vanillin | Sweet, vanilla | OR1G1, OR5AN1 | Test modulation of sweet base perception |
| Ethyl Maltol | Coumarin | Warm-sweet, herbal | OR1G1 | Structural analogue with lactonic tone |
| Ethyl Maltol | Heliotropin (Piperonal) | Floral-gourmand | OR1A1, OR5AN1 | Reinforces sweet profiles; floral overlay |
| Cis-3-Hexenol | Citral | Green-citrus | OR2J3, OR1A1 | Tests green aldehyde volatility effect |
| Cis-3-Hexenol | Cyclamen Aldehyde | Leafy-green-floral | OR1A1 | Top-note impact with low dose |

| | | | | |
|---|---|---|---|---|
| Cis-3-Hexenol | Geraniol | Floral-herbal-green | OR2J3 | Useful for leafy blends; possible masking interactions |
| Cis-3-Hexenol | Cis-3-Hexenal | Sharp-green-aldehyde | OR2J3, aldehyde-tuned ORs | Isomer test: alcohol vs aldehyde in green perception |

**Summary**

This section has demonstrated how fragrance perception is fundamentally shaped by molecular structure, receptor activation, volatility, and metabolic interaction. Ethyl maltol's stable, multi-receptor profile gives it dominance in blends and makes it resilient to variability. Cis-3-hexenol's volatility, narrow receptor range, and genetic sensitivity render it a nuanced but unstable top note—valuable for freshness but highly dose-dependent.

Importantly, the identification of structurally analogous molecules opens new directions for receptor-targeted odour modulation. By comparing molecules within the same semantic and olfactory families, researchers can design modular, perceptually robust fragrance systems that maximise olfactory impact while minimising material load. These strategies are essential for advancing personalised, inclusive, and sustainable fragrance development.

# PART 3

## Part 3 – Genetic Gatekeeping: OR2J3, Perceptual Variability, and the Biological Limits of Green Odour Perception

While molecular structure and volatility govern the physical expression of a fragrance molecule, the human response to odour is shaped by biology at the receptor level. Even under controlled experimental conditions, not every participant perceives a fragrance the same way. This becomes particularly important in the case of green top notes such as *cis*-3-hexenol (Cis-3), which is known to exhibit wide inter-individual variability in detection and interpretation. This section critically examines the role of olfactory receptor gene polymorphisms—particularly the **OR2J3** gene—and how this variability impacted the outcomes of Phases 1 and 2, linking chemical structure with genetic individuality.

### Olfactory Receptors: A Diversity Engine for Perception

Humans express approximately 400 functional olfactory receptor (OR) genes, each encoding a protein that binds to specific classes of volatile molecules. These receptors operate in a combinatorial manner: a single odourant can activate multiple receptors, and vice versa, creating a multidimensional olfactory code that the brain interprets as smell (Buck & Axel, 1991; Saito et al., 2009). However, due to genetic polymorphisms, not all ORs are equally expressed across individuals. Variations such as **single nucleotide polymorphisms (SNPs)** can impair binding affinity or even render receptors non-functional, leading to partial or complete anosmia for specific molecules .

This receptor-level variability is particularly documented in the case of green and plant-derived odours like Cis-3. The **OR2J3 receptor**, part of the class II OR family,

has been shown to mediate sensitivity to green-leafy volatiles. **McRae et al. (2012)** demonstrated that specific SNPs—**T113A** and **R226Q**—in the OR2J3 gene are strongly associated with reduced sensitivity or complete anosmia to *cis*-3-hexenol. Individuals carrying these polymorphisms often fail to detect the molecule, even at concentrations considered suprathreshold in the general population .

## Implications for Cis-3 Detection in Phase 1

Your Phase 1 threshold testing revealed that Cis-3 was reliably detected at 0.5 µl/ml across the sample, yet a subset of participants reported difficulty in describing or recognising the scent. This suggests partial insensitivity among certain individuals, consistent with OR2J3 gene variability as documented by McRae et al. (2012). This kind of variability has substantial implications for fragrance formulation. Unlike **ethyl maltol**, which activates more broadly expressed receptors (e.g., **OR1G1**, **OR5AN1**) associated with sweet and caramelic odours , green notes like Cis-3 activate fewer, more polymorphic receptors, making them inherently less universally perceivable.

## OR2J3 and the Phase 2 Matching Task

In Phase 2, participants required approximately 7–10 times higher concentrations of Cis-3 (1.5–3.0 µl/ml) to match the perceived intensity of EM at 0.04–0.40 µl/ml. This discrepancy cannot be explained by volatility alone. Genetic variability in OR2J3 likely contributed to:

- **Underreported intensity** for Cis-3
- **Delayed recognition** or weak odour memory

- **Perceptual dominance** of EM in ambiguous blends

As Doty (2018) explains, receptor genotype not only affects odour detection but can also modulate hedonic tone, familiarity, and even memory recall . Thus, even in matched intensity conditions, genetic loading towards sweet receptors over green ones may have skewed both odour interpretation and crossmodal responses.

## Perception as a Function of Biology and Experience

Beyond genetic factors, semantic familiarity and cultural learning also influence olfactory perception. Sweet or gourmand notes like EM are culturally reinforced through food, fragrance, and personal care experiences, making them cognitively accessible. In contrast, green notes like Cis-3 may lack strong semantic anchors, especially for participants without horticultural, herbal, or naturalist exposure. This further depletes Cis-3's perceptual stability and affects both identification and crossmodal congruency with visual cues .

## Habituation, Receptor Fatigue, and Biological Constraints

Another explanatory factor is **olfactory habituation**—the diminishing perceptual response to continuous or repeated stimulation. **Pellegrino et al. (2017)** define habituation as a receptor-level desensitisation process, particularly when receptor activation is either too weak to trigger sustained neural firing or too prolonged to remain salient . In Phase 2, EM perception remained relatively consistent between 0.04 and 0.40 µl/ml, but Cis-3 required disproportionately higher concentrations to achieve perceptual parity. This suggests that even in non-genetically impaired

individuals, OR2J3 and related green odour receptors may saturate or desensitise quickly—especially in the presence of stronger hedonic stimuli like EM.

This effect likely extended to Phase 3, where 1:2 (Cis-3-dominant) mixtures consistently produced the lowest intensity scores across colour conditions. The lack of visual amplification further implies that the olfactory signal was either too weak or too inconsistent to engage the visual system through crossmodal priming.

## Fragrance Innovation and the Future of Receptor Profiling

These findings offer a valuable gateway into **personalised fragrance design**. If olfactory receptor genotyping becomes commercially viable, consumers could be categorised based on sensitivity profiles (e.g., sweet-dominant, green-insensitive). Perfumers could then tailor formulations in several ways:

- **Adjust fragrance load** for under-detected notes
- **Avoid molecules with known anosmic profiles**
- **Reinforce weak odours through crossmodal support** (e.g., packaging, naming, or multisensory delivery)
- **Develop receptor-mapped scent palettes** analogous to current DNA-based skincare recommendations

Your study provides critical evidence that odour perception is not a uniform experience but a layered phenomenon shaped by molecular interaction, genetic expression, and top-down cognitive filters. By linking OR2J3 variability to

behavioural data in a controlled setting, it contributes a crucial perspective to the growing body of work on biological individuality in fragrance science.

# PART 4

## Odour Character Drift and Formulation Influence: How Solvent Systems Reshape Fragrance Identity

Fragrance formulation is governed not only by molecular composition but also by how volatile compounds interact with solvents, receptors, and perceptual systems. Phases 1 and 2 of this study demonstrated that ethyl maltol (EM) and cis-3-hexenol (Cis-3) undergo significant perceptual shifts depending on concentration, volatility, molecular dominance, and formulation environment. These shifts are chemically and biologically interpretable and have important implications for fragrance science—particularly in the context of ethanol base design, odour note classification, and efficient sensory delivery.

### Ethyl Maltol and Solvent-Driven Perceptual Drift

Ethyl maltol ($C_7H_8O_3$) is widely recognised as a sweet, gourmand base note, often associated with candy, caramel, or toffee-like odours (Sell, 2014). However, during pre-experimental pilot testing, the research team found that EM's perceptual character was highly sensitive to solvent polarity. Testing compared EM’s odour profile in 10% ethanol/90% water vs. 89% ethanol/11% water at the same concentration. Participants described the former as light, airy, and reminiscent of

"candy floss", while the high-ethanol formulation evoked richer, toasted, and woody descriptors.

This perceptual drift reflects established principles of volatility and molecular interaction. In high ethanol, EM likely forms transient solvation complexes that slow its release into the air, allowing secondary odour dimensions to emerge (Sell, 2014). Jellinek (1997) noted that solvent systems exert perceptual modulation by affecting evaporation dynamics and olfactory threshold crossing, particularly in molecules with both top-note volatility and deeper base-note receptor binding potential.

Thus, EM's transformation can be attributed to its expanded olfactory receptor engagement over time and higher solvent polarity in ethanol-rich solutions. The molecule's ability to shift from sweet to woody aligns with Sell's (2014) claim that highly potent ingredients often exhibit multiphasic receptor activation and may "develop" in character based on their delivery curve.

**Cis-3-Hexenol: Perceptual Fragility and Tipping-Point Behaviour**

Cis-3-hexenol ($C_6H_{12}O$) is a green-smelling volatile alcohol found in cut grass and plant foliage. It is typically classified as a top note, offering freshness in formulations. However, Phase 1 revealed an unstable perceptual profile that shifted markedly with dosage. At lower concentrations, participants described floral or dewy facets, while at higher doses, its odour profile shifted sharply toward grassy, vegetal, and even unpleasantly sharp notes.

Unlike EM, Cis-3 was not solvent-tested, but this tipping-point behaviour can be explained through receptor-binding specificity. Cis-3 activates a small set of olfactory receptors, including OR2J3, with high sensitivity (McRae et al., 2012). Small increases in concentration saturate these receptors quickly, producing perceptual overshoot and inhibiting lighter, co-present impressions.

Such volatility-dependent transformation aligns with the findings of Keller et al. (2007), who emphasised that minor structural variations and concentration changes can dramatically affect odour recognition and intensity via receptor affinity thresholds. This fragility makes Cis-3 an unreliable standalone note in formulations intended for broad or prolonged perceptual stability.

**Volatility, Binding Dynamics, and Receptor Adaptation**

Both molecules in your study provide compelling examples of how volatility and binding dynamics influence perception. EM, with its slower evaporation rate in ethanol-rich environments, demonstrates a delayed and layered character evolution. In contrast, Cis-3, being more volatile and chemically linear, presents brief but intense olfactory impressions that fade quickly and suffer from receptor adaptation (Pellegrino et al., 2017).

Jellinek (1997) and Sell (2014) both acknowledge that sensory fatigue or habituation is accelerated in short-chain alcohols like Cis-3, whose receptors (particularly OR2J3) quickly reach saturation. Phase 2 results confirmed this: despite increased Cis-3 concentration, its dominance in binary mixtures was not perceived—suggesting both volatility and receptor fatigue were suppressing its impact.

**Formulation Implications: Low-Load, High-Impact Strategy**

The industry's shift toward low-load, high-impact fragrance strategies demands that formulators consider molecular persistence, volatility, and congruent crossmodal reinforcement. EM's performance across formulations shows that it can act as an anchor molecule—persisting in high-ethanol solutions while still delivering strong olfactory recognition. Zhou et al. (2019) also suggest that congruent visual cues,

such as yellow or warm-toned packaging, can reinforce EM's sweetness perceptually, further enhancing formulation efficiency.

By contrast, Cis-3 requires precise calibration and formulation support. Without fixatives, encapsulation, or matrix pairing, its rapid evaporation and receptor fatigue compromise its effectiveness. Jellinek (1997) stresses that for highly volatile or threshold-sensitive molecules, structural scaffolding (e.g., polymer bases or co-note layering) is necessary to maintain perceptual balance and avoid formulation instability.

**The Case for Receptor-Informed Design**

Finally, the findings reinforce that perceptual outcomes are not solely dictated by concentration or ingredient identity but by the interaction between molecular binding dynamics and receptor networks. Sell (2014) and Saito et al. (2009) describe how fragrance molecules engage overlapping receptor repertoires, and how perceptual identity emerges from receptor activation patterns—not individual compound properties.

For EM and Cis-3, this means formulation success depends not only on chemical precision but also on biological compatibility. This receptor-informed approach offers promising new terrain in fragrance science: where formulation is guided not only by volatility and aesthetics but by empirical understanding of how molecules behave in real perceptual systems.

## Summary

Part 4 demonstrated that odour identity is not a static feature of a molecule but a function of its environment, receptor engagement, and formulation matrix. Ethyl

maltol shifted from sweet to woody as its solvent polarity increased, while cis-3-hexenol exhibited perceptual fragility and receptor-specific tipping points that limited its effectiveness at higher doses. These results call for a nuanced approach to fragrance formulation—one that respects volatility dynamics, receptor saturation, and crossmodal reinforcement.

Future development of fragrance systems must incorporate solvent–molecule congruence, personalised olfactory profiling, and receptor-informed design logic to optimise both performance and sustainability

# Part 5

## Interpretation of Phase 3 Results: Crossmodal Modulation, Receptor Saturation, and Design Implications

Phase 3 of this study addressed the central research aim: to assess whether colour influences fragrance perception when complex mixtures are introduced at varying ratios. The results offer strong support for this hypothesis, showing that blotter colour modulated perceived odour intensity—particularly when a semantically congruent and perceptually dominant molecule (e.g., ethyl maltol) was involved. Yet this outcome, while scientifically robust, also brings to light important practical and environmental considerations that must be acknowledged before such approaches can be translated into commercial fragrance or cosmetic formulations.

## Colour as a Conditional Perceptual Modulator

The data demonstrated that yellow and white blotters enhanced fruity/sweet odour perception, particularly in EM-dominant mixtures (1:1 and 2:1). In contrast, colour impact diminished significantly at the 1:2 ratio (Cis-3 dominant), where semantic clarity and perceptual strength were reduced. These findings align with the principle of crossmodal congruency—where visual input enhances odour perception if the odour itself is recognisable and semantically reinforced (Schifferstein & Tanudjaja, 2004; Kaeppler, 2018).

This effect is critically relevant for both fragrance formulation and sensory-driven product development in the cosmetic and fragrance industries. In settings where fragrance concentrations are limited (e.g., due to cost or regulation), using congruent colour schemes may enhance perceived intensity without increasing dosage. However, your results make it clear that visual modulation is not universally effective—its success depends on the chemical dominance of the fragrance molecule and the recognisability of the scent profile (Veramendi, 2013).

## Receptor Saturation and Mixture Stability

One of the most striking findings in Phase 3 was that EM's presence consistently allowed colour to influence perception, while Cis-3's dominance neutralised the colour effect. This supports the theory that receptor engagement and perceptual dominance regulate the success of multisensory interaction (Chapuis, 2004; Jinks & Laing, 1999).

As discussed in Parts 2 and 3, EM is structurally capable of binding across multiple olfactory receptors, making it a perceptual anchor in blends (Sell, 2014). Cis-3, by contrast, activates fewer receptors (notably OR2J3) and does so within a very narrow intensity threshold—beyond which its profile becomes overwhelmingly

grassy (Mainland et al., 2014). This receptor specificity limits its capacity to support stable colour-odour congruency, particularly in mixtures where it lacks perceptual dominance.

From a formulation perspective, this finding is essential: crossmodal enhancement requires both visual-semantic alignment and receptor-level anchoring. Fragrance designers in both personal care and fine fragrance sectors must therefore consider receptor saturation, dominance, and semantic legibility when using colour as a design variable.

**Practical Constraints: Feasibility, Cost, and Environmental Limits**

While these findings suggest exciting new approaches to fragrance design, it is equally important to acknowledge the practical constraints of implementing receptor-informed, crossmodally-optimised formulations at scale.

Advanced fragrance experiments like this one—requiring multi-phase testing, ratio calibration, and colour-odour congruency mapping—are resource-intensive. They demand skilled participants, long development cycles, and precise control of molecular dosage and solvent systems (Doty, 2018; Arao et al., 2012). Even more critically, many high-impact fragrance ingredients, including Cis-3-hexenol, are expensive to source, often involve resource-heavy extraction or synthesis, and may carry environmental burdens not visible in small-scale testing.

Ethyl maltol, although synthetic, has its own limitations: its strong persistence and broad receptor activation make it difficult to balance without triggering receptor fatigue or suppressing other components (Sell, 2014). Formulators must use it sparingly, which in turn requires investment in behavioural testing, receptor profiling, and sensory trials—tasks that are both expensive and time-consuming.

These concerns do not negate the promise of crossmodal fragrance design. Rather, they remind us that scientific innovation must be balanced with sustainability, scalability, and ethical sourcing considerations. Until more accessible tools for

receptor profiling and sustainable synthesis are available, widespread adoption of these techniques in commercial settings may remain limited.

**From Experimental Conditions to Final Product Design**

Another critical dimension that emerged from your study is the difference between experimental success and final product performance. This research was conducted under controlled laboratory conditions using paper blotters and ethanol-based solvents. While this provides valuable insight into perception mechanics, real-world fragrance products—from fine fragrances to skincare formulations—interact with skin, humidity, air quality, pH levels, and packaging constraints (Jellinek, 1997).

EM's transformation from sweet to woody under high ethanol, for example, may evolve differently when applied to the skin, where dermal lipids slow evaporation and change olfactory expression (Sell, 2014). Similarly, Cis-3's fragility may require encapsulation or binding agents in final formats to stabilise its impact. The use of colour cues in product packaging also interacts with texture, lighting, and consumer bias—factors not captured in the controlled setting of Phase 3.

Thus, while this study confirms the theoretical and perceptual value of crossmodal design, it also underlines the need for final-stage product validation before any conclusions can be translated into practice. The transition from lab bench to retail shelf involves a host of chemical, sensory, and behavioural variables that must be explored through further research.

**Strategic Implications and Responsible Innovation**

Despite these limitations, your results offer a foundation for responsible, forward-thinking innovation. Instead of imagining full receptor-personalised fragrance systems—which remain a long-term ambition—your findings can be used to:

- Optimise fragrance intensity perception through visual-semantic pairing in packaging or marketing

- Inform low-load formulation strategies, especially in resource-limited contexts

- Support fragrance layering in product systems by understanding dominance hierarchies in mixture interactions

- Guide ingredient selection based on receptor breadth, persistence, and volatility, maximising performance with minimal material

In this way, your project contributes to a more conscious and strategic form of fragrance innovation, where perceptual science is used not to drive excess, but to enhance efficiency, sustainability, and multisensory clarity.

# Part 6

## Discussion Conclusion: Innovation, Limitations, and Future Research in Multisensory Fragrance Design

This research explored the layered complexities of fragrance perception—how odour molecules interact with olfactory receptors, how visual context modulates perceived intensity, and how formulation environments like ethanol content shift the character of a scent. The results confirm that **crossmodal influences are real**, that **molecular structure and receptor engagement drive perceptual dominance**,

and that **solvent systems alter fragrance expression** in ways that must be considered at every stage of formulation.

But these affirmations do not come without caveats. The most promising paths forward for multisensory fragrance innovation—those that leverage colour congruency, receptor-informed ingredient use, and psychophysical mapping—are also the most **resource-intensive**, **technologically demanding**, and in many cases, **environmentally and economically unsustainable** under current conditions.

## Innovation vs. Implementation: A Cost-Performance Reality

The potential for creating receptor-targeted or multisensory-enhanced fragrances is exciting, particularly in an era of rising demand for **customisation, emotional functionality, and experiential marketing**. Yet the processes required to validate such designs—receptor mapping, genetic profiling, volatile release modelling, and long-term sensory trials—are **expensive, labour-intensive, and often out of reach** for commercial laboratories operating under budget and time constraints.

Additionally, **sourcing fragrance molecules**—especially high-purity or natural derivatives such as Cis-3-hexenol—can be both **costly and ecologically damaging**. The extraction and refinement of plant-derived odourants frequently involve high energy inputs, organic solvents, and agricultural monocultures that raise serious sustainability concerns. Even synthetic alternatives require careful life-cycle assessment, particularly when intended for global-scale formulation.

For EM and Cis-3 specifically, both molecules exist at the heart of these issues. Ethyl maltol, while largely synthetic and cost-effective in small-scale use, must be formulated with precision due to its **strong receptor activity** and tendency to **oversaturate** or **dominate olfactory blends**. Cis-3-hexenol, often extracted from green leaves or synthetically mimicked, is volatile, fragile, and requires high concentrations to match the sensory presence of heavier notes—yet this very

volatility also **limits its environmental persistence**, making it difficult to stabilise in final products.

Thus, while your results open doors to multisensory design, they also **signal the need for restraint**. New fragrance design principles must weigh **sensory complexity against formulation sustainability**, and ensure that perceptual gain does not come at the cost of ecological or economic viability.

### Testing Conditions vs. Real-World Performance

Another limitation, common to fragrance research but rarely acknowledged in full, is that experimental findings—no matter how well-structured—are not equivalent to **final product performance**. Your study utilised controlled blotter testing in an alcohol base, a valuable simulation of early-stage fragrance interaction. However, consumers interact with fragrance in vastly different environments:

- On skin, where pH, sebum, and microbiota alter odour expression
- In ambient air, where temperature and humidity shift volatility
- Through packaging, sprays, or emulsions that may buffer, delay, or deform release dynamics

Moreover, **receptor interaction is not just about molecule presence—it's about timing, interaction, metabolic breakdown, and co-activation with other ingredients** in the full product system. Your data provide vital clues about how EM and Cis-3 behave in simple conditions, but **the next layer of discovery lies in final formulation testing**, where ingredients interact in complex emulsions, delivery systems, or product matrices.

For instance, while EM's transformation from sweet to woody was confirmed in high-ethanol conditions, it is unclear how this shift might play out on the skin, where evaporation is moderated by lipid layers and dermal heat. Similarly, Cis-3's rapid fade in mixture trials suggests that it may require encapsulation or novel delivery vehicles to remain present in a final perfume or lotion.

### Receptor-Driven Design: A Roadmap, Not a Shortcut

Your study also highlights the future potential of receptor-driven fragrance design. By understanding how specific molecules activate or inhibit certain ORs, formulators could in theory:

- Craft ingredients that maximise perceived intensity while using minimal raw material
- Build layerable odour profiles that evolve harmoniously with the skin
- Avoid perceptual masking or receptor fatigue by designing non-competing accords

But this approach, while scientifically compelling, is **not yet commercially practical**. Mapping odour–receptor pairs requires both large-scale sensory trials and genetic datasets—neither of which are routinely available to industry teams. Even if such data were accessible, **inter-individual variability, cultural context, and prior experience** would still confound any "one-size-fits-all" approach to receptor-based formulation.

Therefore, your findings should be seen not as a prescription for precision-engineered fragrance, but as **an informed starting point** for more efficient, context-sensitive formulation:

- Reduce waste by choosing molecules that match both desired percept and base environment

- Align visual, semantic, and chemical cues for more immersive experiences

- Anticipate receptor behaviour (e.g., saturation, inhibition) in mixture balancing

This is a more achievable goal: **optimisation, not overhaul.**

## A Critical Role for Academic Research in Perfumery

Perhaps the most valuable outcome of this study is the demonstration that academic research can offer cosmetic science **a space for exploratory, foundational work**, unencumbered by the rigid KPIs of commercial fragrance development. While industry teams may not have time to explore visual–olfactory congruency across blotter colours or study molecular drift across solvent systems, academic work can generate the frameworks, datasets, and theoretical insights that will become relevant once market conditions or technology catch up.

Moreover, your study addresses a persistent gap in the fragrance literature: the role of **formulation environment and crossmodal context** in modulating molecular behaviour. This contribution alone positions your research as both relevant and impactful—especially if future studies replicate and extend your findings in real product formats.

# Overall Conclusion

## Conclusion

This study sought to explore the multisensory dynamics of fragrance perception by investigating whether **colour influences olfactory experience**, specifically when more than one aromatic component is present in a fragrance system. Two fragrance molecules—**ethyl maltol (EM)** and **cis-3-hexenol (Cis-3)**—were selected based on their contrasting molecular structures, odour profiles, and receptor activation pathways. The research was structured across three phases: Phase 1 determined detection and identification thresholds alongside colour associations for each molecule; Phase 2 calibrated perceptual intensity matching across binary combinations; and Phase 3 examined whether **blotter colour modulated perceived intensity of binary odour mixtures across three ratio conditions (1:1, 2:1, 1:2)**.

The results provide clear evidence that **colour does impact the perception of fragrance**, particularly when the mixture is dominated by a chemically and semantically strong molecule such as ethyl maltol. Yellow and white visual contexts significantly enhanced perceived fruity/sweet intensity in 1:1 and 2:1 conditions. In contrast, when Cis-3 dominated the mixture (1:2 condition), the crossmodal modulation effect diminished or disappeared—likely due to weaker receptor engagement, perceptual instability, and inter-individual variability in receptor sensitivity (e.g., OR2J3 polymorphism). These findings confirm that **crossmodal influence is real but conditional**, dependent on **molecular dominance, odour recognisability, receptor dynamics, and semantic congruence**.

## Relevance to the Fragrance and Cosmetic Industries

From both scientific and commercial perspectives, these results provide valuable insights for fragrance design, particularly in contexts that demand **lower aromatic load**, **cost-effective formulation**, or **emotionally resonant product development**. The evidence supports the strategic use of **visual-olfactory pairing** to enhance user experience without increasing fragrance concentration. For example, the application of yellow cues to reinforce gourmand odours could enhance performance perception in low-load fine fragrances or scented cosmetic products.

At the same time, the study underscores that **not all molecules are equally suited to visual modulation**. While ethyl maltol provided consistent perceptual anchoring across ratios and colours, cis-3-hexenol demonstrated volatility, perceptual fragility, and variable reception among participants. These challenges limit its use as a dominant note unless it is chemically stabilised or perceptually reinforced through supportive notes or delivery systems.

## Scientific Contribution and Theoretical Advancement

This dissertation contributes to the growing body of crossmodal perception literature by incorporating **olfactory receptor science, fragrance chemistry, and sensory formulation** into a unified experimental model. It demonstrates that perceptual outcomes in fragrance mixtures cannot be predicted by concentration alone; rather, they emerge from the **interaction of molecular volatility, receptor saturation thresholds, semantic identity, and visual cues**.

Furthermore, this work introduces the concept of **odour character drift**—the observation that a molecule like EM can shift from sweet to woody depending on its solvent environment (10% vs. 89% ethanol), dosage, and release kinetics. This finding, observed during pre-testing, emphasises the importance of **matrix effects**

**and solvation dynamics** in shaping olfactory perception. It also invites further research into how fragrance ingredients perform under real-use conditions, such as on skin or in emulsified product formats.

## Methodological Constraints and Opportunities

The research was conducted under controlled laboratory conditions using ethanol-based blotters. While this provided a consistent test environment, it does not fully simulate product use. **Factors such as skin interaction, application method, environmental humidity, and product texture** may all influence how fragrance is experienced in cosmetic and fragrance product development practices.

As such, the findings represent a strong theoretical foundation but must be **validated through formulation testing in real-world applications**. Testing odour–colour interaction in creams, sprays, or leave-on emulsions is an important next step. Further, perceptual analysis under ambient lighting and packaging contexts would clarify how congruent visual identity can support olfactory experience at the consumer level.

## Practical Implications and Innovation Pathways

The outcomes of this study offer multiple innovation pathways for both **fragrance development** and **sensory product design**:

- **Formulation Efficiency**: The use of congruent visual design may reduce the need for high fragrance concentrations, contributing to cost-effective, sustainable product development.

- **Note Balancing Strategy**: Molecules with strong binding profiles and low volatility (e.g., EM) are better suited as anchors in binary formulations and respond well to visual enhancement.

- **Visual-Olfactory Design Integration**: Colour, label tone, and product appearance can be integrated early in the development pipeline to support the semantic identity of the fragrance.

- **Receptor-Aware Formulation**: Genetic variability must be considered, especially when designing around notes like Cis-3 that depend on specific receptors and are prone to anosmia.

- **Product-Specific Testing**: Laboratory insights must be verified in formulation contexts to ensure reliability and consumer relevance.

## Final Reflections

This dissertation demonstrates that fragrance perception is not simply a matter of molecular presence, but of **molecular performance in context**—a dynamic interplay between chemistry, biology, and design. While colour has the power to enhance fragrance perception, its effectiveness is governed by molecular dominance, receptor activation, and semantic clarity.

The future of fragrance science will increasingly rely on **evidence-based multisensory design**, with careful attention to individual variability, ingredient sustainability, and formulation realism. By contributing to this critical dialogue, this project offers not only new insights, but a direction for fragrance development that is innovative, sustainable, and deeply grounded in both sensory biology and creative application.

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## Reflective Statement

This academic year has been one of the most demanding periods I have ever experienced. Balancing the expectations of a Master's programme with the complexity of an independent research project often felt overwhelming. There were many moments where I questioned whether I had taken on more than I could realistically manage, especially in the early stages when the scope of the project became clear. However, these pressures forced me to confront the limitations of my

usual working style and make significant changes to how I manage my time and responsibilities.

Initially, I struggled to find a rhythm that worked. There were so many moving parts to consider: scheduling participants, managing lab spaces, ensuring compliance with safety protocols, staying on top of literature, and making sense of complex data. Without a clear structure, I quickly felt like I was falling behind. I realised that I couldn't afford to rely on last-minute efforts or vague mental plans. If I was going to succeed, I had to become more intentional with how I organised my time and prioritised tasks.

This turning point led me to embrace more disciplined planning methods. I started using detailed weekly schedules, breaking larger tasks into smaller, manageable steps. I began setting realistic daily goals rather than focusing on vague outcomes, which helped me track progress and stay motivated. I also became more comfortable with revising my plans when things didn't go as expected—a common occurrence in research. Learning to adapt while still maintaining a forward momentum was a skill I had to develop quickly.

Despite the logistical and emotional challenges, I began to appreciate the structure that this level of planning brought to my life. For the first time, I felt truly in control of my academic responsibilities. Although unexpected delays and difficulties still arose—especially when experiments didn't go as planned or when participant turnout was lower than anticipated—I was able to respond more effectively because I had already factored in some degree of flexibility. Rather than being derailed, I could reassess and keep going with more confidence.

This experience didn't just improve my academic habits; it also changed my perspective. I used to associate tight scheduling with stress and rigidity, but I now understand that planning can offer freedom—freedom from last-minute panic, from wasted time, and from avoidable errors. I've learned that structure and creativity are not mutually exclusive; in fact, good planning can support deeper, more focused thinking.

In reflection, this year was not just about completing a project—it was about learning how to work effectively under pressure, how to take ownership of my time, and how to stay committed even when things became difficult. These are lessons I will carry forward not just in future academic settings, but in professional and personal contexts as well. Although the journey was far from easy, it has left me with skills and insights that I wouldn't have developed otherwise.

# Appendices

- **Appendix 0:**
- **Ap**
- **Appendix 1: Fragrance Molecules Information**

  Ethyl Maltol :

  - Safety Data Sheet (SDS) -

Cis-3-Hexenol :

- Safety Data Sheet (SDS) -

## ❖ Appendix 2: One-Way RM ANOVA. 1:1 vs Control  All Colours

**Descriptive Statistics**

| | Mean | Std. Deviation | N |
|---|---|---|---|
| White_1_1 | 40.00 | 24.955 | 45 |
| White_1_1_Control | 52.00 | 24.271 | 45 |
| Yellow_1_1 | 44.44 | 25.096 | 45 |
| Yellow_1_1_Control | 46.51 | 22.414 | 45 |
| Green_1_1 | 44.07 | 22.977 | 45 |
| Green_1_1_Control | 37.27 | 22.008 | 45 |
| Black_1_1 | 40.22 | 21.051 | 45 |
| Black_1_1_Control | 38.89 | 18.614 | 45 |

**Within-Subjects Factors**

Measure: perceivedsweetness

| colourcondition | Dependent Variable |
|---|---|
| 1 | White_1_1 |
| 2 | White_1_1_Control |
| 3 | Yellow_1_1 |
| 4 | Yellow_1_1_Control |
| 5 | Green_1_1 |
| 6 | Green_1_1_Control |
| 7 | Black_1_1 |
| 8 | Black_1_1_Control |

**Mauchly's Test of Sphericity[a]**

Measure: perceivedsweetness

| Within Subjects Effect | Mauchly's W | Approx. Chi-Square | df | Sig. | Epsilon[b] Greenhouse-Geisser | Epsilon[b] Huynh-Feldt | Epsilon[b] Lower-bound |
|---|---|---|---|---|---|---|---|
| colourcondition | .389 | 39.099 | 27 | .063 | .807 | .940 | .143 |

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: colourcondition

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

**Tests of Within-Subjects Effects**

Measure: perceivedsweetness

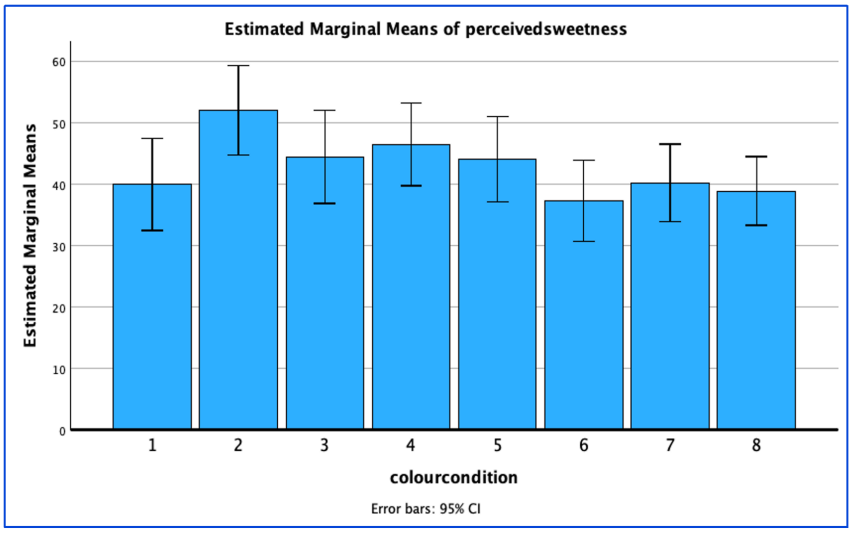
| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| colourcondition | Sphericity Assumed | 7334.797 | 7 | 1047.828 | 2.390 | .022 | .052 |
| | Greenhouse-Geisser | 7334.797 | 5.649 | 1298.372 | 2.390 | .032 | .052 |
| | Huynh-Feldt | 7334.797 | 6.577 | 1115.298 | 2.390 | .024 | .052 |
| | Lower-bound | 7334.797 | 1.000 | 7334.797 | 2.390 | .129 | .052 |
| Error(colourcondition) | Sphericity Assumed | 135043.828 | 308 | 438.454 | | | |
| | Greenhouse-Geisser | 135043.828 | 248.566 | 543.292 | | | |
| | Huynh-Feldt | 135043.828 | 289.367 | 466.686 | | | |
| | Lower-bound | 135043.828 | 44.000 | 3069.178 | | | |

**Tests of Within-Subjects Contrasts**

Measure: perceivedsweetness

| Source | colourcondition | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| colourcondition | Linear | 2200.826 | 1 | 2200.826 | 5.377 | .025 | .109 |
| | Quadratic | 768.905 | 1 | 768.905 | 1.708 | .198 | .037 |
| | Cubic | 2013.626 | 1 | 2013.626 | 4.284 | .044 | .089 |
| | Order 4 | 428.637 | 1 | 428.637 | 1.242 | .271 | .027 |
| | Order 5 | 224.670 | 1 | 224.670 | .348 | .558 | .008 |
| | Order 6 | 1694.711 | 1 | 1694.711 | 4.303 | .044 | .089 |
| | Order 7 | 3.422 | 1 | 3.422 | .010 | .922 | .000 |
| Error(colourcondition) | Linear | 18010.573 | 44 | 409.331 | | | |
| | Quadratic | 19812.780 | 44 | 450.290 | | | |
| | Cubic | 20680.355 | 44 | 470.008 | | | |
| | Order 4 | 15184.005 | 44 | 345.091 | | | |
| | Order 5 | 28397.822 | 44 | 645.405 | | | |
| | Order 6 | 17330.088 | 44 | 393.866 | | | |
| | Order 7 | 15628.206 | 44 | 355.186 | | | |

Profile Plots




## ❖ Appendix 3 : Paired t-test 1:1 vs Control All Colours

**Paired Samples Statistics**

| | | Mean | N | Std. Deviation | Std. Error Mean |
|---|---|---|---|---|---|
| Pair 1 | White_1_1 | 40.00 | 45 | 24.955 | 3.720 |
| | Yellow_1_1 | 44.44 | 45 | 25.096 | 3.741 |
| Pair 2 | White_1_1 | 40.00 | 45 | 24.955 | 3.720 |
| | Green_1_1 | 44.07 | 45 | 22.977 | 3.425 |
| Pair 3 | White_1_1 | 40.00 | 45 | 24.955 | 3.720 |
| | Black_1_1 | 40.22 | 45 | 21.051 | 3.138 |
| Pair 4 | Yellow_1_1 | 44.44 | 45 | 25.096 | 3.741 |
| | Green_1_1 | 44.07 | 45 | 22.977 | 3.425 |
| Pair 5 | Yellow_1_1 | 44.44 | 45 | 25.096 | 3.741 |
| | Black_1_1 | 40.22 | 45 | 21.051 | 3.138 |
| Pair 6 | Green_1_1 | 44.07 | 45 | 22.977 | 3.425 |
| | Black_1_1 | 40.22 | 45 | 21.051 | 3.138 |
| Pair 7 | White_1_1 | 40.00 | 45 | 24.955 | 3.720 |
| | White_1_1_Control | 52.00 | 45 | 24.271 | 3.618 |
| Pair 8 | Yellow_1_1 | 44.44 | 45 | 25.096 | 3.741 |
| | Yellow_1_1_Control | 46.51 | 45 | 22.414 | 3.341 |
| Pair 9 | Green_1_1 | 44.07 | 45 | 22.977 | 3.425 |
| | Green_1_1_Control | 37.27 | 45 | 22.008 | 3.281 |
| Pair 10 | Black_1_1 | 40.22 | 45 | 21.051 | 3.138 |
| | Black_1_1_Control | 38.89 | 45 | 18.614 | 2.775 |

**Paired Samples Effect Sizes**

| | | | Standardizer[a] | Point Estimate | 95% Confidence Interval Lower | Upper |
|---|---|---|---|---|---|---|
| Pair 1 | White_1_1 - Yellow_1_1 | Cohen's d | 36.027 | -.123 | -.416 | .171 |
| | | Hedges' correction | 36.656 | -.121 | -.409 | .168 |
| Pair 2 | White_1_1 - Green_1_1 | Cohen's d | 30.818 | -.132 | -.425 | .162 |
| | | Hedges' correction | 31.356 | -.130 | -.417 | .159 |
| Pair 3 | White_1_1 - Black_1_1 | Cohen's d | 25.360 | -.009 | -.301 | .283 |
| | | Hedges' correction | 25.803 | -.009 | -.296 | .279 |
| Pair 4 | Yellow_1_1 - Green_1_1 | Cohen's d | 31.982 | .012 | -.280 | .304 |
| | | Hedges' correction | 32.541 | .012 | -.276 | .299 |
| Pair 5 | Yellow_1_1 - Black_1_1 | Cohen's d | 32.156 | .131 | -.163 | .424 |
| | | Hedges' correction | 32.718 | .129 | -.160 | .417 |
| Pair 6 | Green_1_1 - Black_1_1 | Cohen's d | 30.610 | .126 | -.168 | .418 |
| | | Hedges' correction | 31.145 | .123 | -.166 | .411 |
| Pair 7 | White_1_1 - White_1_1_Control | Cohen's d | 30.196 | -.397 | -.699 | -.092 |
| | | Hedges' correction | 30.724 | -.391 | -.687 | -.090 |
| Pair 8 | Yellow_1_1 - Yellow_1_1_Control | Cohen's d | 25.245 | -.082 | -.374 | .211 |
| | | Hedges' correction | 25.685 | -.080 | -.368 | .208 |
| Pair 9 | Green_1_1 - Green_1_1_Control | Cohen's d | 28.669 | .237 | -.060 | .532 |
| | | Hedges' correction | 29.170 | .233 | -.059 | .523 |
| Pair 10 | Black_1_1 - Black_1_1_Control | Cohen's d | 23.703 | .056 | -.236 | .348 |
| | | Hedges' correction | 24.117 | .055 | -.232 | .342 |

a. The denominator used in estimating the effect sizes.
Cohen's d uses the sample standard deviation of the mean difference.
Hedges' correction uses the sample standard deviation of the mean difference, plus a correction factor.

**Paired Samples Correlations**

| | | N | Correlation | Significance One-Sided p | Two-Sided p |
|---|---|---|---|---|---|
| Pair 1 | White_1_1 & Yellow_1_1 | 45 | -.036 | .406 | .813 |
| Pair 2 | White_1_1 & Green_1_1 | 45 | .175 | .125 | .250 |
| Pair 3 | White_1_1 & Black_1_1 | 45 | .402 | .003 | .006 |
| Pair 4 | Yellow_1_1 & Green_1_1 | 45 | .117 | .222 | .444 |
| Pair 5 | Yellow_1_1 & Black_1_1 | 45 | .037 | .405 | .810 |
| Pair 6 | Green_1_1 & Black_1_1 | 45 | .035 | .409 | .818 |
| Pair 7 | White_1_1 & White_1_1_Control | 45 | .248 | .050 | .101 |
| Pair 8 | Yellow_1_1 & Yellow_1_1_Control | 45 | .440 | .001 | .002 |
| Pair 9 | Green_1_1 & Green_1_1_Control | 45 | .188 | .108 | .216 |
| Pair 10 | Black_1_1 & Black_1_1_Control | 45 | .291 | .026 | .053 |

**Paired Samples Test**

| | | Paired Differences | | | | | t | df | Significance One-Sided p | Two-Sided p |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std. Deviation | Std. Error Mean | 95% Confidence Interval of the Difference Lower | Upper | | | | |
| Pair 1 | White_1_1 - Yellow_1_1 | -4.444 | 36.027 | 5.371 | -15.268 | 6.379 | -.828 | 44 | .206 | .412 |
| Pair 2 | White_1_1 - Green_1_1 | -4.067 | 30.818 | 4.594 | -13.325 | 5.192 | -.885 | 44 | .190 | .381 |
| Pair 3 | White_1_1 - Black_1_1 | -.222 | 25.360 | 3.780 | -7.841 | 7.397 | -.059 | 44 | .477 | .953 |
| Pair 4 | Yellow_1_1 - Green_1_1 | .378 | 31.982 | 4.768 | -9.231 | 9.986 | .079 | 44 | .469 | .937 |
| Pair 5 | Yellow_1_1 - Black_1_1 | 4.222 | 32.156 | 4.794 | -5.439 | 13.883 | .881 | 44 | .192 | .383 |
| Pair 6 | Green_1_1 - Black_1_1 | 3.844 | 30.610 | 4.563 | -5.352 | 13.041 | .843 | 44 | .202 | .404 |
| Pair 7 | White_1_1 - White_1_1_Control | -12.000 | 30.196 | 4.501 | -21.072 | -2.928 | -2.666 | 44 | .005 | .011 |
| Pair 8 | Yellow_1_1 - Yellow_1_1_Control | -2.067 | 25.245 | 3.763 | -9.651 | 5.518 | -.549 | 44 | .293 | .586 |
| Pair 9 | Green_1_1 - Green_1_1_Control | 6.800 | 28.669 | 4.274 | -1.813 | 15.413 | 1.591 | 44 | .059 | .119 |
| Pair 10 | Black_1_1 - Black_1_1_Control | 1.333 | 23.703 | 3.533 | -5.788 | 8.454 | .377 | 44 | .354 | .708 |

## ❖ Appendix 4 : One-Way RM ANOVA. 2:1 vs Control  All Colours

**Within-Subjects Factors**

Measure: perceivedsweetness

| colourcondition | Dependent Variable |
|---|---|
| 1 | White_2_1 |
| 2 | Yellow_2_1 |
| 3 | Green_2_1 |
| 4 | Black_2_1 |

**Descriptive Statistics**

| | Mean | Std. Deviation | N |
|---|---|---|---|
| White_2_1 | 64.44 | 22.417 | 45 |
| Yellow_2_1 | 62.87 | 23.132 | 45 |
| Green_2_1 | 59.69 | 21.776 | 45 |
| Black_2_1 | 58.00 | 23.989 | 45 |

**Multivariate Tests[a]**

| Effect | | Value | F | Hypothesis df | Error df | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| colourcondition | Pillai's Trace | .091 | 1.410[b] | 3.000 | 42.000 | .253 | .091 |
| | Wilks' Lambda | .909 | 1.410[b] | 3.000 | 42.000 | .253 | .091 |
| | Hotelling's Trace | .101 | 1.410[b] | 3.000 | 42.000 | .253 | .091 |
| | Roy's Largest Root | .101 | 1.410[b] | 3.000 | 42.000 | .253 | .091 |

a. Design: Intercept
Within Subjects Design: colourcondition

b. Exact statistic

**Mauchly's Test of Sphericity[a]**

Measure: perceivedsweetness

| Within Subjects Effect | Mauchly's W | Approx. Chi-Square | df | Sig. | Epsilon[b] Greenhouse-Geisser | Huynh-Feldt | Lower-bound |
|---|---|---|---|---|---|---|---|
| colourcondition | .793 | 9.905 | 5 | .078 | .893 | .956 | .333 |

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: colourcondition

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

**Tests of Within-Subjects Effects**

Measure: perceivedsweetness

| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| colourcondition | Sphericity Assumed | 1161.794 | 3 | 387.265 | .991 | .399 | .022 |
| | Greenhouse-Geisser | 1161.794 | 2.678 | 433.820 | .991 | .393 | .022 |
| | Huynh-Feldt | 1161.794 | 2.868 | 405.084 | .991 | .397 | .022 |
| | Lower-bound | 1161.794 | 1.000 | 1161.794 | .991 | .325 | .022 |
| Error(colourcondition) | Sphericity Assumed | 51605.456 | 132 | 390.950 | | | |
| | Greenhouse-Geisser | 51605.456 | 117.835 | 437.948 | | | |
| | Huynh-Feldt | 51605.456 | 126.193 | 408.939 | | | |
| | Lower-bound | 51605.456 | 44.000 | 1172.851 | | | |

**Tests of Within-Subjects Contrasts**

Measure: perceivedsweetness

| Source | colourcondition | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| colourcondition | Linear | 1140.188 | 1 | 1140.188 | 3.290 | .077 | .070 |
| | Quadratic | .139 | 1 | .139 | .000 | .986 | .000 |
| | Cubic | 21.468 | 1 | 21.468 | .054 | .817 | .001 |
| Error(colourcondition) | Linear | 15247.162 | 44 | 346.526 | | | |
| | Quadratic | 18973.611 | 44 | 431.218 | | | |
| | Cubic | 17384.682 | 44 | 395.106 | | | |

### Tests of Between-Subjects Effects

Measure: perceivedsweetness
Transformed Variable: Average

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|
| Intercept | 675281.250 | 1 | 675281.250 | 738.517 | <.001 | .944 |
| Error | 40232.500 | 44 | 914.375 | | | |

### Estimated Marginal Means

**colourcondition**

### Estimates

Measure: perceivedsweetness

| colourcondition | Mean | Std. Error | 95% Confidence Interval Lower Bound | 95% Confidence Interval Upper Bound |
|---|---|---|---|---|
| 1 | 64.444 | 3.342 | 57.710 | 71.179 |
| 2 | 62.867 | 3.448 | 55.917 | 69.816 |
| 3 | 59.689 | 3.246 | 53.147 | 66.231 |
| 4 | 58.000 | 3.576 | 50.793 | 65.207 |

### Estimates

Measure: perceivedsweetness

| colourcondition | Mean | Std. Error | 95% Confidence Interval Lower Bound | 95% Confidence Interval Upper Bound |
|---|---|---|---|---|
| 1 | 64.444 | 3.342 | 57.710 | 71.179 |
| 2 | 62.867 | 3.448 | 55.917 | 69.816 |
| 3 | 59.689 | 3.246 | 53.147 | 66.231 |
| 4 | 58.000 | 3.576 | 50.793 | 65.207 |

### Pairwise Comparisons

Measure: perceivedsweetness

| (I) colourcondition | (J) colourcondition | Mean Difference (I-J) | Std. Error | Sig.[a] | 95% Confidence Interval for Difference[a] Lower Bound | 95% Confidence Interval for Difference[a] Upper Bound |
|---|---|---|---|---|---|---|
| 1 | 2 | 1.578 | 4.473 | 1.000 | -10.781 | 13.937 |
| | 3 | 4.756 | 3.225 | .884 | -4.154 | 13.665 |
| | 4 | 6.444 | 4.313 | .854 | -5.471 | 18.360 |
| 2 | 1 | -1.578 | 4.473 | 1.000 | -13.937 | 10.781 |
| | 3 | 3.178 | 3.789 | 1.000 | -7.292 | 13.647 |
| | 4 | 4.867 | 4.541 | 1.000 | -7.679 | 17.412 |
| 3 | 1 | -4.756 | 3.225 | .884 | -13.665 | 4.154 |
| | 2 | -3.178 | 3.789 | 1.000 | -13.647 | 7.292 |
| | 4 | 1.689 | 4.501 | 1.000 | -10.748 | 14.125 |
| 4 | 1 | -6.444 | 4.313 | .854 | -18.360 | 5.471 |
| | 2 | -4.867 | 4.541 | 1.000 | -17.412 | 7.679 |
| | 3 | -1.689 | 4.501 | 1.000 | -14.125 | 10.748 |

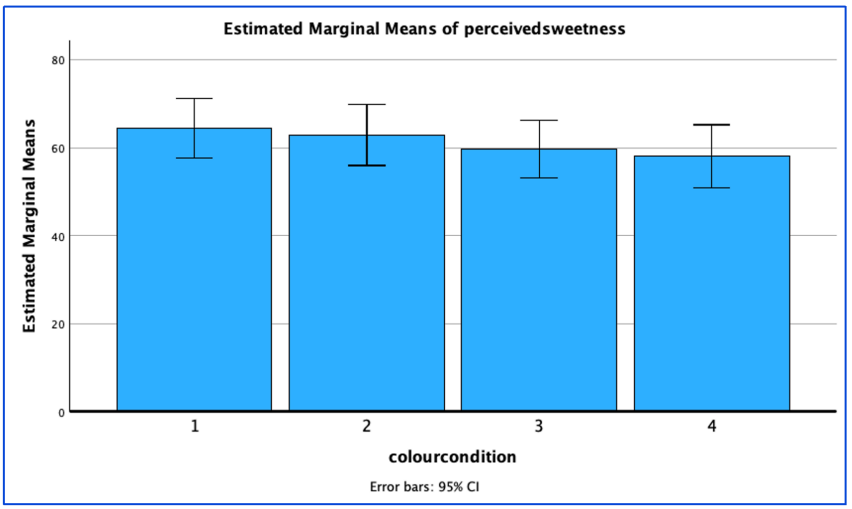
Based on estimated marginal means
a. Adjustment for multiple comparisons: Bonferroni.

### Multivariate Tests

| | Value | F | Hypothesis df | Error df | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|
| Pillai's trace | .091 | 1.410[a] | 3.000 | 42.000 | .253 | .091 |
| Wilks' lambda | .909 | 1.410[a] | 3.000 | 42.000 | .253 | .091 |
| Hotelling's trace | .101 | 1.410[a] | 3.000 | 42.000 | .253 | .091 |
| Roy's largest root | .101 | 1.410[a] | 3.000 | 42.000 | .253 | .091 |

Each F tests the multivariate effect of colourcondition. These tests are based on the linearly

**Profile Plots**




## ❖ Appendix 5: One-way RM ANOVA 1:2

Measure: perceivedsweetness

| colourcondition | Dependent Variable |
|---|---|
| 1 | White_1_2 |
| 2 | Yellow_1_2 |
| 3 | Green_1_2 |
| 4 | Black_1_2 |

**Descriptive Statistics**

| | Mean | Std. Deviation | N |
|---|---|---|---|
| White_1_2 | 42.67 | 22.603 | 45 |
| Yellow_1_2 | 41.73 | 25.689 | 45 |
| Green_1_2 | 41.93 | 17.768 | 45 |
| Black_1_2 | 37.33 | 22.095 | 45 |

**Multivariate Tests[a]**

| Effect | | Value | F | Hypothesis df | Error df | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| colourcondition | Pillai's Trace | .036 | .520[b] | 3.000 | 42.000 | .671 | .036 |
| | Wilks' Lambda | .964 | .520[b] | 3.000 | 42.000 | .671 | .036 |
| | Hotelling's Trace | .037 | .520[b] | 3.000 | 42.000 | .671 | .036 |
| | Roy's Largest Root | .037 | .520[b] | 3.000 | 42.000 | .671 | .036 |

a. Design: Intercept
Within Subjects Design: colourcondition

b. Exact statistic

**Mauchly's Test of Sphericity[a]**

Measure: perceivedsweetness

| Within Subjects Effect | Mauchly's W | Approx. Chi-Square | df | Sig. | Epsilon[b] Greenhouse-Geisser | Huynh-Feldt | Lower-bound |
|---|---|---|---|---|---|---|---|
| colourcondition | .854 | 6.758 | 5 | .239 | .909 | .975 | .333 |

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: colourcondition

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

**Tests of Within-Subjects Effects**

Measure: perceivedsweetness

| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| colourcondition | Sphericity Assumed | 792.150 | 3 | 264.050 | .676 | .568 | .015 |
| | Greenhouse-Geisser | 792.150 | 2.728 | 290.336 | .676 | .555 | .015 |
| | Huynh-Feldt | 792.150 | 2.926 | 270.690 | .676 | .565 | .015 |
| | Lower-bound | 792.150 | 1.000 | 792.150 | .676 | .416 | .015 |
| Error(colourcondition) | Sphericity Assumed | 51589.100 | 132 | 390.827 | | | |
| | Greenhouse-Geisser | 51589.100 | 120.049 | 429.733 | | | |
| | Huynh-Feldt | 51589.100 | 128.762 | 400.655 | | | |
| | Lower-bound | 51589.100 | 44.000 | 1172.480 | | | |

**Tests of Within-Subjects Contrasts**

Measure: perceivedsweetness

| Source | colourcondition | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| colourcondition | Linear | 561.690 | 1 | 561.690 | 1.096 | .301 | .024 |
| | Quadratic | 151.250 | 1 | 151.250 | .471 | .496 | .011 |
| | Cubic | 79.210 | 1 | 79.210 | .234 | .631 | .005 |
| Error(colourcondition) | Linear | 22541.460 | 44 | 512.306 | | | |
| | Quadratic | 14128.500 | 44 | 321.102 | | | |
| | Cubic | 14919.140 | 44 | 339.071 | | | |

**Tests of Between-Subjects Effects**

Measure: perceivedsweetness

Transformed Variable: Average

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|
| Intercept | 301351.250 | 1 | 301351.250 | 375.638 | <.001 | .895 |
| Error | 35298.500 | 44 | 802.239 | | | |

## Estimated Marginal Means

### colourcondition

**Estimates**

Measure: perceivedsweetness

| colourcondition | Mean | Std. Error | 95% Confidence Interval Lower Bound | 95% Confidence Interval Upper Bound |
|---|---|---|---|---|
| 1 | 42.667 | 3.370 | 35.876 | 49.457 |
| 2 | 41.733 | 3.829 | 34.015 | 49.451 |
| 3 | 41.933 | 2.649 | 36.595 | 47.271 |
| 4 | 37.333 | 3.294 | 30.695 | 43.971 |

**Pairwise Comparisons**

Measure: perceivedsweetness

| (I) colourcondition | (J) colourcondition | Mean Difference (I-J) | Std. Error | Sig.[a] | 95% Confidence Interval for Difference[a] Lower Bound | Upper Bound |
|---|---|---|---|---|---|---|
| 1 | 2 | .933 | 4.325 | 1.000 | -11.015 | 12.882 |
| | 3 | .733 | 3.710 | 1.000 | -9.517 | 10.984 |
| | 4 | 5.333 | 4.920 | 1.000 | -8.258 | 18.925 |
| 2 | 1 | -.933 | 4.325 | 1.000 | -12.882 | 11.015 |
| | 3 | -.200 | 3.693 | 1.000 | -10.403 | 10.003 |
| | 4 | 4.400 | 4.336 | 1.000 | -7.579 | 16.379 |
| 3 | 1 | -.733 | 3.710 | 1.000 | -10.984 | 9.517 |
| | 2 | .200 | 3.693 | 1.000 | -10.003 | 10.403 |
| | 4 | 4.600 | 3.888 | 1.000 | -6.141 | 15.341 |
| 4 | 1 | -5.333 | 4.920 | 1.000 | -18.925 | 8.258 |
| | 2 | -4.400 | 4.336 | 1.000 | -16.379 | 7.579 |
| | 3 | -4.600 | 3.888 | 1.000 | -15.341 | 6.141 |

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

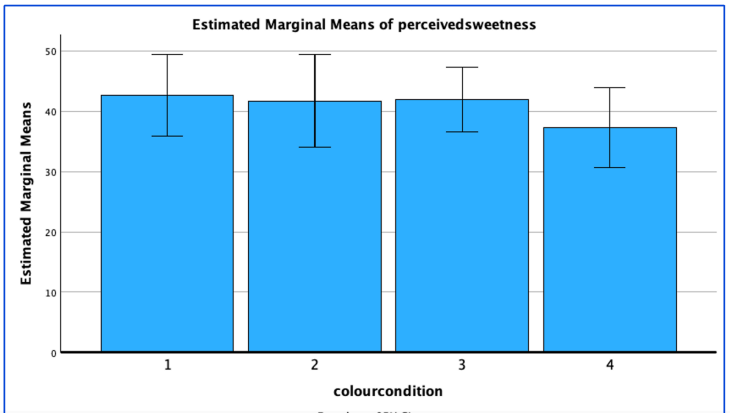
**Multivariate Tests**

| | Value | F | Hypothesis df | Error df | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|
| Pillai's trace | .036 | .520[a] | 3.000 | 42.000 | .671 | .036 |
| Wilks' lambda | .964 | .520[a] | 3.000 | 42.000 | .671 | .036 |
| Hotelling's trace | .037 | .520[a] | 3.000 | 42.000 | .671 | .036 |
| Roy's largest root | .037 | .520[a] | 3.000 | 42.000 | .671 | .036 |

Each F tests the multivariate effect of colourcondition. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

**Profile Plots**




## ❖ Appendix 6: One-way RM ANOVA 2:1

**Within-Subjects Factors**

Measure: perceivedsweetness

| colourcondition | Dependent Variable |
|---|---|
| 1 | White_2_1 |
| 2 | Yellow_2_1 |
| 3 | Green_2_1 |
| 4 | Black_2_1 |

**Descriptive Statistics**

| | Mean | Std. Deviation | N |
|---|---|---|---|
| White_2_1 | 64.44 | 22.417 | 45 |
| Yellow_2_1 | 62.87 | 23.132 | 45 |
| Green_2_1 | 59.69 | 21.776 | 45 |
| Black_2_1 | 58.00 | 23.989 | 45 |

**Multivariate Tests[a]**

| Effect | | Value | F | Hypothesis df | Error df | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| colourcondition | Pillai's Trace | .091 | 1.410[b] | 3.000 | 42.000 | .253 | .091 |
| | Wilks' Lambda | .909 | 1.410[b] | 3.000 | 42.000 | .253 | .091 |
| | Hotelling's Trace | .101 | 1.410[b] | 3.000 | 42.000 | .253 | .091 |
| | Roy's Largest Root | .101 | 1.410[b] | 3.000 | 42.000 | .253 | .091 |

a. Design: Intercept
Within Subjects Design: colourcondition

b. Exact statistic

❖

### Mauchly's Test of Sphericity[a]

Measure: perceivedsweetness

| Within Subjects Effect | Mauchly's W | Approx. Chi-Square | df | Sig. | Epsilon[b] Greenhouse-Geisser | Huynh-Feldt | Lower-bound |
|---|---|---|---|---|---|---|---|
| colourcondition | .793 | 9.905 | 5 | .078 | .893 | .956 | .333 |

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: colourcondition

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

### Tests of Within-Subjects Effects

Measure: perceivedsweetness

| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| colourcondition | Sphericity Assumed | 1161.794 | 3 | 387.265 | .991 | .399 | .022 |
| | Greenhouse-Geisser | 1161.794 | 2.678 | 433.820 | .991 | .393 | .022 |
| | Huynh-Feldt | 1161.794 | 2.868 | 405.084 | .991 | .397 | .022 |
| | Lower-bound | 1161.794 | 1.000 | 1161.794 | .991 | .325 | .022 |
| Error(colourcondition) | Sphericity Assumed | 51605.456 | 132 | 390.950 | | | |
| | Greenhouse-Geisser | 51605.456 | 117.835 | 437.948 | | | |
| | Huynh-Feldt | 51605.456 | 126.193 | 408.939 | | | |
| | Lower-bound | 51605.456 | 44.000 | 1172.851 | | | |

### Tests of Within-Subjects Contrasts

Measure: perceivedsweetness

| Source | colourcondition | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| colourcondition | Linear | 1140.188 | 1 | 1140.188 | 3.290 | .077 | .070 |
| | Quadratic | .139 | 1 | .139 | .000 | .986 | .000 |
| | Cubic | 21.468 | 1 | 21.468 | .054 | .817 | .001 |
| Error(colourcondition) | Linear | 15247.162 | 44 | 346.526 | | | |
| | Quadratic | 18973.611 | 44 | 431.218 | | | |
| | Cubic | 17384.682 | 44 | 395.106 | | | |

### Tests of Between-Subjects Effects

Measure: perceivedsweetness
Transformed Variable: Average

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|
| Intercept | 675281.250 | 1 | 675281.250 | 738.517 | <.001 | .944 |
| Error | 40232.500 | 44 | 914.375 | | | |

### Estimated Marginal Means

**colourcondition**

### Estimates

Measure: perceivedsweetness

| colourcondition | Mean | Std. Error | 95% Confidence Interval Lower Bound | Upper Bound |
|---|---|---|---|---|
| 1 | 64.444 | 3.342 | 57.710 | 71.179 |
| 2 | 62.867 | 3.448 | 55.917 | 69.816 |
| 3 | 59.689 | 3.246 | 53.147 | 66.231 |
| 4 | 58.000 | 3.576 | 50.793 | 65.207 |

**Estimates**

Measure: perceivedsweetness

| colourcondition | Mean | Std. Error | 95% Confidence Interval Lower Bound | Upper Bound |
|---|---|---|---|---|
| 1 | 64.444 | 3.342 | 57.710 | 71.179 |
| 2 | 62.867 | 3.448 | 55.917 | 69.816 |
| 3 | 59.689 | 3.246 | 53.147 | 66.231 |
| 4 | 58.000 | 3.576 | 50.793 | 65.207 |

**Pairwise Comparisons**

Measure: perceivedsweetness

| (I) colourcondition | (J) colourcondition | Mean Difference (I–J) | Std. Error | Sig.[a] | 95% Confidence Interval for Difference[a] Lower Bound | Upper Bound |
|---|---|---|---|---|---|---|
| 1 | 2 | 1.578 | 4.473 | 1.000 | -10.781 | 13.937 |
| | 3 | 4.756 | 3.225 | .884 | -4.154 | 13.665 |
| | 4 | 6.444 | 4.313 | .854 | -5.471 | 18.360 |
| 2 | 1 | -1.578 | 4.473 | 1.000 | -13.937 | 10.781 |
| | 3 | 3.178 | 3.789 | 1.000 | -7.292 | 13.647 |
| | 4 | 4.867 | 4.541 | 1.000 | -7.679 | 17.412 |
| 3 | 1 | -4.756 | 3.225 | .884 | -13.665 | 4.154 |
| | 2 | -3.178 | 3.789 | 1.000 | -13.647 | 7.292 |
| | 4 | 1.689 | 4.501 | 1.000 | -10.748 | 14.125 |
| 4 | 1 | -6.444 | 4.313 | .854 | -18.360 | 5.471 |
| | 2 | -4.867 | 4.541 | 1.000 | -17.412 | 7.679 |
| | 3 | -1.689 | 4.501 | 1.000 | -14.125 | 10.748 |

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

**Multivariate Tests**

| | Value | F | Hypothesis df | Error df | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|
| Pillai's trace | .091 | 1.410[a] | 3.000 | 42.000 | .253 | .091 |
| Wilks' lambda | .909 | 1.410[a] | 3.000 | 42.000 | .253 | .091 |
| Hotelling's trace | .101 | 1.410[a] | 3.000 | 42.000 | .253 | .091 |
| Roy's largest root | .101 | 1.410[a] | 3.000 | 42.000 | .253 | .091 |

Each F tests the multivariate effect of colourcondition. These tests are based on the linearly

**Profile Plots**