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Color–taste correspondences influence visual binding errors

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ABSTRACT

People consistently associate tastes with colors (e.g., sweet-red, sour-yellow, salty-blue). Here, we examined the effect of the congruency of color–taste correspondences on unimodal visual feature binding by studying illusory conjunctions (binding errors). The visual stimuli were typical food words associated with sweet, sour, and salty tastes, and were presented in red, yellow, and blue font. The participants reported the font color of one of the two words with food names presented in pairs briefly under conditions of divided spatial attention. The words were either congruent or incongruent with the color-taste correspondences. The participants made more Illusory conjunctions in the incongruent condition (e.g., sweet-yellow and sour-red) than in the congruent condition (e.g., sweet-red and sour-yellow). These results suggest that the congruency of color-taste correspondences can bias unimodal visual binding errors, likely through a top-down effect.

1. Introduction

The ability to perceive the world around us as a unified whole, rather than as a chaotic jumble of independent features, is a remarkable feat of the brain. This process, known as feature binding, is essential for accurate object recognition (Spence, 2023; Spence & Frings, 2020; Treisman & Gelade, 1980; Wolfe & Cave, 1999). However, sometimes our brains get it wrong, leading to errors called 'illusory conjunctions' (ICs), Illusory conjunctions (ICs) occur when features from multiple objects are incorrectly combined, resulting in a putatively perceptual error where attributes such as color, shape, or location are mismatched. It has been argued that these phenomena may offer valuable insights into the mechanisms of visual perception and attention (Robertson, 2003). These errors provide several key insights into (visual) perception and attention. First, ICs demonstrate that feature binding is not necessarily automatic, but requires attentional resources - when attention is divided or limited, features can be incorrectly combined, suggesting that attention plays a crucial role in accurate feature integration. Second, the pattern of ICs reveals that visual features (such as color, shape, and location) are initially processed separately before being bound together into coherent objects. Third, ICs show that top-down factors such as expectations and prior knowledge can influence how features are bound together, indicating that feature binding isn't purely a bottom-up process. Finally, the temporal dynamics of ICs - when and how they occur - help illuminate the time course of feature integration in visual (and possibly also multisensory) information processing (Spence, 2023; Spence & Frings, 2020). The exact mechanisms of feature binding remain a topic of debate amongst neuroscientists. Some theories propose that specialized brain regions, like the parietal cortex, play a crucial role in binding visual features (Friedman-Hill et al., 1995). Other researchers, however, have suggested that binding might be more of a distributed process, with different areas of the brain contributing to integration (Treisman, 1996). Some research has also explored the role of neural synchronization in feature binding, proposing that temporally coordinated neural activity might serve as a mechanism for integrating disparate sensory information, proposing that temporally coordinated neural activity across different brain regions might serve as a mechanism for integrating disparate sensory information (Ding et al., 2017: Valencia & Froese, 2020; Singer et al., 1995). This supports the idea of distributed brain mechanisms, where multiple areas of the brain work together in a synchronized manner to achieve appropriate feature binding. These insights from ICs are particularly relevant when it comes to studying how our brains process and integrate information across different sensory modalities. For example, understanding how feature binding works - and when it fails - can help explain how crossmodal associations like color-taste correspondences influence our perception. If feature binding requires attention and can be influenced by prior knowledge, then established associations between colors and tastes

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might affect how accurately we bind visual features when processing food-related information.

Separately, an emerging experimental literature has highlighted the existence of color-taste correspondences, with certain colors being consensually associated with particular tastes (e.g., Spence et al., 2015; Spence & Levitan, 2021). For example, the color pink is often associated with sweet tastes, while green is linked to sour tastes (see Wan et al., 2014). This association is thought to be due to the common presence of red in naturally sweet fruits like strawberries and cherries, and green in sour fruits such as limes and green apples. Another example is the association between the color yellow and sour tastes. Spence et al. (2015) demonstrated that yellow is frequently linked to sour tastes. This is likely because many sour fruits, such as lemons and grapefruits, are yellow.

1.1. Historical context

The awareness of crossmodal associations has deep historical roots, with glimpses of color-taste connections appearing, for instance, in the writings of ancient Greeks and Romans (Gage, 1999). These early references suggest an intuitive awareness of this phenomenon, even without the benefit of scientific inquiry. However, it wasn't until the 19th Century, that researchers started to embark on more systematic investigations (Brewer & Schommer-Aikins, 2006). Recent studies have used innovative methods, such as crossmodal correspondences and color-taste mapping, to reveal consistent links between specific colors and basic tastes (Spence & Levitan, 2021). For example, Woods and Spence (2016) demonstrated that people associate each of the basic tastes (e.g., sweet, sour, bitter, and salty) with specific colors (e.g., red, green, black, and white) (Woods & Spence, 2016). Meanwhile, another study by Spence et al. (2015) reviewed the growing body of scientific research showing that people systematically associate specific colors with particular tastes, highlighting how these correspondences generalize across cultures (Spence et al., 2015). The convergence of research on feature binding errors and color-taste correspondences raises intriguing questions about how these crossmodal associations might influence unisensory information processing. Specifically, if color-taste correspondences are robust enough to generalize across cultures, they might also be strong enough to affect how we bind visual features, particularly when processing food-related information. Understanding this interaction could provide valuable insights into both the strength of crossmodal associations and the factors that influence feature binding. The last century has witnessed a surge in research on the topic of color-taste crossmodal correspondences. Cognitive neuroscience researchers have explored the underlying mechanisms that might explain how our brains connect these seemingly disparate senses (Bolam et al., 2024; McEwan et al., 2024; Sadaghiani et al., 2009; Sciortino & Kayser, 2023; Spence et al., 2010; Velasco et al., 2018).

1.2. Recent advances in color-taste associations

Recent investigations have explored how color-taste associations may vary across cultures (Bortolotti et al., 2022; Raevskiy et al., 2022; Wan et al., 2014; Woods et al., 2016), as well as highlighting the existence of individual differences (see Spence, 2022, for a review). These studies highlight the complex interplay between innate predispositions, such as the universal tendency to associate sweetness with the color red (Spence, 2019), and learned associations, such as the cultural linkage of yellow with sour tastes due to common fruits like lemons (Woods & Spence, 2016). This interplay between innate and learned associations is particularly relevant to our understanding of feature binding errors. If color-taste correspondences arise from both universal and learned sources, they might influence feature binding through multiple pathways - both automatic, bottom-up processes and top-down, experience-dependent mechanisms. This complexity makes them an excellent test case for investigating how different types of associations affect visual processing and feature binding. As our understanding of color-taste crossmodal correspondences continues to evolve, it opens up new avenues for research in sensory science, cognitive psychology, and neuroscience. Despite the significant advances in our understanding of color-taste correspondences, much remains to be discovered.

The present study aims to investigate the congruency effect of color-taste correspondence on visual feature binding. Much remains to be explored, particularly in the realm of implicit associations (Bortolotti, Padulo, et al., 2024; Parise & Spence, 2012; Spence, 2011; Velasco et al., 2018). In the context of color-taste crossmodal correspondences, implicit associations might lead people to subconsciously link certain colors with specific tastes, even without being explicitly instructed to do so. By using implicit tasks, such as the Implicit Association Test (IAT) or priming paradigms, it is possible to delve deeper into these subconscious connections and gain a more nuanced understanding of how color and taste interact at a cognitive level (Greenwald et al., 1998; Parise & Spence, 2012, 2013). Furthermore, by examining how these implicit associations influence feature binding errors, we can better understand the automaticity of color-taste correspondences and their impact on basic visual processing. While previous research has focused on explicit judgments about color-taste relationships, studying their effects on ICs allows us to examine how these associations operate at a more fundamental level of visual processing.

It is, however, also important to consider the possibility that these ICs might arise from errors in memory rather than from perceptual miscombinations. Virzi and Egeth (1984) demonstrated that ICs could occur at an abstract, polymodal level, influenced by the meaning of words or memory errors. They found that participants sometimes reported seeing words in the color of the color name in the display, suggesting that semantic representations can lead to confusion about the source of the representation. This indicates that ICs need not only reflect perceptual miscombination but could also involve higher-level cognitive processes (e.g., a miscombination that takes place in short term memory).

Understanding the congruency effect of color-taste correspondences on visual feature binding is significant for several reasons. First, it provides insights into how multisensory integration influences basic perceptual processes. By examining how congruent and incongruent color-taste pairings affect visual binding errors, we can better understand the cognitive mechanisms underlying feature integration. Second, this research has practical implications for fields such as marketing, product design, and human-computer interaction, where color-taste associations can be leveraged to enhance user experience and consumer behavior. Finally, exploring these correspondences contributes to the broader framework of embodied cognition, emphasizing the interconnected nature of sensory, motor, and cognitive processes.

2. Methods

2.1. Participants

Twenty-three Italian students (12 females and 11 males, Mage = 23.52 years, SD = 4.38) from the University of Chieti-Pescara took part in the study. The sample size was determined using prior experiments that had investigated similar effects (Chen & Watanabe, 2021), other experiments in the field have used similar sample sizes to study crossmodal correspondences and visual perception (e.g., Spence et al., 2015; Woods & Spence, 2016). Additionally, we used G*Power, a statistical power analysis program, to calculate the appropriate sample size. G*Power allows researchers to determine the required sample size to achieve a desired power level, given the expected effect size and alpha level. Our calculations confirmed that 23 participants would be sufficient to detect the expected effects with an adequate power level. All of the participants had normal or corrected-to-normal visual acuity and normal color vision, and were naïve to the purpose of the experiment. The study was conducted in accordance with the ethical standards of the

1964 Declaration of Helsinki. Written informed consent was obtained from all participants in advance.

2.2. Materials

The experiment was programmed in E-Prime 3.0 (Psychology Software Tools, Inc.; https://www.pstnet.com/eprime.cfm). The stimuli were displayed on a 25-inch Monitor (Monitor Led 25″ Iiyama, 1920 × 1200 p), with a 1920 × 1080-pixel resolution and a refresh rate of 60 Hz. Participants viewed the monitor from a distance of approximately 60 cm.

Nine Italian words consisting of food names that are typically associated with the three tastes (i.e., sweet, sour, salty) in three font colors (i.e., red, yellow, blue) were used as visual stimuli; these associations are well-documented in the literature on color-taste correspondences (e.g., Spence & Levitan, 2021; Woods & Spence, 2016). The three food names associated with the sweet taste were: Zucchero (sugar), Miele (honey), Ciambelle (donuts), the sour-tasting foods were: Limone (lemon), Prugna (plum), Aceto (vinegar), and for the salty taste: Prosciutto (ham), Oliva (olive), and Formaggio (cheese). The font color information was as follows: Yellow, RGB: 245, 195, 67; Red, RGB: 233, 52, 35; Blue, RGB: 79, 114, 191. The word stimuli were presented in bold in 40 Pt Times New Roman. See Fig. 1 for an example.

3. Procedure

The experiment was conducted in a dimmed laboratory to minimize external visual distractions and ensure that participants focused solely on the stimuli presented on the screen. This controlled environment allowed us to maintain consistent lighting conditions for all participants, thus reducing variability in the collected data. At the start of the task, written instructions were provided on the computer screen, followed by 30 practice trials. Participants initially completed 30 practice trials to familiarize themselves with the task. Of these, 20 trials included feedback to help participants better understand the task and improve their accuracy. The remaining 10 practice trials did not include feedback, preparing participants for the main experimental phase. The feedback during the practice trials was provided to ensure that participants correctly understood the instructions and the task. In each trial, a black fixation cross was presented for 300 ms. Next, two food names were presented in colored text, flanked by an integer on either side for 600 ms (see Fig. 1). Following the stimulus display, two pattern masks with two hash symbols were presented for 300 ms in the location where the two colored-words had been presented. The participants were instructed to add the two numbers first (i.e., this was the primary task). After entering the digit with a keypress (the number was always between 1 and 6), the second question was presented. The participants were instructed to report the color of one of the two words, by pressing labelled keys. The letters j, k, and l were labelled red, yellow, and blue, respectively. 216 trials, equally presented all combinations in two conditions (i.e., congruent and incongruent colored food names) were presented. There were 20 practice trials with feedback, and the 216 experimental trials without feedback were broken into six blocks of 36 trials. At the end of each block, participants took a self-determined break. The whole experiment took approximately 20 min to complete. The numbers presented to participants for the addition task were randomly selected between 1 and 6. This task was designed to divide the participant's attention, making the secondary task of reporting the color of the words more challenging. The goal was to simulate conditions of divided attention, which are common in everyday life, and to examine how color-taste correspondences influence visual binding errors under such conditions.

Fig. 1. An example of the stimuli display. The participants were instructed to add the two digits first. Next, they had to report the color of a specific taste food (e.g., What color was the sweet food? Press *j* for red, *k* for yellow, and *l* for blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Data analysis

The R.4.2.3 statistical software (R Core Team, 2023) was used for data analysis. There were three possible outcomes of reporting the color of the word: Hit, illusory conjunction (IC), and feature error (FE). A hit occurs when the participant correctly reports the target color. An illusory conjunction (IC) occurs when the participant reports the color of the distractor word instead of the target word, indicating a miscombination of features. A feature error (FE) occurs when the participant reports a color that was not presented in the display, indicating a memory or guessing error. Taking the stimuli displayed in Fig. 1 as an example, when the question asking for the color of the salty food (here, olive), a hit would be correctly reporting the target color (i.e., "red"), an IC is reporting the color of the distractor (i.e., "blue"), while an FE would involve reporting a color that was not presented in the display (i.e., "yellow"). The mean proportion of hits, ICs, and FEs (number of trials × 100 %/216 trials) for each participant in the congruent and incongruent conditions were calculated. A paired sample *t*-test with Bonferroni correction (the significance level was $0.05/3 = 0.017$) was used to examine the color-taste correspondence congruency effect on hits, ICs, and FEs for the three colored-word pairs, separately. To further quality the results, the Bayes Factors (BF10) were referred to, in order to determine whether or not there was empirical support in favor of the alternative (H1) or null (H0) hypotheses (Morey & Rouder, 2018).

5. Results

Participants made 13.6 % errors for the first question (adding the two numbers together), and those error trials were excluded from subsequent analysis. For the second question of reporting the color of a specific taste, participants made 55.5 % correct hits, 34.4 % binding errors (BEs), and 10.1 % feature errors. The mean proportion of hits, ICs, and FEs in congruent and incongruent conditions with color-taste correspondence were calculated (see Fig. 2). A paired-sample *t*-test showed a significant difference on ICs between congruent and incongruent conditions, $t(22) = 3.52$, Bonferroni-corrected $p = .006$, Cohen's $d = 0.73$, BF10 = 19.87. The participants made more ICs in the incongruent conditions (20.5 %) than in the congruent conditions (9.18 %), as expected. For hits, a paired-sample *t*-test also revealed a significant difference, $t(22) = 3.89$, Bonferroni-corrected $p = .002$, Cohen's $d = 0.81$, BF10 = 43.73, with participants making significantly more hits on congruent (30.0 %) than on incongruent trials (17.9 %). FEs did not differ between the congruent (4.3 %) and incongruent conditions (5.6 %), $t(21) = 1.06$, Bonferroni-corrected $p > .1$, $d = 0.23$, BF10 = 0.37. These results indicate that participants tended to make more ICs for incongruent colored-taste words than for congruent colored-taste words.

Next, we further explored the ICs in the congruent and incongruent conditions by examining each pair of taste combinations separately (e.g., for the sour/salty pair, congruent: sour–yellow/salty–blue; incongruent: sour–blue/salty–yellow; see Fig. 3; The graphs clearly show that BEs are significantly more frequent in the incongruent conditions than in the congruent conditions for all taste pairs, suggesting a robust effect of color-taste congruency on visual feature binding). Paired sample *t*-tests revealed that for each taste pair, there were significantly more ICs in the incongruent condition than in the congruent condition (Sour/Salty pair, 7.35 % vs. 2.92 %, $t(22) = 4.08$, Bonferroni corrected $p = .001$, $d = 0.85$, BF10 = 65.93; Sweet/Salty pair, 6.84 % vs. 3.26 %, $t(22) = 2.93$,

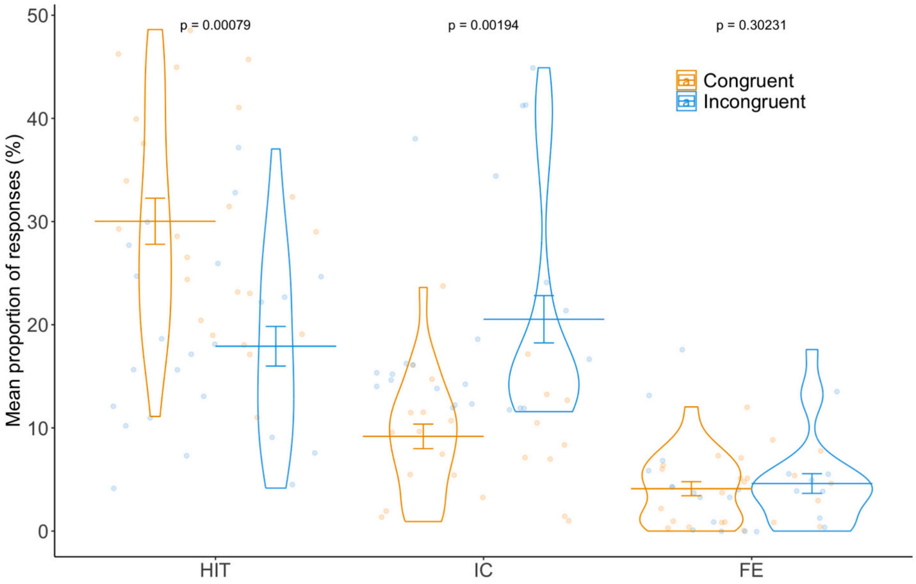

Fig. 2. Violin plot visualizing the distribution and density of the data. The horizontal lines within the violin plot represent the median of the data. Error bars indicate the standard deviations. The shapes of the violins capture the density of the data at different values, with wider sections indicating a higher density of data points. Mean proportion of the three response types: hits (HIT), illusory conjunctions (IC), and feature errors (FE) for both congruent and incongruent conditions. Note that participants made significantly more ICs in incongruent conditions (20.5 %) compared to congruent conditions (9.18 %). There was no significant difference in FEs between congruent (4.3 %) and incongruent conditions (5.6 %).

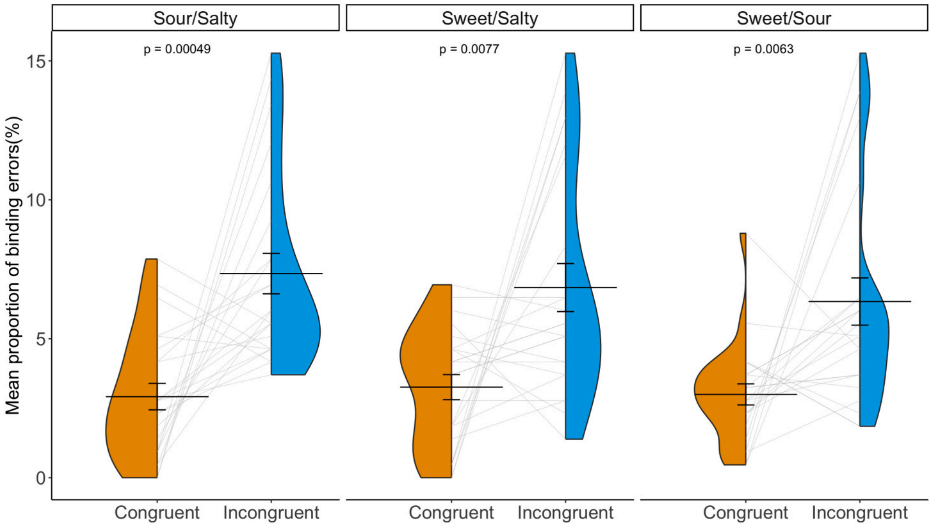

Fig. 3. Violin plot visualizing the distribution and density of the data. The horizontal lines within the violin plot represent the median of the data. Error bars indicate the standard deviations. The shapes of the violins capture the density of the data at different values, with wider sections indicating a higher density of data points; the faint grey lines indicate the range of the data, showing the minimum and maximum values. Mean proportion of binding errors (BEs) for each taste pair (sweet/sour, sweet/salty, sour/salty) under congruent and incongruent conditions. The graphs clearly show that binding errors are significantly more frequent in the incongruent conditions than in the congruent conditions for all taste pairs, suggesting a robust effect of color-taste congruency on visual feature binding. The figure shows that participants made significantly more ICs in the incongruent condition than in the congruent condition for each taste pair. For the Sour/Salty pair, the rates were 7.35 % vs. 2.92 %; For the Sweet/Salty pair, the rates were 6.84 % vs. 3.26 % and For the Sweet/Sour pair, the rates were 6.34 % vs. 3.00 %.

Bonferroni corrected $p = .02$, $d = 0.61$, BF10 = 6.13; Sweet/Sour pair, 6.34 % vs. 3.00 %, $t(22) = 3.02$, Bonferroni corrected $p = .02$, $d = 0.63$, BF10 = 7.25). These results therefore show that ICs occurred more frequently in the incongruent conditions than in the congruent conditions for all three taste pairs.

6. Discussion

The results of the present study provide compelling evidence for the influence of color-taste crossmodal correspondences on visual feature binding. Participants made significantly more ICs in the incongruent color-taste pairings than in the congruent ones, suggesting that these crossmodal associations can bias visual information processing even in a task that is not explicitly related to taste perception. This finding aligns with previous research on crossmodal correspondences affecting perception and cognition (Parise & Spence, 2013; Spence, 2011), and extends our understanding of how these associations can sometimes operate at a fundamental cognitive level (Spence, 2023; Spence & Frings, 2020). The observed effect was consistent across all taste pairs (sweet/sour, sweet/salty, sour/salty), indicating a robust empirical phenomenon. This consistency suggests that color-taste correspondences may be deeply ingrained in our cognitive systems, presumably due to prior learning (Spence & Deroy, 2013; Velasco et al., 2018). The effect on ICs, rather than just response times or accuracy, implies that these associations influence early stages of visual processing and feature integration or else that they reflect memory errors. This is particularly interesting in light of theories proposing that crossmodal correspondences sometimes operate at a perceptual (and/or as well as at a decisional level; Marks, 2004; Gallace & Spence, 2006; Parise & Spence, 2009; Spence, 2011).

These findings extend the understanding of how multisensory associations can impact visual perception. While previous studies have shown that color can influence taste perception (Spence et al., 2010; Velasco et al., 2016), our research demonstrates a reciprocal effect: taste associations can influence feature binding in color perception or memory (Spence et al., 2010; Stevenson, 2014). It also aligns with the broader framework of embodied cognition, which emphasizes the interconnected nature of sensory, motor, and cognitive processes (Barsalou, 2008). The increase in ICs observed in the incongruent conditions also helps to shed some light on the mechanisms underpinning feature binding. These results suggest that top-down influences, such as learned associations or expectations, can modulate the binding process. This aligns with models of feature integration that incorporate both bottom-up and top-down processes (Humphreys, 2016; Treisman, 2013). The findings also resonate with predictive coding theories of perception, which propose that the brain constantly generates predictions based on prior knowledge and experiences (Friston, 2013). In this context, color-taste crossmodal correspondences may serve as priors that shape our perceptual predictions and influence feature binding processes (Chen & Spence, 2017).

Moreover, the results of the present study contribute to the growing body of research on the cognitive and neural bases of crossmodal correspondences. The fact that these correspondences can influence such a fundamental process as feature binding suggests that they may be more deeply rooted in our cognitive architecture than previously thought. This raises interesting questions about the development of these associations and their potential role in cognitive development and learning (Barenholtz et al., 2014; Lewkowicz & Ghazanfar, 2009; Spence & Deroy, 2013). Future research could explore how these associations develop over the lifespan and whether they can be modified through experience or training. From a methodological perspective, our use of the IC paradigm to study crossmodal effects is novel and opens up new avenues for investigating the interaction between multisensory integration and visual attention. Future studies could, for example, adapt this paradigm to explore other types of crossmodal correspondences and their effects on perception (and/or memory). For instance, researchers could investigate whether similar effects occur with other sensory pairings, such as sound-shape or smell-texture correspondences (e.g., Crisinel & Spence, 2010; Spence & Deroy, 2013).

The findings reported here may have implications that extend beyond basic cognitive science. For instance, in the field of product design and marketing, understanding how color-taste correspondences influence visual perception could inform more effective packaging and branding strategies (Piqueras-Fiszman & Spence, 2015; Velasco et al., 2018). In the domain of human-computer interaction, these insights could guide the development of more intuitive and hence effective multisensory interfaces (Pinardi et al., 2023; Spence et al., 2017).

7. Conclusions

This study provides novel evidence for the impact of color-taste correspondences on visual feature binding. Through comprehensive analysis of hits, ICs, and feature errors, we found that participants made significantly more accurate responses (hits) in congruent conditions and more binding errors in incongruent color-taste pairings. This pattern of results demonstrates the influence of crossmodal associations on visual processing and/or memory. By demonstrating increased illusory conjunctions in incongruent color-taste pairings, we highlight the pervasive influence of crossmodal associations on basic perceptual processes. The findings on color-taste correspondences have significant implications for the food and beverage industry. The visual presentation of food, including color schemes and descriptive words, can significantly influence our taste perception and expectations (Bortolotti et al., 2023; Bortolotti, Cannito, et al., 2024; Piqueras-Fiszman & Spence, 2015). This research can inform product design, marketing strategies, and consumer behavior (Spence, 2012; Spence & Velasco, 2018). While our behavioral findings provide important insights into how color-taste associations influence visual processing, we acknowledge certain limitations. Although we did not employ electrophysiological methods, it is still possible to infer the stages of visual processing involved through clever psychophysical experiments. For instance, studies like McEwan et al. (2024) have demonstrated the involvement of the superior colliculi in crossmodal correspondences using psychophysical techniques. Future research could adopt similar approaches to elucidate the neural mechanisms underlying these effects, potentially offering a more detailed understanding without the need for direct electrophysiological data. Future research incorporating EEG or brain imaging techniques would be valuable in clarifying the neural mechanisms underlying these effects.

These findings have significant implications for theories of multisensory integration, feature binding, and the interplay between perception and higher-level cognitive processes. Our results challenge the traditional view of sensory processing as a strictly hierarchical and modality-specific process (Barlow & Mollon, 1982). Instead, they support a more interactive and flexible model of perception, where information from different senses and prior knowledge can influence even early stages of sensory processing (Ghazanfar & Schroeder, 2006; Talsma et al., 2010).

CRediT authorship contribution statement

Alessandro Bortolotti: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Na Chen:** Writing – original draft, Software, Formal analysis, Data curation, Conceptualization. **Charles Spence:** Writing – review & editing, Writing – original draft, Supervision. **Riccardo Palumbo:** Writing – review & editing, Supervision.

Ethics approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study received approval from the Institutional Review Board (IRB) of the University of Chieti-Pescara, in particular by the Department of Neuroscience e Imaging.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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