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Effect of Cross-Modal Odor-Color Associations in Stroop-like Paradigm

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EFFECT OF CROSS-MODAL ODOR-COLOR ASSOCIATIONS IN STROOP-LIKE PARADIGM

BY

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Abstract

The investigation into synesthesia and its underlying mechanisms prompts inquiry into the prevalence of cross-modal associations within the general population and their influence on our lives, yet this domain remains relatively unexplored. This study aims to elucidate the impact of odor-color associations on odor recognition utilizing a Stroop-like paradigm. Participants were tasked with establishing odor-color associations, then subsequently recalling the odors paired with congruent, incongruent, or neutral colors. Reaction times and accuracy of odor recognition were recorded, and analysis revealed a significant effect of congruent versus incongruent color condition on odor recognition accuracy, with congruent color and odor having a higher recall identification accuracy than incongruent color and odor. There was no significant relationship found between condition and reaction time. Additionally, this study corroborates findings that odors are non-randomly characterized by colors (Gilbert et al., 1996). Future research should explore the memory effects of odor-color associations on unknown odors, as well as the effects of interference through other sensory modalities.

Keywords: perception, synesthesia, olfaction, color, Stroop task

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Effects of Cross-Modal Odor-Color Associations in Stroop-like Paradigm

Background about Synesthesia

Our senses combine to form our reality. Experience is made up of five main types of sensory input that combine to form the basis of our understanding of our lives and the world around us; vision, audition (hearing), olfaction (smell), gustation (tasting), and somatosensation (touch). Synesthesia is a phenomenon where one experiences extra sensory input that is cued by another sensory stimuli (Cytowic 2018, Simner et al., 2006, Ramachandran & Hubbard, 2001). When people with synesthesia, called synesthetes, are presented with one type of sensory inducer–like music as an auditory input–simultaneously experience a concurrent sensory perception in correlation with the specific stimuli. Synesthesia can exist within any combination of senses, and can also either be externally perceived or consist of internal representations (Simner et al., 2006). In synesthesia, the inducing sensory modality produces concurrent stimuli, and typically the relationship between inducing sense and concurrent sense only goes in one direction (Cytowic, 2018). The stimulus that provokes another stimulus is called the "inducer", while the pseudo stimulus provoked is called the "concurrent". There are over 52 types of documented synesthesia (Cytowic, 2018), with three of the most common types being color-grapheme, taste-shape, and music-color synesthesia (Simner et al., 2006). In color-grapheme synesthesia, words, letters, and/or numbers appear in specific colors. In taste-shape synesthesia, tasting food induces shapes to appear in the visual field. Finally, in music-color synesthesia, listening to music, or sometimes other auditory stimuli as well, induces color percepts in the visual field.

Genuine synesthesia is established by five important characteristics: it is involuntary and automatic, spatially-extended, consistent, memorable, and affect-laden (Cytowic, 2003). While there are cases of acquired synesthesia after brain injury (Sinke et al., 2012), genuine synesthesia is understood to develop before or during childhood and remain consistent throughout the synesthete's life. A popular theory of synesthesia is the cross-activation model, which postulates that the "wiring" between senses is overconnected or under regulated in the brains of synesthetes, and these extra connections or lack of regulation cause involuntary responses to stimuli (Ramachandran & Hubbard, 2001). This theory largely explains key tenets of synesthesia, such as the consistency over one's lifetime. While neuroimaging studies have been able to validate the subjective experience of synesthesia through observing activation in senses not stimulated, currently there is no definitive biological cause or understanding of synesthesia despite concerted efforts by cognitive scientists.

The prevalence of synesthesia has been debated and is largely unknown. A main reason for this is because synesthesia is experienced subjectively and usually is not noticeably detrimental to one's life. Because genuine synesthesia is experienced throughout one's life, many synesthetes might never know that what they experience is anything out of the norm if it doesn't come up in discussion. Estimates of the prevalence of synesthesia in the general population range from 0.024% (Rich, Bradshaw, & Mattingley, 2005 as cited in Johnson et al., 2013) to 16.5% (Flournoy, 1893 as cited in Johnson et al., 2013). One of the largest studies surveying the general population attempted to minimize the self-referral bias by surveying large populations at museums and universities, and found the general population to be comprised of 4.4% synesthetes (Sumner et. al 2006), a finding which is also endorsed by Cytowic (2018). Sumner et. al (2006) found synesthesia to be more prevalent than previous reports, which serves as a foundational starting point for my research question; *does synesthesia exist to an extent in a greater population than those with documented synesthesia?*

To begin with the historical background, synesthesia was first documented as a medical phenomenon in 1710, but reports of synesthetic experiences have been found to date back further. Intellectuals of various disciplines gained interest in synesthesia research in the 1800's through the 1900's, but as behaviorism grew in popularity, people began to view subjectivity as unworthy of scientific inquiry (Cytowic, 2003). As synesthesia is a subjectively experienced disorder, questions arose about how to properly quantify people who had synesthesia and the validity of their experiences. The many different types as well as its subjective state make it hard to devise a standardized method for diagnosis. A recent attempt to standardize confirmation of color-grapheme synesthesia is the Synesthesia Battery (Eagleman et al., 2007). The battery utilizes several types of tasks in order to be certain of the validity of one's synesthesia. A main method requires participants to choose a color association for each letter or number. This task is then repeated at a later time period, and color-number and color-letter associations are compared. In genuine synesthesia, the inducer-concurrent stimuli couplings are consistent, so genuine synesthetes will give consistent color to letter and number associations each time they complete the synesthesia battery. (Eagleman et al. 2007)

While a defining characteristic of synesthesia is that synesthetes each have unique inducer and concurrent stimuli, studies of synesthetes have demonstrated that some inducer concurrent pairings are more common than others. In one of the most common types of synesthesia, color-grapheme, synesthetes are more likely to have the letter A associated as red than other colors (Cuskley & Kirby, 2013). This finding demonstrates the possibility that some inducer-concurrent pairings are acquired as a result of one's environment, as A is often represented in red while learning the alphabet. Because there have also been correlations found with non-synesthetes and identifying the letter A with red, this example ties into a larger possibility about the prevalence of synesthesia or cross-modal associations in the general population. (Cuskley & Kirby, 2013, Grossenbacher & Lovelace, 2001). As non-synesthetes have also shown to have cross-modal associations such as the letter A with the color red, there is a possibility that non-synesthetes also experience other cross-modal associations that haven't been discovered yet.

Cross-modal associations

Cross-modal associations are experienced when an input for one sense has a direct association for another sensory modality (Gilbert et al., 1996, Cuskley & Kirby, 2013). A sensory modality is a method through which we receive information in a sense. Some examples of sensory modalities are texture, color, orientation, pitch, and sweetness. In lexical-gustatory synesthesia, an example of a cross-modal association would be the word "dog" (a visual input) evoking the taste of peach (a gustatory phenomena). Marks (2013) proposes the concept of "weak synesthesia", in contrast with genuine synesthesia. Genuine synesthesia is characterized by consistent associations between an inducer and a concurrent, whereas weak synesthesia consists of "cross-sensory (and other) correspondences that are readily apprehended by the general population" (Marks, 2013, p.762). The general population has been shown to have cross-modal associations without experiencing synesthesia (Parise & Spence, 2013). There are widespread cross-modal associations between color and temperature, as well as color and weight (Parise & Spence, 2013). For example, we associate a hotter temperature with colors like red and orange, and cooler temperatures with colors like blue or purple. Whether these seemingly arbitrary associations are examples of synesthesia in the general public, or rather just learned associations from correlations present in the real world is a topic of debate (Parise & Spence, 2013). Parise & Spence (2013) argue that these cross-modal associations are not synesthetic in nature because they lack the inducer and concurrent stimuli that are present in genuine synesthesia. Moreover, other key defining factors of synesthesia, such as uniqueness of modal associations, are not present in cross-modal associations found in the general public (Cytowic, 2018).

Other sensory combinations have also been shown to have cross-modal associations in non-synesthetes, such as olfaction and gustation (Stevenson et al., 1998), olfaction and color (Osterbauer et al., 2005, Gilbert et al., 1996), color and gustation (Levitan et al., 2008), and color and music (Palmer et al., 2016). These findings and their implications will be explored in the next section.

Properties of synesthesia and effects of synesthesia on sensory processing

Synesthesia is a condition where very few experience deficits due to the condition. In fact, synesthesia has been shown to be a benefit for certain tasks. Synesthesia has shown to have advantages for memory; as Daniet Tammet, who holds the record for the most digits of pi memorized, has color-grapheme synesthesia (Miller, 2005). His synesthesia allows him to be able to remember and recall the numbers both as themselves and also as their concurrent grapheme representations (Miller, 2005). Synesthesia has also been shown to be an advantage for other types of sensory tasks. A study on odor-color synesthetes found they consistently outperformed non-synesthetes in odor-discrimination and odor-threshold tasks. These findings demonstrated that synesthetes experience enhanced perception in both the inducer sensory modality as well as the concurrent sensory modality for odor and color perception (Speed & Majid, 2018).

Emotion has also been demonstrated to have an effect on synesthesia (Palmer et al., 2013, Lebeau & Richter, 2022). A study on synesthetes with music-color synesthesia found that on average they have heightened emotional responsiveness to music, which researchers hypothesize is due to “their predisposition to increased cerebral connectivity” (Lebeau & Richter, 2022, p. 80). This finding aligns with the cross-activation model, as it suggests that synesthetes may have more brain cross-activation between synesthetic senses, and potentially also more cross-activation to other brain processes such as emotional processing. Strong music-color associations to emotions have also been observed in non-synesthetes, indicating that emotional processing plays a key role in cross-modal associations in non-synesthetes (Palmer et al., 2016, Lebeau & Richter, 2022). Studies of cross-modal associations between music, color, and emotion propose that emotional processing plays a key part in cross-modal associations for music and color in non-synesthetes (Palmer et al., 2013).

Cross-modal impacts on illusions

A topic that has been explored in relation to the cross-activation theory of synesthesia are illusions, which are often caused by conflicting information in cross-modal information integration (O’Callaghan, 2017). A popular illusion in perception studies is the McGurk effect (McGurk & McDonald, 1976), where a video is shown of a speaker saying a syllable, with audio of a different syllable actually being played. The participant uses both auditory and visual information to form a judgment on the syllable being said, and as a result, misjudges both the actual syllable mouthed and the syllable played over audio. As demonstrated by the McGurk effect, vision informs and has the capacity to alter our perception of auditory stimuli. The presence of illusions in the general population demonstrates that we rely on more than one sense to form our experience, and when our inputs from different modalities create an error in perception, that’s really just when we notice it. Color creates a similar illusion on odor perception, with colors having the capacity to alter odor judgements (Gilbert et al., 1996, Osterbauer et al., 2005). As I will further discuss later, when color is incongruent with the odor (an example of this is green with a strawberry scent), people judge the scent as less pleasant (Osterbauer et al., 2005).

The enhanced sensory perception of inducer and concurrent senses is not the only sensory aptitude that synesthetes display above non-synesthetes. Synesthetes have also shown to have enhanced illusion effects (O'Callaghan, 2017, Ramachandran & Marcus, 2017). Some conflate cross-modal illusions with synesthesia or synesthetic experiences, but they differ in important qualities. While both synesthesia and cross-modal illusions provoke associations between sensory modalities that don't exist in the general population, cross-modal illusions are not synesthesia because they lack fundamental properties of synesthesia, such as consistency over time (Cytowic, 2003).

A further illusion that informs our understanding of the cross-activation theory of synesthesia is The McCollough effect. In the task, the subject focuses on a pattern of horizontal single-color and black stripes, then experiences an after-effect of the pattern projected on the next place they look. This is an example of a visual illusion, as there is no pattern that exists where they look after focusing on the original pattern. Color-grapheme synesthetes experience an enhanced McCollough effect, which could be a result of the cross-activation theory of synesthesia (Ramachandran & Marcus, 2017). If the cross-activation theory is correct and color-grapheme synesthetes do have higher connectivity between color and visual processing in the brain, then it is hypothesized that the heightened McCollough effect could be due to the greater connectivity.

Inducing Synesthesia

Synesthesia is a consistent, lifelong condition. As previously mentioned, a defining characteristic of synesthesia is the lifelong consistency of stimulus received, or the inducer, and the concurrent stimulus that results (Cytowic, 2018). Current research about inducing synesthesia does not provoke synesthesia with the same life-long consistency, but rather uses the term "synesthesia" to refer to induced synesthetic experiences, or uncovering cross-modal associations (Parise & Spence, 2013). It is not genuine synesthesia because the inducer-concurrent pairing either does not persist after the study conditions resign, or did not exist before the study.

One such study that explored the induction of synesthesia in non-synesthetes found that non-synesthetes experienced synesthetic concurrents when given auditory stimuli after visual deprivation (Nair & Brang, 2019). The study induced visual synesthetic concurrents by depriving the participant of light, then enacting auditory stimuli. Participants were instructed to describe or illustrate any induced visual perceptions they experienced, which researchers mentioned might occur (as a part of the study procedure, not as a result of the auditory stimuli). Because some participants reported visual percepts, the study concluded that they were able to induce synesthetic percepts in an environment where one sense was diminished, and ergo another sense was heightened. This challenges the current scientific characteristic of synesthesia as a lifelong condition, and instead suggests that it's possible for more than just synesthetes to experience synesthesia when one's sensory balance is disrupted.

A contributing piece of evidence to the possibility of non-synesthetes experiencing synesthesia are the results of studies about learned synesthesia. Participants in Bor et al. (2014) were trained with specific letter-color associations by performing tasks and reading articles with the corresponding colors over a period of several months. The results demonstrated their ability to acquire some capacity for color-grapheme synesthesia, with 9 out of 14 participants experiencing synesthesia-like phenomena in their everyday lives. An example of this is a street sign appearing with colored letters. Further testing also confirmed the heightened synesthetic experiences as the participants' scores on tasks like the Synesthetic Stroop Task increased, tasks which are used as indicators of synesthesia. Learned synesthesia is a new topic of research, but synesthetic occurrences in people without synesthesia have been occurring in the general population for centuries with the use of mind-altering substances.

Psychedelic drugs and other mind-altering substances have been shown to induce synesthetic experiences, though with notable differences than genuine synesthesia. Sinke et al. (2012) compare the properties of drug induced and genuine synesthesia throughout many different drug induced synesthesia studies. Drug induced synesthesia has similar experiential qualities as genuine synesthesia, such as visual percepts induced by auditory stimuli. However, drug-induced synesthesia has inconsistent inducer-concurrent couplings, whereas a defining feature of genuine synesthesia is the consistency of inducer-concurrent couplings. (Terhune et al. 2016, Sinke et al., 2012, Cytowic, 2018). Because the drug-induced synesthesia lacks some of the key characteristics of genuine synesthesia, they must be studied independently. Even though these synesthetic experiences are due to the effects of drugs, researchers postulate that the cross-modal activation experienced in drug-induced synesthesia would not be possible without extra cross-modal connections between sensory modalities (Ramachandran & Hubbard, 2001, Grossenbacher & Lovelace, 2001). Perhaps the drugs temporarily deactivate the regulation between sensory modalities that typically prevent non-synesthetes from having induced cross-modal percepts in everyday life. More research must be done on the effects of drugs on perception in order to understand how synesthetic experiences arise due to these drugs, and whether this supports the presence of cross-modal associations within the general population.

Background on olfaction and odor processing

As the present study aims to explore cross-modal associations in non-synesthetes through associations between color and olfaction, it is important to understand how we process odors. Odor perception, along with the rest of our senses, is influenced by information from other senses, especially vision and gustation (taste). Odor processing, called olfaction, is not our main sense, but is the only sense other than gustation in which information is not routed through the thalamus, but rather relayed directly to the cortex of the rhinencephalon (Cytowic, 2018). Due to their structural organization in the brain, smell and taste are three synapses away from the hippocampus, which is key in memory formation (Cytowic, 2018). Even familiar odors are difficult for people to identify (Gilbert et al., 1996), with odor detection relying on visual cues (Osterbauer et al., 2005). Attempts to classify odors as well as localize where input for different odors is received and processed in the brain have been made, but there is a lack of consensus on how and where specific odor processing occurs in the olfactory cortex. Whereas other senses combine perceptual cues from several aspects of the input (such as vision looking at color and shape), odor processing is unique in that each odor has its own receptor responsible for identifying it. There is no concrete understanding as to how these receptors are organized in the brain, but attempts at schematic organization have been suggested (Lee et al., 2023). Odor perception is also affected by factors of the odor itself, such as pleasantness or emotional valence (Cytowic, 2002). Odors can elicit strong memories associated with the odors, but the memory of an odor is rarely experienced (Cytowic, 2002). Further, odors are often judged with qualities that apply to taste, which technically makes the experience of odor synesthetic in itself. For example, when asked to describe the odor "*strawberry*", the most common descriptor was "*sweet*", which is not a characteristic of odor, but rather a descriptor for taste (Cytowic, 2018). The self-rated pleasantness of an odor also affects how it is further processed in the brain, with pleasant odors activating a region of medio-rostral OFC, which is not activated with unpleasant odors (Rolls et al., 2003).

Gilbert et al. (1996) explored odor-color associations in non-synesthetes by assigning a color to correspond to an odor. Subjects were instructed to describe an odor sample by distributing five points across 11 colors. Gilbert et al. found that "odors are nonrandomly characterized by colors," with these characterizations being stable over a period of two years (Gilbert et al., 1996, p. 342). One possible explanation suggested for this is that the semantic labels of smells have color associations, and the labels themselves and their color associations are stable over time. However, further studies show that color-odor associations exist independently of semantic labels (Speed & Majid, 2023), which might disprove this explanation. Regardless of explanation, the findings of Gilbert et al. (1996) indicate that one should expect to find consistent odor-color associations with non-synesthetes.

Now I will further go into how odor-color associations that exist in non-synesthetes impact perception. Color has also shown to affect odor perception, as when color is altered, there can be a resulting change in odor perception (Osterbauer et al., 2005, Speed et al., 2023). This change in odor perception as a result of color alteration has further impact on our sensory perceptions, as odor perception has also been shown to affect taste. A study examining odor perception and its impact on taste instructed participants to smell a drink, and then taste it through a straw. In the task, participants were unaware that the sweetness of the smell was manufactured and not representative of the actual taste. Results demonstrated an effect of odor on the sweetness perception of the drink, where odors that had an artificially produced sweeter scent were perceived as sweeter even when the drink was the same (Stevenson et al., 1998). Another study examined the impact of odor-color congruency on taste pleasantness and found that a drink with congruent color and odor is judged as tasting more pleasant, even when the drink remains constant through conditions (Zellner et al., 1991). These studies illustrate the cross-modal influence of olfaction on taste perception.

Odor-perception's influence on judgements

Odor has further influence on our perception beyond taste, an example of this being the role of odor in perception of attractiveness (Demattè, 2006). Participants in Demattè (2006) rated the attractiveness of men higher when the image was accompanied with a pleasantly scented body spray than when the image was presented solo. Label-color congruency also has been demonstrated to have an effect on the perception of odor pleasantness. A study explored this by examining the odor pleasantness ratings of items with congruent color-label associations and the odor pleasantness ratings of items with incongruent color-label associations. An example of this would be the scent lemon with the color yellow (congruent condition), and the scent lemon with the color purple (incongruent condition). They found a correlation between congruent color-label associations and odor pleasantry ratings, indicating that people perceive congruent color-odor associations as more pleasant than incongruent ones (Zellner et al., 1991). Because of this correlation, one might hypothesize that language, specifically the odorant labels, moderate odor perception. Speed and Majid (2023) explored this theory in a research study, where they tasked participants with creating odor-color associations with fourteen possible odors and twelve possible colors. One group had a language interference task, which in theory prevented them from being able to verbalize or label the odorants. They found that the language interference group formed associations the same as the control group, leading to the analysis that color-olfactory associations exist independent of language. Integrating this information with previous studies, we see how labels can alter our odor perception, but also aren't necessary for forming odor-color associations.

These findings of Speed and Majid (2023) also demonstrate that people find congruent color-associations more pleasant, which might be indicative of how likely they are to remember them and choose them when developing odor-color associations. It also leads one to the question– what happens when we have no semantic label associated color with an odor? Through my method, I aim to explore the impact of cross-modal associations of odor and color on odor perception. My method will further explore the strength of one's cross-modal associations of odor and color, as well as how the strength of cross-modal odor-color associations impacts odor identification and differentiation.

The present study

Our knowledge of cross-modal associations is still developing. While certain cross-modal associations have been found to be widespread in non-synesthetes, such as the letter "A" with the color red (Cuskley & Kirby, 2013, Grossenbacher & Lovelace, 2001), we can be confident that we are still discovering just how prevalent cross-modal associations are in the general population. Through my methodology, I aim to explore the prevalence of cross-modal associations between olfaction and color. As I am exploring the potential for cross-modal associations between olfaction and vision (specifically color), my methodology relies mainly on stimuli and methodology from prior research on olfactory-color associations. The specific background for methodology and stimuli for the present study will be developed in the next section.

The procedure for the present study is based on the Stroop task (Stroop, 1935). In the Stroop task, participants are presented with words that are the names of colors. These words have colors themselves. Participants are then asked to say the colors of the words, which are all names of colors themselves (Stroop, 1935). For example, the word "*green*" is printed in blue text. The main finding of the Stroop task is that when the color of the word and the word itself are different, participants take longer to name the color of the word. It follows that when the color of the word and the word itself are congruent, participants are faster to name the color of the word. This task demonstrates that when one receives conflicting information about a stimulus (in the case of the Stroop task, the color the word is presented in and what the word itself means), cognitive interference affects the response time of correctly describing the stimulus (Stroop, 1935). The present study adapts this experimental paradigm of congruent and incongruent pairings to odor-color associations, which will be described in-depth in the procedure section.

Hypothesis

The current literature leads us to the hypothesis that participants will have cross-modal associations between color and olfaction, and because of this will score both more rapidly and accurately with the congruent color-odor condition. The color odor association would function as another memory cue for the label of the odor when tasked with recalling the odor. This hypothesis is supported by prior research demonstrating the associations between odor and color (Gilbert et al. 1996, Osterbauer et al., 2005), as well as the Stroop task, as congruent stimulus pairings had a shorter response time (Stroop, 1935). In contrast to this hypothesis, if participants do not have strong cross-modal associations between color and olfaction, the color conditions will not affect how rapidly or accurately participants label odors.

Methodology Background

To determine the color-association method for my experiment, I examined how color was presented and measured in several cross-modal studies. One study that was measuring the impact of color associations on odor perception in non-synesthetes presented participants with 11 colors, for which they were asked to distribute 5 points based on their color perception of the odor. A benefit of this method is the limited number of colors as well as the ability for participants to choose more than one color proportionally, which allows for a variety of color associations without having too many color stimuli options. (Gilbert et al. 1996). A similar study by Osterbauer et al. (2005) that examined how color affects odor responses in the brain utilized 10 colors presented virtually for their study.

For my method, I needed participants to be specific in their color choices as they weren't just describing the color associated with the odor, but it would also be used as a modifier in the recall condition in the second half of the task. My method has a selection of 20 colors, which are recognizably distinct, cover the normal color spectrum, and each have a distinct name (Trubetskoy, 2017).

In order to determine the amount of odorants to present to participants (as well as which), I also reviewed the odors and presentation methods used in six studies about odor-color associations, as well as studies that looked at odor perception in general. Speed et al. (2023), which focused on odor-color associations mediated by language, presented 14 odors to participants in varying methods of odors. For example, the odor "*orange*" was presented by a piece of orange, while the odor "*grass*" was presented in a bottle of grass essence. All odors were presented inside an opaque jar with scent ventilation on top to maintain congruence between odors. For their initial odor-color association matching, Osterbauer et al. (2005)

presented participants with 17 odors. They ended up only utilizing four of the odors with the strongest color associations in their experiment; lemon, strawberry, spearmint, and caramel. Research on synesthetes' induced odor-color associations utilized 16 Sniffin' Sticks, which are frequently used in a standardized test method for odor perception ability (Speed & Majid, 2018). Gilbert et al. (1996) presented participants with 20 odorants, all used primarily in fragrances, which meant that most of the odors had less common labels and smells. For the odorants themselves, I compared odors used in Gilbert et al. 1996, Speed et al. 2023, Osterbauer et al. 2005, Dematte 2006, Yoshida 1975, Lötsch 2016, as well as in the Sniffin' Sticks test for odor perception (Hummel et al. 1997). My study utilizes 15 different odors, chosen from the most frequently appearing odors utilized in these studies, which are presented using essential oils in Nasal Inhaler Tubes.

Method

Participants

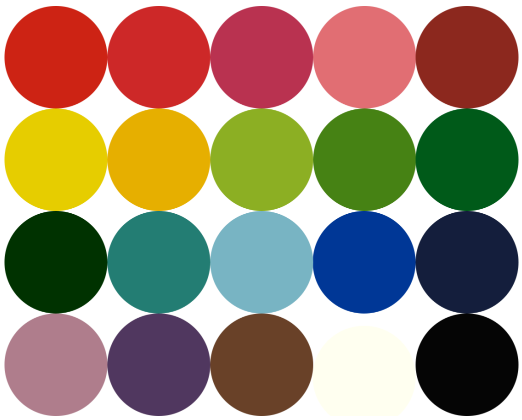
The participant population consisted of 30 people; 21 female, 5 male, 3 non-binary and 1 gender-fluid person. The participant population was 43.3% Caucasian, 6.7% Black or African American, 10% Hispanic or Latino, 33.3% Asian or Pacific Islander, and 6.7% mixed ethnicity. Participants were recruited through word of mouth, Pomona College student communication channel CHIRPS, as well as the Scripps College Student newsletter. All participants recruited were current students at the Claremont Colleges in Claremont, California, and were between the ages of 18 - 24. The screening process required participants to not have strong smell sensitivities, severe food allergies, or synesthesia. After completing the study, one participant who displayed a significant result on the synesthesia questionnaire was excluded from analysis. The study utilized a within-subjects design, with each participant completing all conditions. All participants gave written informed consent and were compensated $15 via Venmo or Zelle. The Scripps College IRB and the Pomona College IRB approved this study prior to data collection.

Materials

The odor stimuli consisted of 15 varying types of essential oils, each of which represented a specific smell; coffee, orange, apple, mango, leather, banana, lemongrass, lavender, rose, peppermint, eucalyptus, plumeria, vanilla, licorice and clove. Odors were presented in white nasal inhaler tubes with small holes (~ 2 mm) drilled in the top for ventilation. To prepare odors, ten drops were added to a cotton insert of the Nasal Inhaler Stick, which was capped at the bottom and labeled underneath with a letter for researcher identification. Labels were printed in a black font on a white background and stuck on the outside of the tube. Color was specified by selecting a circle sticker with one of 20 colors (Figure 1). A small undulating fan was utilized to ensure fresh air in front of the participant in between odors. The synesthesia questionnaire given to participants is from the Synesthesia Battery, a standardized collection of tests for synesthesia (Appendix 1). The response data for this experiment was collected using voice recordings, which collected reaction-time and accuracy of stimuli identification through the voice recording program Audacity. This was combined with the hand-recorded input and color assignment data for each participant for further analysis of reaction-time and accuracy for each condition. Participants ran the study in the same testing room at an empty white desk.

Figure 1

Color stimuli options for odor-color association task



Procedure

Following giving informed consent, participants were given the first part of the task; assigning individual odor-color associations. After smelling an identified odor with a label presented in a Nasal Inhaler tube for as much time as they needed, participants chose a color from a sticker sheet of colored circles out of 20 possible colors, then the researcher placed a copy of that sticker in a stack and recorded it. The Nasal Inhaler Tube was handed to the participant after instructing the participant how to open the tube, and to smell from the hole at the top. Participants were instructed to identify the color that they thought of most when they smelled the scent presented, as is common in odor research (de Valk et al., 2017; Demattè et al., 2006, Gilbert et al., 1996, Speed et al., 2023). After the participant created the odor-color pairing by choosing a color, they were given 30 seconds of clean air from the fan to let the odor dissipate, then presented the next odor by the researcher and the association task was repeated. Participants made odor-color associations for all 15 odors. Colors were allowed to be repeated for different odors.

Participants then completed the digit span test online as a distractor task, which measures working memory (Miller, 1956). This task presents participants with a sequence of digits and asks the participant to recall the digits after the presentation sequence finishes. If correct, the next sequence presented increases by one digit. The aim of this task was to eliminate the possibility for label-color rehearsal. Participants also completed demographic information and a synesthesia questionnaire after completing the digit task. Both the demographic information sheet and the synesthesia questionnaire were de-identified, and participants were informed they were permitted to leave any question blank they didn't want to answer.

After completing the task, participants moved on to the odor recall procedure, where participants were instructed to provide the label for the odor presented to them. The odors were the same 15 odors used in the previous task, and were presented in Nasal Inhaler Tubes in one of the following three conditions. The Nasal Inhaler Tube for all conditions was handed to the participant by the researcher, and instructed to be uncapped, but not smelled until a starting beep was heard.

In the recall portion of the procedure, the odor was either presented: with no color, with the congruent color they chose, or with an incongruent color. This procedure is based on the Stroop task, where color-word pairings are presented in congruent and incongruent pairs. The third recall procedure, of no color, is added to address the possibility that the addition of any color impacts odor recall abilities. These recall conditions were randomly assigned to each odor, and presented in a random order. The color (or lack of) was displayed simultaneously with the odor presentation on the nasal inhaler tube which the odor was presented in.

For the first condition, the nasal inhaler tube was left blank. For the congruent recall condition, the color of the sticker on the tube matched the original unique color-odor pairing the participant had assigned in the first portion of the task. For the incongruent color condition, a randomly chosen color sticker was displayed on the tube. Participants were instructed to smell the tube once they heard a beep and then recall the label of the odor as quickly as possible and say the label out loud. They were allowed to keep smelling the tube for as long as needed until they recognized the odor. If they couldn't recall the label of the odor after 90 seconds, the lack of odor recollection was marked and they were informed the study would continue to the next step. Between the recall of each odor and the next odor, participants were given time with no odor and the fan running, in order to not contaminate across odors. Participants were not informed whether they successfully labeled each odor. After completing recall and labeling of all 15 odors, participants were given an opportunity to ask any questions they had, as well as debriefed about the study methodology and purpose.

Results

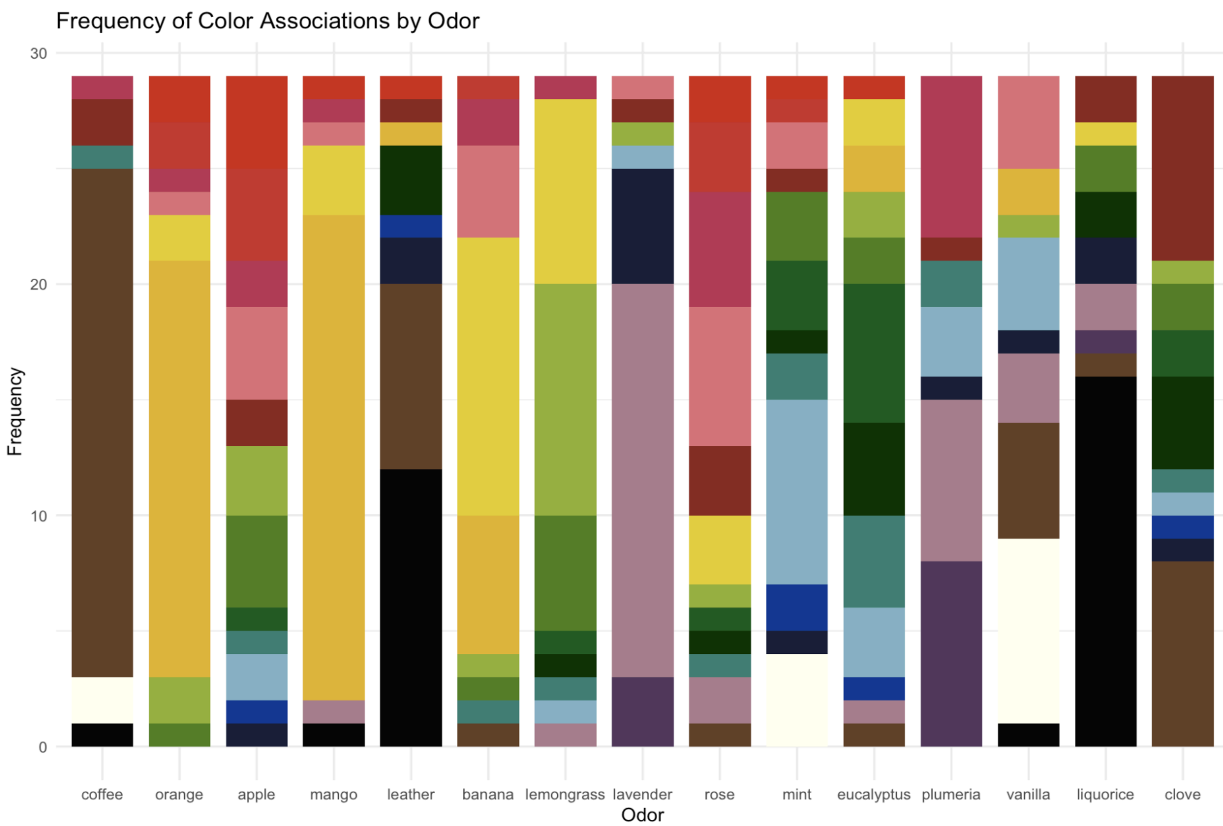
Data Measurement

Response time was measured by manually playing back voice recordings and measuring time between the starting beep and participant response which was then recorded as the variable ('response_time'). Participants' identification of the odor label was compared to the actual label of odor, identified using the variables ('odor') and ('recall_order'), and then marked '1' for correct identification and '0' for incorrect identification as the variable ('response_accuracy'). Points were not given for a correct category definition, such as "*flower*" or "*fruit*". Points were given for incorrect pronunciations such as "*plumbria*" instead of "*plumeria*" as well as shortenings such as "*mint*" instead of "*peppermint*". All participants in this study fell inside the normal range for working memory measured by the digit span test (M = 7.41, SD = 0.98).

Odor-Color Association Assignment

A Pearson's Chi-squared test was conducted to assess the correlation between odor and color association. The test revealed a significant association ($\chi^2(266) = 1319.6$, $p < .001$), indicating that odors were non-randomly characterized by color associations. These associations are depicted in Figure 2. Pearson residuals for each odor and color were calculated. The odor with the greatest strength for the common color association was *'coffee'* (P = 10.66) with the color *brown*, and *'rose'* had the weakest common color association (P = 3.61) with the color *light pink*.

Figure 2

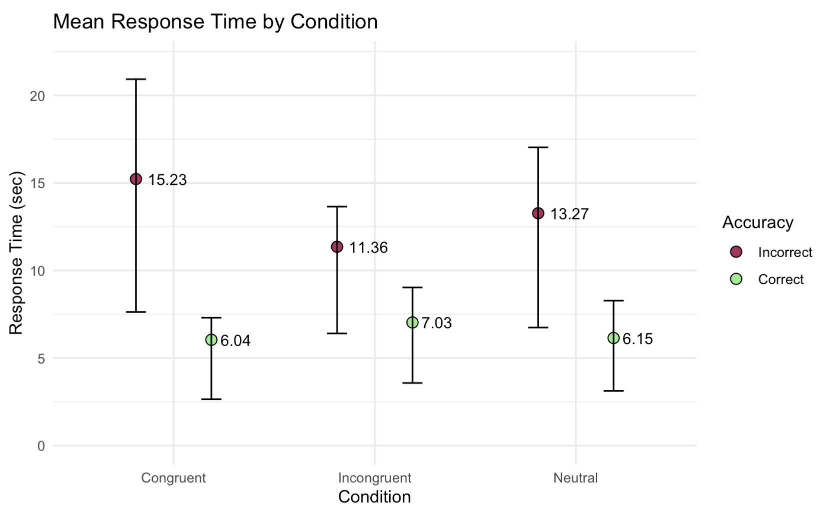


Note. This figure shows odor-color associations, with odors labeled on the x-axis and the frequency of color choices for each odor on the y-axis. The height of each color band represents the frequency of color selection for each odor-color association. "Mint" refers to peppermint.

Effect of Condition on Response Time

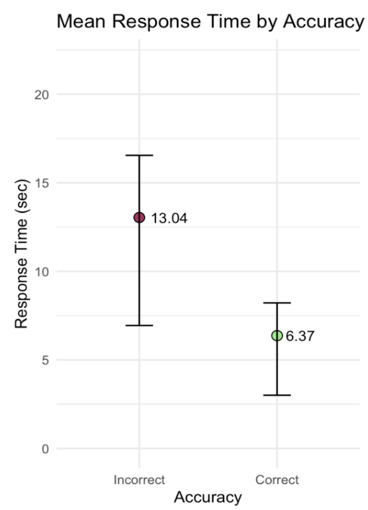
The congruent condition had the lowest average response times for correct responses (*M* = 6.04 seconds, *SD* = 5.69 seconds) and the neutral condition had slightly higher average response times for correct responses (*M* = 6.15, *SD* = 4.88). The incongruent condition had a slower average response time (*M*=7.03, *SD*= 5.51) than neutral and congruent conditions. Correct odor identification across all subjects and conditions had a quicker response time (*M*=6.37, *SD*=5.38) than incorrect odor identification (*M*=13.04, *SD*=9.20). These results are depicted in Figure 3 and Figure 4.

Figure 3



Note. In the figure, the x-axis represents the different recall conditions, and the y-axis shows response time in seconds per condition. Colored dots indicate mean response time, with direct labels on the right. Error bars show the range between the 3rd and 1st quartiles, providing insight into response time variability across conditions and accuracy levels.

Figure 4



Note. The figure shows accuracy differences for all recall conditions, with incorrect odor identification on the left and correct odor identification on the right. Circles represent mean accuracy, with error bars indicating the 3rd and 1st quartiles of response times.

Table 1 *Average Response Time per Odor for Recall Conditions (seconds)*

Odor	All conditions	Congruent	Incongruent	Neutral
coffee	3.53 s	3.93 s	2.88 s	4.14 s
orange	9.26 s	5.34 s	11.87 s	5.61 s
apple	7.93 s	7.85 s	8.53 s	5.37 s
mango	4.10 s	3.94 s	4.23 s	7.46 s
leather	4.76 s	5.10 s	4.03 s	4.57 s
banana	5.21 s	4.12 s	6.30 s	3.66 s
lemongrass	4.92 s	4.72 s	5.71 s	9.32 s
lavender	7.53 s	5.02 s	10.03 s	4.05 s
rose	5.04 s	4.15 s	5.92 s	4.06 s
peppermint	7.36 s	6.01 s	8.37 s	6.55 s
eucalyptus	8.49 s	15.27 s	6.23 s	9.20 s
plumeria	13.13 s	13.91s	11.05 s	3.77 s
vanilla	6.91 s	6.51 s	7.47 s	7.19 s
liquorice	4.97 s	2.87 s	7.68 s	5.65 s
clove	5.41 s	5.76 s	4.97 s	9.10 s

Note. Data presented in the table is only from responses with correct odor identification.

The effect of condition on response time was assessed using a two-way repeated measures analysis of variance test (ANOVA), looking at the factor condition (‘recall_cond’). The main effect of condition on response time was found to be insignificant, $F(2, 49) = 0.78$, $p = 0.464$, suggesting that the hypothesis regarding condition effect on response time was not supported. Table 1 (page prior) represents the mean response time for each odor per condition for correct responses.

Effect of Condition on Accuracy

The odors “*coffee*” and “*apple*” had the highest and lowest identification rates, at 81.25% and 36.36% respectively. The mean odor identification rate per smell was (M=59.54*,* SD=12.73). Odor identification accuracy rates for each odor and congruent and incongruent color recall conditions are presented in Table 2.

Table 2 *Average Identification Rate per Odor for Congruent and Incongruent Color*

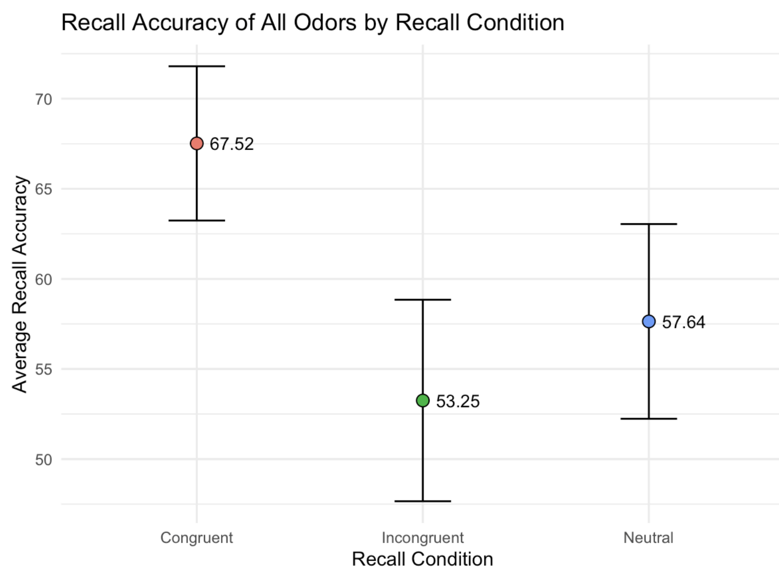
Odor	All Conditions	Congruent	Incongruent	Neutral
coffee	81.25%	100%	62.5%	92.31%
orange	62.50%	66.67%	60%	61.54%
apple	36.36%	46.67%	14.29%	42.86%
mango	56.25%	50.0%	62.5%	61.54%
leather	80.0%	91.67%	62.5%	44.44%
banana	66.67%	60.0%	75.0%	45.45%
lemongrass	50.0%	88.89%	18.18%	66.67%
lavender	70.59%	66.67%	75.0%	33.33%
rose	47.62%	62.5%	38.46%	62.50%
peppermint	66.67%	75.0%	61.54%	75.0%
eucalyptus	60.0%	42.86%	69.23%	44.44%
plumeria	47.83%	57.14%	33.33%	16.67%
vanilla	52.17%	58.33%	45.45%	50.0%
liquorice	80.0%	75.0%	87.5%	77.78%
clove	47.37%	71.43%	33.33%	90.0%

Note. Percentage is used to indicate the average accuracy rate.

The mean accuracy rate across participants showed that individual participants on average correctly identified about ten out of fifteen smells (M=59.54, SD=22.32), with accuracy rates ranging from 6.7% to 100% correct odor identification.

The incongruent condition had the least accurate odor recognition (M = 53.25%, SD = 21.65), with the neutral condition having slightly greater accuracy (M = 57.64%, SD = 20.93), and the congruent odor recognition condition having the greatest accuracy (M = 67.52 , SD = 16.58) (Figure 5). To determine the effect of recall condition on accuracy, an analysis of variance test (ANOVA) was conducted to compare recall accuracy across the conditions. The test revealed a significant correlation between the recall condition and accuray, $F(2, 56) = 4.28$, $p = 0.0186$, indicating that the recall condition influenced recall accuracy. Post-hoc pairwise t-test demonstrated that there was a significant relationship between the congruent and incongruent conditions (p = 0.035), but not the congruent and neutral (p = 0.589), or neutral and incongruent conditions (p = 0.659).

Figure 5



Note. Mean recall accuracy and standard error (shown as error bars) are presented for each odor-color recall condition. Means were computed by averaging the recall accuracy for each odor within each condition.

Discussion

The results of this study support the first hypothesis that participants have greater accuracy with the congruent color-odor condition because the odor-color associations provide another memory cue. However, results did not support the second hypothesis that participants will also have a quicker reaction time for the congruent color-odor condition because the odor-color associations provide another memory cue.

Odor-color Associations

This study was able to replicate the finding that odors are non-randomly characterized by colors, which indicates the existence of inherent odor-color associations in the general population (de Valk et al., 2017, Dematté et al. 2006, Gilbert et al. 1996, Speed et al. 2023). However, the quantity of odor presentation and color selection choices differed in all of these; prior studies utilized other methods such as uncommon smells and a greater or smaller variety of colors and odors. In the current study, participants created odor-color associations by choosing one of 20 possible colors for each one of 15 odors which were essential oils.

The odors used in this study had a range of consensus on color characterizations, with "*coffee*" having the highest color-odor characterization frequency of brown with 75.86% of participants, to "*rose*", which had the lowest color-odor characterization frequency, with the odor the most chosen light pink, by 20.69% of participants. The degree to which the general population holds an established color association for each odor differed and was not measured in the present study. Without further analysis of the strength of pre-established odor-color associations, it is unknown how much the strength of pre-established associations plays a role in the recall and interference of odor. If preconceived connections between colors and certain odors are stronger for some color-odor pairings than others, those pairings could impact the reaction time and accuracy outside of the study conditions. To observe this, I compared the difference in reaction accuracy for the odor with the greatest color consensus for the most frequently chosen color and the odor with the least color consensus for the most frequently chosen color. The odor that had the greatest color consensus for the most frequently chosen color "*coffee*", was characterized with the color brown for 75.86% of participants, and is commonly portrayed in the media as brown. The strength of this association could be demonstrated in the difference in recall accuracy in the congruent and incongruent conditions, with the congruent condition having a 60% increase in accuracy than the incongruent condition. In contrast, the odor with the least color consensus for the most frequently chosen color "*rose*" had a less established color-association, with the highest consensus color agreed upon by 20.69% of participants. The congruent condition also improved recall of the odor plumeria, and the congruent condition had a 62.51% increase in accuracy than the incongruent condition. The two odors with the greatest difference in odor-color consensus both found around the same improvement in recognition between the congruent and incongruent conditions, which could indicate that the strength and collective consensus of odor-color encodings does not affect individual association strength and impact the task conditions.

Effect of Condition on Response Time

As the ANOVA revealed the effect of condition reaction time was insignificant, this study was unable to reject the null hypothesis for condition affecting reaction time. Because previous studies have observed an effect of incongruence on reaction time for odor-color pairings (Dematté et al. 2006), this finding could be due to the wide range of familiarity with the odors, as Dematté et al. focused on two common odors, which participants just had to choose between. In the current study, participants were choosing between 15 odors, and did not have a list of them, including some odors which had possibly just been introduced to them in the first part of the study. This methodology then adds in the encoding of new words and odors as well as the ability to identify them, a variable which was not present in other research that found a significant effect of reaction time. Further, the Stroop task, which the methodology of this study is based on, does not involve the possibility of unknown colors or words. In the Stroop task, reaction time was a significant indicator of cognitive interference because people are always able to correctly identify the color of words, whereas there was not a baseline knowledge or competency of labeling odors in the present study.

Effect of Condition on Accuracy

The significant effect of the ANOVA of recall condition on accuracy finding supports my hypothesis that the condition affects the accuracy of identifying odors. Specifically, this finding supports my hypothesis that the interference of incongruent color would affect the ability to correctly identify odors. Because significance was found between the incongruent and congruent condition, but not the neutral condition, this finding aligns with prior research about the Stroop effect–where incongruent recall causes interference (Stroop, 1935). This is a novel finding and could demonstrate the presence of odor-color associations in the general population such as semantic associations with color–as demonstrated by the original Stroop task. Further, the finding that incongruent color presentation interfered with correct identification of odor confirms prior findings that color plays a role in odor perception (Osterbauer et al., 2005, Stevenson et al., 1998).

Limitations

A main limitation in the study was the participant population size, which affects the generalizability of the study results. This limitation was a restriction created by the duration of the study as well as the window of availability of the research to be conducted. Because the study has 15 odors, each odor was only recorded in each condition around 10 times, which may not have been enough to account for confounding variables from the participants, such as smell ability. An attempt at mitigating the variability of individual participants is the within subjects study design, however, the study design did not account for individual familiarity with specific odors, which could have affected recall. Further, some participants noted an emotional association with an odor, which could cause the odor to be easier to recall, as it is encoded both as the smell itself and also as a memory or feeling (Cytowic, 2002). The generalizability of the findings of odor-color associations and recall improves with a larger participant population, as individual trials and confounding variables become less influential in a larger dataset.

Further, participants who had a pre familiarity with essential oils which may have provided them with prior understanding/experience with smells that appear less frequently in the general environment, which in turn were harder for the general participant population to identify (an example of this is "*eucalyptus*," which was only correctly identified 55.17%). The methodology of essential oils provided other challenges, such as not perfectly mimicking or aligning with participant's conception of certain smells. Some odors were perceived to be more representative with the smell of the actual thing it represented, while others were notably more artificial in smell and in turn– possibly weren't as associated with the actual label of the odor. The least correctly recognized smell, *'apple'*, was noted to smell artificial, which makes sense considering actual apples don't have a very strong smell.

A possible source of variability of the study is running the study on human participants who are simultaneously forming a schema of the study goal and design while undergoing the task. For example, one participant noted when being asked to recall an odor label that had an incongruent color condition, "it smells like apple, but I know I didn't choose blue for apple". This participant had developed a schema for the study design that the colors on the recall condition would match the ones they had previously chosen, and didn't follow the instructions because of this schema. While they could have been potentially correct about the task design, assumptions made may have affected responses on the task.

The color method was chosen for this study due to the feasibility of choice for the odor to be physically presented in that color. However, this meant that there were less options than some studies use when forming odor-color associations. Two sets of odors ('*liquorice*' and '*leather*', *'banana'* and *'mango'*) both had the same colors chosen the most frequently when creating odor-color associations. For these odors, seeing the congruent color then could mean either of these smells, whereas for other smells they had an individual color association that was solely with that odor.

Future Research

As mentioned in the paragraph above, odor-color associations in the present study were assigned and recalled by participants, but not practiced or trained. Further studies should explore the effect of odor-color associations post recall training using those associations, which may help to account for and minimize the effect of prior experience and associations with specific odors. This study primarily looked at odors already familiar to the general population, but future research should explore the difference between known odors and their associations and unknown odors and their associations (although this approach provides its own challenges) as in the methodology of Gilbert et al. (1996), which utilized scientific names of odors used for perfumery as stimuli. Both of these research proposals would also contribute to our understanding of how cross-modal associations are generated, as discussed by Dematté et al. (2006), as a study that utilized odors without previous odor-color-learned associations would be able to observe the development and strength of associations throughout the study. Further, the present study explores the impact of odor-color associations created by olfaction and vision, but more research should also be done in general with other sensory-modalities about cross-modal associations. Olfaction and gustation are deeply linked senses, and as such it would be interesting to see if the cross-modal interference of color with odor also applies when the sense taste is also added in.

Conclusion

Proposed biological explanations for the condition synesthesia illuminate the question of how our senses are connected and affect each other. The present study aimed to explore the strength and influence of odor-color cross-modal associations through a stroop-like task. Findings of the task confirm that odors are non-randomly characterized by colors, which is demonstrated also by prior olfaction research. The results confirmed the hypothesis that cross modal odor-color associations would impact odor-recognition accuracy, demonstrating that color plays a role in odor-identification, and also possibly suggesting that color can mediate odor-perception. This study was not able to confirm the hypothesis that there would be an impact of odor-color congruency in odor-recognition on recall time, but future studies that train odors and establish familiarity before testing recall may see effects.

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Appendix

Synesthesia Questionnaire

Subject ID _______________

Do numbers or letters cause you to have a color experience? Example: Does the letter J 'mean' yellow to you? Or does '5' make you perceive purple?

- ☐ Yes, I have had similar experiences
- ☐ No, I have not had such experiences

Do weekdays and months have specific colors? Example: Does July always mean Navy Blue to you? Is Wednesday always orange?

- ☐ Yes, I have similar associations
- ☐ No, I do not have such associations

Do you imagine or visualize weekdays, months and/or years as having a particular location in space around you? Example: Is September always located two feet in front of you to the left?

- ☐ Yes, I have always felt these specific spatial locations
- ☐ No, I have never had this kind of association

Does hearing a sound make you perceive a color? Example: Does a shrill car horn cause you to see the color green? Does C sharp make you see pink?

- ☐ Yes, I do have such experiences
- ☐ No, I have not had such experiences

Do certain words trigger a taste in your mouth? Example: Does the name 'Derek' taste like earwax?

- ☐ Yes, this is familiar to me
- ☐ No, I have never felt like this

Do you feel a sense of touch when you smell things? Example: Does the smell of coffee make you feel as though you are touching a cold glass surface?

- ☐ Yes, I have had such experiences
- ☐ No, this doesn't happen with me

We have described a few types of synesthesia. Many other unusual blendings of the senses have been reported. Do you suspect that you experience an unusual blending that other people do not have (other than the ones listed above)? These could include automatically hearing a sound when you see movement, or the sense of a shape being triggered by a taste, or experiencing a color when feeling pain.

- ☐ Yes, I believe I may have other forms of unusual sensory experiences
- ☐ Not that I know of

A positive response on any of these could be indicative of synesthesia and was used as exclusion criteria for the participant population.