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Odor-Color Associations Are Not Mediated by Concurrent Verbalization

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Abstract

Odor and color are strongly associated. Numerous studies demonstrate consistent odor-color associations, as well as effects of color on odor perception and language. Yet, we know little about how these associations arise. Here, we test whether language is a possible mediator of odor-color associations, specifically whether odor-color associations are mediated by implicit odor naming. In two experiments, we used an interference paradigm to prevent the verbalization of odors during an odor-color matching task. If participants generate color associations subsequent to labeling an odor, interfering with verbalization during the task should affect the ability to make color associations. In Experiment 1, contrary to our hypothesis, verbal interference did not affect odor-color matches. However, since performance accuracy on the verbal interference task was high, it is possible our task did not sufficiently disrupt verbal processing. In Experiment 2, we, therefore, used an active verbal interference task, and still found no difference across interference conditions. Odor naming accuracy, odor familiarity, and odor pleasantness, however, did predict odor-color matches. This suggests that although color associations are related to semantic factors, they are not generated by recruiting odor labels in the moment. Overall, our results do not provide evidence that language plays an online role in odor-color associations, instead, they are consistent with the claim that language may have shaped associations during development.

Keywords: Cross-modal associations; Olfaction; Color; Odor-color; Language and Thought

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1. Introduction

The world is perceived through multiple channels, and the sense of smell—although often overlooked—is one of these. The existence of systematic crossmodal associations between odors and other sensory modalities has been observed (for review, see Deroy, Crisinel, & Spence, 2013). People easily match a color to an odor when instructed to do so, and their matches are consistent within and between participants (de Valk, Wnuk, Huisman, & Majid, 2017; Demattè, Sanabria, & Spence, 2006; Gilbert, Martin, & Kemp, 1996; Goubet, Durand, Schaal, & McCall, 2018; Jacquot, Velasco, & Spence, 2016; Levitan et al., 2014; Maric & Jacquot, 2013; Spector & Maurer, 2012; Speed, Croijmans, Dolscheid, & Majid, 2021). Colors associated with odors often match the color of the odor source (e.g., yellow for a lemon odor), suggesting the associations are learned from experience. Odor-color associations have been observed across development (Goubet et al., 2018; Speed et al., 2021), and, therefore, may play an important role in olfactory cognition. In two studies, we assess whether language plays a causal role in the associations between odor and color.

Aside from explicit crossmodal odor-color associations, there is a strong link between odor and color perception. Individuals who have automatic and vivid associations between odor and color in synaesthesia are better at discriminating between odors than people without synaesthesia (Speed & Majid, 2018). Similar effects are found in the general population too. Odor discrimination is impaired when odors (e.g., strawberry vs. cherry odor) are presented with an inappropriate color (e.g., green) rather than an appropriate color (e.g., red) (Stevenson & Oaten, 2008). Color also affects perceived odor intensity. For example, colored odorous solutions are perceived to have a stronger odor intensity than colorless odorous solutions (Koza, Cilmi, Dolese, & Zellner, 2005; Zellner & Kautz, 1990).

Effects of odor-color associations are also observed in language. Odor-color synaesthetes are more accurate and more consistent over time in naming odors than nonsynaesthetes (Speed & Majid, 2018). In the general population, identification of fruit odors is more accurate when odorous solutions are appropriately rather than inappropriately colored (Blackwell, 1995; Zellner, Bartoli, & Eckard, 1991) or when there are no color cues (e.g., when blindfolded) (Zellner et al., 1991). Similarly, relevant color cues (color patches or color words) improve odor identification compared to an irrelevant color cue, and this effect is stronger with words than patches (Davis, 1981). Color can also affect how a wine odor is described: when a white wine is artificially colored red, its odor is described using red wine descriptors (e.g., *raspberry*, *cherry*) (Morrot, Brochet, & Dubourdieu, 2001). This is seen even in experts (Wang & Spence, 2019; Williams, Langron, & Noble, 1984).

Despite the wealth of studies, it is unclear how such odor-color associations arise. Explanations focus on either perceptual or semantic mechanisms (Stevenson, Rich, & Russell, 2012). There are two possible perceptual mechanisms. Odor-color associations could be learned from statistical associations in the environment. For example, seeing the yellow of a lemon when we smell a lemon odor could form an association between yellow and lemon odor. Alternatively, associations may be the result of natural biases in connections in the brain between visual and olfactory systems (Spector & Maurer, 2012). Functional connections present at birth may not have been completely pruned during development, leaving systematic associations between sensory cortices.

In terms of a semantic mechanism, de Valk et al. (2017) proposed that language plays an active role in odor-color associations. This proposal may seem unlikely at first, since odor language is notoriously poor in European languages (Majid, 2021; Majid & Burenhult, 2014; Majid et al., 2018; Olofsson & Gottfried, 2015). At the same time, there are numerous demonstrations that odor perception is influenced by language (Herz, 2003, 2005; Herz & Clef, 2001; Speed & Majid, 2019; Stevenson, 2011). In particular, odor-color associations are affected by odor naming. Odor-color associations are more consistent for odors that are named correctly than incorrectly (de Valk et al., 2017; Kaeppler, 2018; Speed & Majid, 2018). The way odors are described also affects color associations (de Valk et al., 2017; Stevenson & Oaten, 2008; Zellner, McGarry, Mattern-McClory, & Abreu, 2007): if people incorrectly name a lemon odor as *lime*, they are more likely to associate the odor with green than yellow (Stevenson et al., 2012); and fragrances described as being for women versus men lead to different color associations (Zellner et al., 2007). Furthermore, de Valk et al. (2017) identified two linguistic strategies to describe odors, and found these affected color choices. When odors were described using source-based terms—referring to the source of the odor, for example, *smells like banana*—participants were more likely to choose colors that accurately reflected the odor source (i.e., yellow), compared to when odors were described using abstract terms—terms used to describe smell qualities and not linked to an odor source (e.g., *stinky*).

Based on the link between language and odor-color associations, it is plausible that odor-color associations arise through language. As stated by Miller (1956): "language is tremendously useful in repackaging material into a few chunks rich in information" (p. 95). Other crossmodal associations—for example, between musical pitch and space—are influenced by the language one speaks (Dolscheid et al., 2013, 2020; Fernandez-Prieto et al., 2017; Shayan et al., 2014). For example, Dutch participants associate high pitch with high space; but Farsi speakers do not, instead, they associate high pitch with thickness consistent with metaphors in their language (Dolscheid et al., 2013). Although speakers of different languages display different crossmodal associations between sound and space, under verbal interference, the same associations are still apparent, suggesting that language does not play an online role in these mappings (i.e., language does not affect processing in-the-moment, Dolscheid et al., 2013). This contrasts with what has been found with the categorical perception of color. Across cultures, there are different ways to label colors, with some languages making a lexical distinction, where others do not: for example, Celtic languages collapse the distinction between blue and green, whereas Greek makes a lexical distinction between light blue and dark blue. In perceptual tasks, people differentially perceive colors in line with the distinction in their language, but with verbal interference, this effect disappears (e.g., Gilbert, Regier, Kay, & Ivry, 2006; Roberson, Pak, & Hanley, 2008; Winawer et al., 2007).

If language plays a role in odor-color associations, this means it could do so in different ways: either language plays an online role during odor perception, affecting odor perception in-the-moment, or it only plays a formative role in the development of associations instead. Having a source-based term for an odor could strengthen odor-color associations in development, but the label itself may not be necessary to retrieve color associations. In line with an online role of language in odor-color associations, Stevenson and Oaten (2008) suggested that odor perception is affected by color via odor identification. As described above, they found that participants made more odor discrimination errors (e.g., between strawberry and cherry odor) when odors were presented with inappropriate colors. Crucially, the difference between appropriately and inappropriately colored odors disappeared during an articulatory suppression task, suggesting that identification of the odor was necessary for the effect. In the present study, we use a similar methodology to elucidate the relationship in the other direction, that is, whether language mediates color associations elicited from smelling odors.

We hypothesized that odor-color associations could arise online through verbalization: participants label an odor upon smelling it and choose a color in line with that label. So, when smelling the odor of lemon, participants activate the label *lemon* and subsequently choose yellow. To test this, we adopted a verbal interference paradigm. By having participants memorize digit strings while making odor-color associations, the opportunity to label the odor is removed. This methodology has been used previously to eliminate effects of language on color perception (e.g., Winawer et al., 2007). If language mediates odor-color associations online, we would expect verbal interference to reduce matching odors to colors in line with the odor source (i.e., less likely to match lemon odor to yellow color).

We first conducted a norming study to ascertain which colors were associated with a set of odor-source objects. Since we were interested in color associations driven by naming an odor, we chose to norm color associations based on object concepts rather than odors. Determining odor-color matches in terms of the typical color of an object was the procedure followed by de Valk et al. (2017), who found that participants were more likely to choose a color match when an odor was named correctly and when it was named with a source-based term (e.g., *banana*) rather than an abstract smell term (e.g., *stinky*).

Following this, we assessed the effect of verbal interference on odor-color matches and compared this to the effects of spatial interference and no interference (baseline). We assessed odor-color matches by explicitly asking participants which color they thought went best with an odor, as is typical in the literature (de Valk et al., 2017; Demattè et al., 2006; Gilbert et al., 1996; Goubet et al., 2018; Jacquot et al., 2016; Levitan et al., 2014; Maric & Jacquot, 2013; Spector & Maurer, 2012; Speed et al., 2021). We also collected odor naming responses and a measure of semantic fluency to test the role of naming ability in odor-color matches. If odor naming is related to verbal proficiency (cf. Larsson, Lövdén, & Nilsson, 2003), then this could be an important mediator for odor-color associations. Finally, we collected ratings of odor familiarity, intensity, and pleasantness as a further test of factors related to odor-color matches.

2. Norming study

2.1. Method

2.1.1. Participants

Twenty-eight Dutch participants (17 females) completed the survey. Age ranged from 27 to 59 (one age response was missing) (M = 33.37, SD = 9.75). This and the

Table 1
Odors, odor objects, and their corresponding colors determined through norming

Odors	**Objects**	**Color**	**Additional colors**
Coconut	Coconut oil	White (96.4%)	Brown (3.6%)
Banana	Piece of banana	Yellow (100%)	
Peanut butter	Peanut butter	Brown (75%)	Orange (14.3%), yellow (10.7%)
Mint	Essence	White (71.4%)	Light blue (17.9%), green (10.7%)
Orange[1]	Piece of orange	Orange (96.4%)	Red (3.6%)
Coffee	Coffee (liquid form)	Brown (67.9%)	Black (32.1%)
Lemon	Piece of lemon	Yellow (100%)	
Strawberries	Frozen strawberry (defrosted in microwave)	Red (100%)	
Grass	Essence	Green (100%)	
Liquorice	Liquorice candy	Black (96.4%)	Brown (3.6%)
Broccoli	Frozen broccoli (defrosted in microwave)	Green (100%)	
Pineapple	Pineapple (piece preserved in jar)	Yellow (100%)	
Lavender	Essence	Purple (75%)	Pink (21.4%), green (3.6%)
Tomato	Tomato passata	Red (96.4%)	Orange (3.6%)

Note: Proportion of participants selecting each color indicated in brackets.

following studies were approved by the Radboud University Ethics Assessment Committee of the Faculty of Arts and the Faculty of Philosophy, Theology and Religious Studies (EACH).

2.1.2. *Materials and procedure*

An online survey was created using Qualtrics (Provo, UT, version May 2017). Participants were given the names of objects (see Table 1) and were asked to choose which color belonged to the object from a set of 12 colors (brown, red, orange, yellow, green, light blue, blue, purple, pink, white, gray, and black) presented in a three (column) by four (row) grid. The objects selected were highly familiar to Dutch participants. Participants made their responses by clicking on a color displayed onscreen. The presentation order of colors was randomized. Participants were allowed to choose one color for each object. It was not possible to go back to previously answered questions.

2.2. *Results*

Participants were unanimous in their color choices for six out of 14 objects; for the remaining eight objects, two or three different colors were chosen. Overall, there was a clear predominant color response for all objects, confirming their suitability for the critical experiments. Table 1 displays objects and their chosen colors.

3. Experiment 1

3.1. Method

3.1.1. Participants

Ninety-nine native speakers of Dutch (33 in each condition, 81 females, 18 males) who had not participated in the earlier norming study were recruited through Radboud University's Sona participant database. Participants' age ranged from 18 to 65 ($M = 23.7$, $SD = 7.8$). This sample size is larger than those used in previous by-participants analyses in studies of odor-color associations (e.g., de Valk et al., 2017) and verbal interference (e.g., Winawer et al., 2007). Participants were instructed not to take part in the study if they had a cold, and were instructed not to eat, drink (except water), or smoke, at least 30 min before taking part in the study.

3.1.2. Stimuli

The stimuli were odorants corresponding to each of the objects in the norming study. They were either real objects or essential oils, placed in small opaque jars with a layer of odorless white polyfiber placed on top to conceal the contents (see Table 1). Odors were refreshed every other day, or every day if they were natural food objects. The same amount of odorant was used each time, measured either with a pipette or weighing scales. Each odor was assigned a dominant color match, determined through the norming procedure.[2]

3.1.3. Design and procedure

Participants were randomly assigned to a baseline, verbal interference, or spatial interference condition. Participants in both interference conditions performed a staircase threshold test to determine individual level of interference prior to the main experiment, so that working memory was taxed equally across participants. Following Winawer et al. (2007), we used digits for verbal interference and block patterns for spatial interference. To determine the level of interference in the verbal condition, participants were given a sequence of digits to retain, and after 3.5 s, they saw two sequences of digits and had to decide which they had seen previously. For spatial interference, participants saw a pattern of black-and-white blocks to remember, and after 3.5 s saw two block patterns and had to decide which they had seen previously. The starting level of difficulty was four digits in the verbal task, and a three-by-three grid with four black squares in the spatial task. If participants performed at 80% accuracy or more in a block of 11 trials, the next level of difficulty was presented with the maximum being 10 digits or a five-by-five grid with 12 black squares, increasing over seven difficulty levels. If accuracy was less than 80%, then participants stayed on that level. When participants remained at the same level for two blocks that constituted the individual's interference level.

Once individual interference threshold levels were established, the critical odor-color association task began. In a trial, participants were first presented with a stimulus to encode for 4 s (either a string of digits in the verbal condition, or a block pattern in the spatial condition). The experimenter then presented participants a randomly selected odor for approximately 4 s. A screen then appeared displaying 12 color squares presented in a random order (brown, red, orange, yellow, green, light blue, blue, purple, pink, gray, and black), and participants were instructed to click on the color that best matched the odor. At the end of the trial, participants viewed a pair of stimuli (either digit strings or block patterns) and had to select which they had seen at the trial onset. The stimuli remained onscreen until participants made their choice. Each trial ended with a 5-s pause. The baseline condition proceeded in the same manner minus the memory task.

After the odor-color task, the odors were presented again in a random order and rated on pleasantness, familiarity, and intensity (7-point Likert scale), and then named. The final task measured semantic fluency. Participants were instructed to name as many members from the categories “animals” and “professions” as they could (following Rommers, Meyer, & Huettig, 2015).

3.2. *Results*

Trials were excluded when participants reported not smelling anything ($n = 5$) or failed to rate odor pleasantness ($n = 1$). One participant was excluded because of missing semantic fluency data. We report data regardless of whether participants were accurate or inaccurate in the interference tasks, so as not to lose statistical power by removing trials. However, the pattern of results remains the same if inaccurate trials are removed. All data are available at: https://osf.io/urzjc/.

3.2.1. *Interference accuracy*

We first established performance on the interference tasks. Accuracy was significantly higher in the spatial, $M = .95$, $SD = .06$, than verbal interference condition, $M = .80$, $SD = .12$, $t(64) = 6.63$, $p < .001$, $d = 1.63$.

3.2.2. *Odor-color associations*

We coded color choices in terms of whether they matched the odor (1) or not (0), based on the norming study. We also coded odor naming accuracy: a response was scored correct if it included the label for the smell (e.g., *coconut candy* would be correct for coconut odor). For the semantic fluency task, mean number of responses were calculated per participant.

Color matches were analyzed with mixed logit models in R (R Development Core Team, 2015) using the lme4 package (Bates, Maechler, Bolker & Walker, 2014). Interference condition (baseline, verbal, spatial), semantic fluency, naming accuracy (correct, incorrect), ratings of odor familiarity, ratings of odor pleasantness, and ratings of odor intensity were entered as fixed factors. We also included the interaction between interference condition and naming accuracy, as verbal interference may only be effective for odors that are easily named. Participants and odors were modeled as random intercepts.[3] To assess statistical significance, we

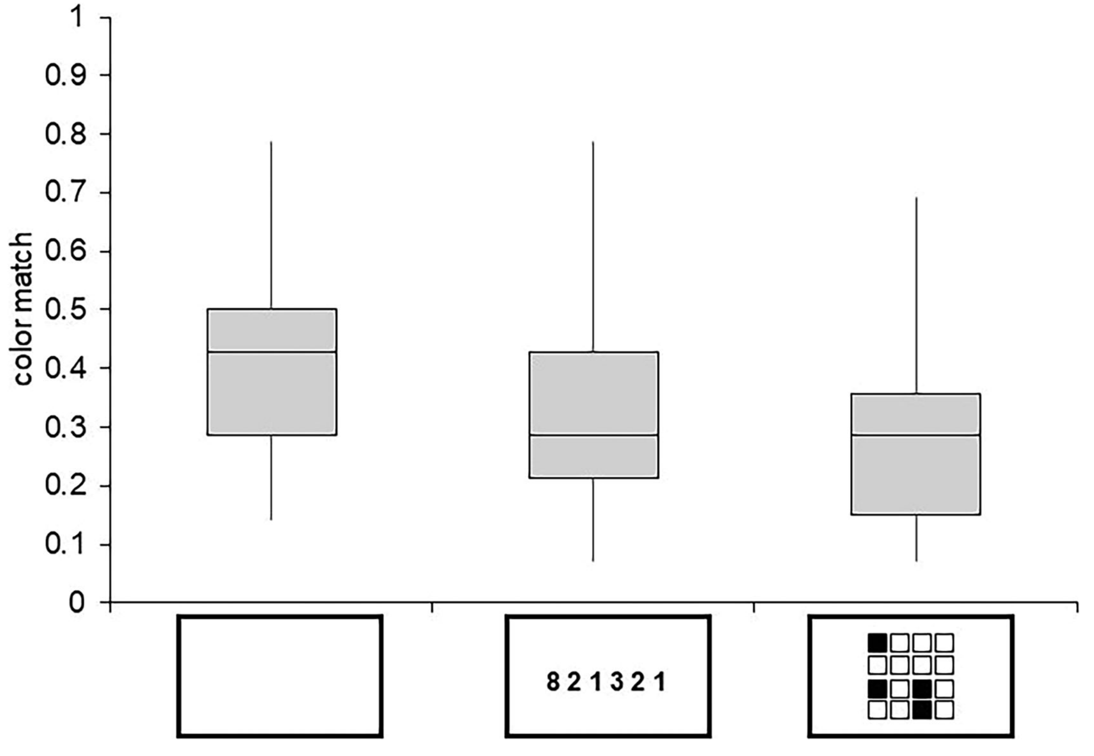

Fig. 1. Color matches for odor-color associations in Experiment 1. Boxplots display the median, first and third quartiles of participant data, and whiskers indicate the range.

used likelihood ratio tests with chi-square, comparing models with and without the factors of interest.

There was no effect of interference condition, χ^2 (2) = 3.66, p = .16, and no interaction between interference condition and naming, χ^2 (2) = 1.55, p = .46. The effect of naming accuracy was significant, χ^2 (1) = 82.67, b = 1.41, SE = .16, p <.001, with higher color matching for correctly named odors, M = .60, SD = .49, than incorrectly named odors, M = .21, SD = .41. Familiarity was also a significant predictor of color match, χ^2 (1) = 11.77, b = .19, SE = .06, p <.001; odor-color matching was higher for odors that were rated more familiar. Fluency, χ^2 (1) = 1.94, p = .16, pleasantness, χ^2 (1) = 1.16, p = .28, and intensity, χ^2 (1) = .19, p = .66, did not predict color match. Mean color match accuracy across interference conditions is depicted in Fig. 1, and mean color match accuracy, naming accuracy, familiarity, intensity, and pleasantness for each odor can be found in Appendix 1.

3.3. Discussion

Contrary to our hypothesis, verbal interference did not affect color matching. We did, however, find that odor-color matching was higher for more familiar odors and odors named correctly. This suggests there are semantic influences on odor-color matches, but these are not driven by odor labeling in the moment. Before accepting this conclusion, however, one potential reason we did not observe an effect of verbal interference on odor-color matching is that our verbal interference task did not sufficiently disrupt verbal processing during the odor-color association task. Digits were presented visually at encoding and test, so it is possible that people remembered them visually, and not verbally. In addition, the high interference accuracy suggests the recognition task we implemented was too easy. To address this, we ran a second experiment where we used an active verbal interference paradigm in which participants recalled digits by saying them out loud. We also introduced a nonverbal auditory interference condition "rhythm interference" where participants had to remember rhythms and recall them through tapping, and which served as another comparison point to our spatial interference task. Finally, interference difficulty was fixed across participants based on an additional norming study.

4. Experiment 2

4.1. Method

4.1.1. Participants

One hundred and thirty-three native Dutch speakers (age range 18–53, $M = 24$, $SD = 6.09$, 98 females, 30 males, 5 did not report gender) recruited via Radboud University's Sona participant database were assigned to one of the four interference conditions: baseline (34), verbal (32), spatial (34), and rhythm (33). Participants were recruited as before and again instructed not to take part in the study if they had a cold, and not to eat, drink (except water), or smoke, at least 30 min before taking part in the study.

4.1.2. Material

Odors and colors were as in Experiment 1.

4.1.3. Design and procedure

A pilot study with 14 participants was conducted to match difficulty level across interference tasks. Participants completed the verbal, spatial, and rhythm interference task with 5, 6, and 7 stimuli, and mean accuracy for each task and level was calculated. We aimed to find a level of interference at which participants performed on average around 80% accuracy. Six items were shown to be sufficient (six digits, six filled in grids, six beeps, mean 82.5% accuracy).

In the final experiment, participants in the verbal interference condition viewed a string of six digits for 4 s at the beginning of the trial, they were then presented with an odor for approximately 4 s and asked to click on the color match. Afterward, they had to repeat the six digits out loud. In the spatial interference condition, participants viewed a four-by-four grid with six black boxes filled for 3 s,[4] completed an odor-color match, and then recalled the grid by clicking on the relevant empty cells on a blank four-by-four grid. In the rhythm interference condition, participants heard a rhythm of six beats, completed an odor-color match, and recalled the rhythm by tapping it on the table. In the baseline condition, participants completed the odor-color task only. The odor-color task proceeded as in Experiment 1, except that colors were presented in a fixed location on screen. Verbal and rhythm recall were recorded by microphone and coded for accuracy later. As in Experiment 1, in a second block, odors were again rated on pleasantness, familiarity, and intensity (100-point scale), and then named. We did not include verbal fluency since Experiment 1 did not reveal it to be relevant for odor-color matches.

4.2. Results

Two participants were removed from analysis—baseline condition ($n = 1$), verbal condition ($n = 1$)—for having eaten or drank immediately before the study against instructions. As in Experiment 1, we report data from all trials regardless of interference accuracy, but once again the pattern of results remains the same when inaccurate interference trials are removed.

4.2.1. Interference accuracy

Due to a microphone error, there was no accuracy data for one participant in the verbal condition and two participants in the rhythm condition. A one-way ANOVA assessing interference accuracy found no difference across conditions $F(2, 93) = 1.12$, $p = .33$ (verbal $M = .69$, $SD = .21$; spatial $M = .65$, $SD = .19$; rhythm $M = .61$, $SD = .24$), indicating difficulty was indeed matched across interference tasks.

4.2.2. Odor-color associations

Odor-color matching was analyzed as in Experiment 1 except that interference had four levels (baseline, verbal, spatial, and rhythm) and there was no measure of semantic fluency. Furthermore, because an error led to 32 participants receiving odors in a fixed order, we include the trial number as a covariate.

Due to problems with model convergence, ratings of familiarity, intensity, and pleasantness were not included in the models. There was no effect of interference condition on color match, χ^2 (3) $= 3.78$, $p = .29$. As in Experiment 1, there was a significant effect of naming accuracy, χ^2 (1) $= 226.22$, $b = 1.90$, $p < .001$, with more color matches for odors that were correctly named, $M = .40$, $SD = .55$, than incorrectly named, $M = .22$, $SD = .42$. There was no interaction between interference condition and naming, χ^2 (3) $= 0.90$, $p = .82$. (see Fig. 2).

Again, due to problems with model convergence, models testing the effects of odor familiarity, intensity, and pleasantness were compared to baseline models that included only trial number and ratings of either familiarity or pleasantness. There was a significant effect of familiarity, χ^2 (1) $= 82.69$, $b = .023$, $p < .001$, with more familiar odors leading to higher color matching. There was no effect of pleasantness, χ^2 (1) $= 2.33$, $b = .005$, $p = .13$. The model testing odor intensity would converge only including trial number. There was a significant effect of odor intensity, χ^2 (1) $= 23.87$, $b = .013$, $p < .01$, but this should be interpreted with caution since odor familiarity and odor intensity were highly correlated ($r = .45$). It is possible that intensity would not be a significant predictor over and above familiarity if it

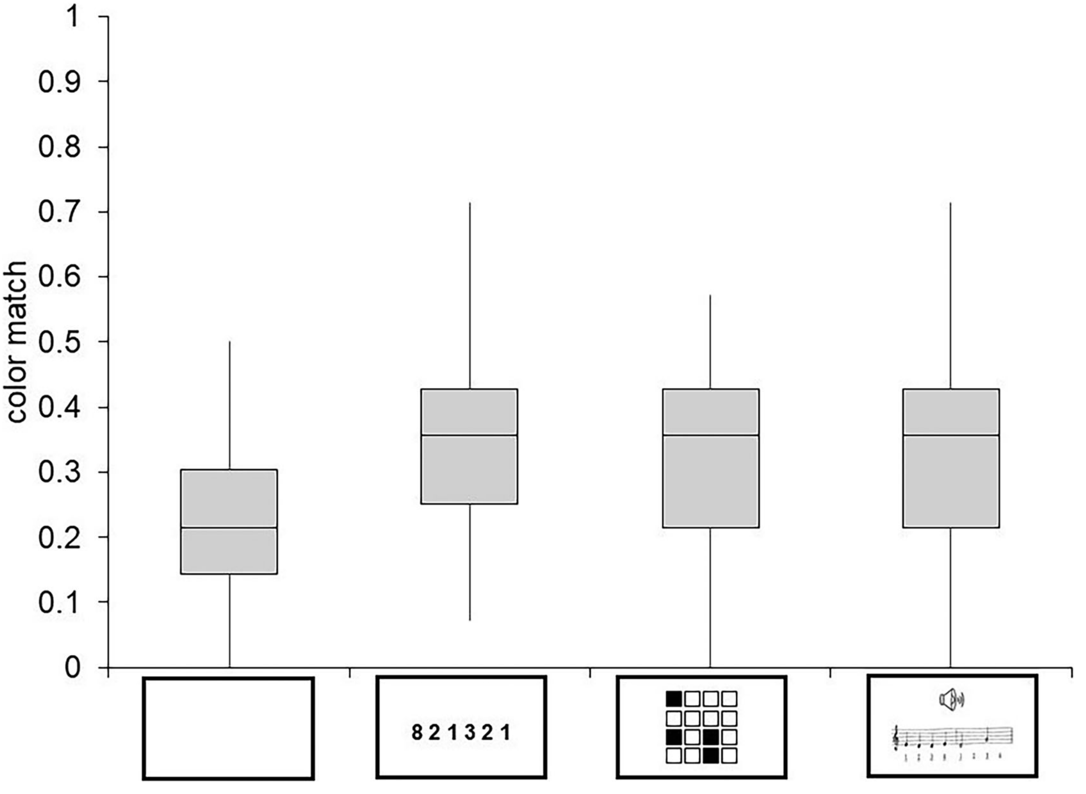

Fig. 2. Color matches for odor-color associations in Experiment 2. Boxplots display the median, first and third quartiles of the participant data, and whiskers indicate the range. Asterisks indicate a significant difference at $p < .05$.

could be included in the model. Mean color match accuracy across interference conditions is depicted in Fig. 2, and mean color match accuracy, naming accuracy, familiarity, intensity, and pleasantness for each odor can be found in Appendix 2.

4.3. Discussion

When the difficulty of interference tasks was equated across conditions, there was no difference in how well colors were matched to odors. Interestingly, color match accuracy appeared to be lowest in the no interference condition. While this pattern is opposite to predicted, it could simply reflect the fact that participants in the interference conditions were more focused because they had to concentrate on the interference task.

The results of Experiment 2 suggest that language does not play an online role in odor-color associations. However, as in Experiment 1, we found that odor-color matching was predicted by odor naming and odor familiarity. This suggests that although implicit naming is not necessary for odor-color associations, the associations are semantically mediated. We turn to this in the General Discussion.

5. General discussion

Evidence exists for a tight connection between odor and color (de Valk et al., 2017; Demattè et al., 2006; Gilbert et al., 1996; Levitan et al., 2014; Spector & Maurer, 2012; Speed et al., 2021); however, there is little direct evidence for how these associations arise. In two experiments, we find no evidence that interfering with verbalization when smelling affects the color matches chosen. Our results, therefore, suggest that odor-color associations do not recruit language online. This is in line with a recent systematic review of verbal interference paradigms that found little evidence for a role of "internal" language in crossmodal integration (Nedergaard et al., 2022).

Although we did not observe a direct effect of language on odor-color matching, odor naming accuracy and odor familiarity were related to odor-color matches. Language could, therefore, be indirectly related to odor-color associations in two ways. First, color may be activated via semantic associations to odors (and likewise this semantic activation may positively predict odor naming). Words are powerful cues to concepts, but semantic information can be activated in a nonlinguistic manner too. For example, Lupyan and Thompson-Schill (2012) showed characteristic sounds (e.g., a cow mooing) activate visual information (e.g., an image of a cow), although verbal labels do so more effectively. That semantic activation could play a role in odor-color associations without necessarily activating verbal representations is in line with results from Spector and Maurer (2012), who found that participants selected odor-color associations based on odor sources, even though odors were not correctly identified. They propose that upon smelling a familiar odor, semantic knowledge is activated—even without odor identification. Similarly, Herz and Cupchik (1992) found that memories could be elicited from odors even when participants could not name an odor. This suggests that previous studies showing a link between odor naming and odor-color associations (e.g., de Valk et al., 2017; Goubet et al., 2018; Speed & Majid, 2018) could be the result of conceptual, but not specifically verbal activation.

Second, instead of verbally mediating odor-color associations online, language may instead play a role in forming and strengthening associations between sensory information during development. This aligns with what has previously been found for pitch-space associations. Just as there are cross-cultural differences in naming musical pitches and nonlinguistic pitch-space associations (Dolscheid et al, 2013, 2020), there are cross-cultural differences in naming odors and concomitant odor-color associations (de Valk et al., 2017). Despite this, verbal interference does not disrupt sound-space associations (Dolscheid et al., 2013), nor do it appear to disrupt odor-color associations, as demonstrated in this paper. Nevertheless, Dolscheid et al. (2020) found that metaphors in language play a key role in boosting certain pitch-space mappings in cognition over others. Our findings suggest the same could be true for odor-color associations. This suggestion could be tested directly in future studies by teaching participants novel odor-color combinations with or without labels. It has been shown, for example, that training Dutch participants with Farsi pitch-thickness metaphors increases pitch-thickness associations (Dolscheid et al., 2013). Despite a general consensus that language can influence associations between sensory modalities, little work has explored whether language continues to play a direct role in such associations after they have been formed.

In the present experiments, we found no effects of verbal interference. Although the absence of evidence does not necessarily indicate evidence of absence, we are confident in our choice of verbal interference tasks to be informative about the nature of odor-color associations because this methodology has been shown elsewhere to remove the effect of language on perception (Gilbert et al., 2006; Roberson et al., 2008; Winawer et al., 2007). It is possible, however, that results could change with another set of odors, for example, more nameable odors. We selected odors familiar to Dutch participants, but naming accuracy across the two experiments remained low (31% accuracy), typical of other odor naming studies in Dutch (e.g., de Valk et al., 2017; Huisman & Majid, 2018). Nevertheless, participants are able to name some odors with more accuracy than others. Perhaps odors with higher naming accuracy would show a more potent effect of verbal labels in the moment.

Although odor-color associations are influenced by semantic information, there are undoubtedly other factors that influence odor-color associations too (Stevenson, Rich, & Russell, 2012), such as affective valence (Schifferstein & Tanudjaja, 2004) and perceptual biases (Spector & Maurer, 2012), and these may have influenced responses in the present tasks too. In fact, across both experiments, participants chose colors matching the odor source only 33% of the time, suggesting that additional factors have to be considered in future studies.

One could argue our measure of odor-color association, that is, color match accuracy, is biased because the norming study we conducted was with concepts rather than odors. However, this choice was motivated by the fact that our primary interest was to investigate whether odor-color associations are driven by the color of an odor source which in turn would be elicited via activation of its concept (as in de Valk et al., 2017). So, norming concepts rather than odors was the preferred method. Using our method, we found the expected effects of odor naming accuracy and familiarity, which supports our operationalization of color match accuracy. Nevertheless, future studies could apply our interference paradigm to other ways of eliciting odor-color associations to establish the generality of our conclusions.

Finally, in both Experiments 1 and 2, the majority of participants were female. This may also impact the generalizability of our findings in two ways. First, it has been suggested that females and males differ in odor perception and odor identification (Majid et al., 2017; Sorokowski et al., 2019). In addition, judgments of odor familiarity and pleasantness may differ across females and males (e.g., lavender and coconut odor may be more typically found in female toiletry products). In general, research suggests that females perform better in tasks of odor identification and naming (for review, see Majid et al., 2017; Sorokowski et al., 2019), which would suggest that an effect of verbal interference on odor-color matching would be more likely in females than males.

Language is involved in odor-color associations in many ways, including, for example, learning associations (Goubet et al., 2018) and facilitating effects of color on odor discrimination (Stevenson & Oaten, 2008). Conversely, odor-color associations play a facilitatory role in odor naming (Speed & Majid, 2018), with stronger odor-color associations leading to higher odor naming accuracy. In this paper, our results suggest that there may be a limit to the effect of language: while semantic information predicts odor-color associations, verbalization appears not to play an online role in these associations.

Notes

1 Note, unlike English, the Dutch word for the fruit orange (*sinasappel*) is different to the color orange (*oranje*).
2 If we consider all colors chosen at a frequency greater than chance in the norming task, then a correct match for coffee odor would also be black and a correct match for lavender would also be pink. When including these colors as a color match, the results remain the same.
3 Models did not converge with participants as random slopes.
4 Due to an error in the experiment programming, the visual grid was shown for 1 s less than digits. However, this did not lead to differences in accuracy across conditions for the interference tasks.

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Appendix 1: Odor information Experiment 1

Odor	Color match accuracy	Naming accuracy	*M* familiarity	*M* intensity	*M* pleasantness
Banana	0.46	0.39	4.30	3.96	3.62
Broccoli	0.10	0.40	3.34	3.97	1.72
Coconut	0.40	0.28	4.28	3.57	4.18
Coffee	0.53	0.46	4.27	4.27	3.28
Grass	0.08	0.28	2.06	4.80	1.80
Lavender	0.46	0.43	4.73	5.09	3.88
Lemon	0.34	0.38	3.44	4.0	3.85
Liquorice	0.61	0.36	4.36	3.82	3.81
Mint	0.42	0.18	5.19	5.32	4.35
Orange	0.47	0.45	4.18	4.08	4.14
Peanut Butter	0.63	0.75	5.22	4.74	3.51
Pineapple	0.05	0.13	2.49	3.38	2.41
Strawberry	0.19	0.16	3.29	4.05	3.77
Tomato	0.21	0.26	3.40	3.78	2.60

Appendix 2: Odor information Experiment 2

Odor	Color match accuracy	Naming accuracy	*M* familiarity	*M* intensity	*M* pleasantness
Banana	0.51	0.52	75.98	59.55	62.44
Broccoli	0.27	0.15	53.66	59.26	25.89
Coconut	0.34	0.31	64.70	47.38	64.89
Coffee	0.52	0.38	57.54	57.05	48.68
Grass	0.27	0.01	58.36	68.09	57.38
Lavender	0.34	0.40	77.55	79.32	66.241
Lemon	0.27	0.26	47.09	48.86	55.15
Liquorice	0.25	0.31	58.16	48.61	61.14
Mint	0.28	0.53	85.62	83.57	70.13
Orange	0.18	0.26	51.34	50.90	57.76
Peanut Butter	0.60	0.38	66.35	59.89	52.29
Pineapple	0.15	0.08	48.11	58.33	45.95
Strawberry	0.17	0.22	57.76	59.46	60.70
Tomato	0.14	0.05	46.31	64.39	32.54