



Losing the sense of smell does not disrupt processing of odor words

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ABSTRACT

Whether language is grounded in action and perception has been a key question in cognitive science, yet little attention has been given to the sense of smell. We directly test whether smell is necessary for comprehension of odor language, by comparing language processing in a group of participants with no sense of smell (anosmics) to a group of control participants. We found no evidence for a difference in online comprehension of odor and taste language between anosmics and controls using a lexical decision task and a semantic similarity judgment task, suggesting olfaction is not critical to the comprehension of odor language. Contrary to predictions, anosmics were better at remembering odor words, and rated odor and taste words as more positively valenced than control participants. This study finds no detriment to odor language after losing the sense of smell, supporting the proposal that odor language is not grounded in odor perception.

1. Introduction

Embodied theories of language processing suggest that when we read a word like *firework*, we understand its meaning using perceptual systems; so, for example, we activate visual and auditory information (Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012). Language comprehension is claimed to be grounded in perceptual representations via mental simulation: the reenactment of sensory states acquired during everyday experience (Barsalou, 2008). This is demonstrated, for example, through activation in the brain's perceptual systems during language comprehension (e.g., Pulvermüller & Hauk, 2005; Simmons et al., 2007). While debates continue about the exact nature and extent of mental simulation, and the conditions under which it occurs during language comprehension (see, e.g., Connell, 2019; Ibañez et al., 2022; Ostarek & Huettig, 2019), it is notable that the role perceptual information from the chemical senses—such as olfaction—plays in word meaning is significantly neglected in this field (Speed & Majid, 2019). Recent work suggests there may be greater difficulty grounding language in the sense of olfaction than in the dominant senses of vision and audition (Speed & Majid, 2018, 2019). Here we directly test the role of olfaction in comprehension by studying language in people with anosmia.

Westerners typically find it difficult to name odors, correctly naming

only around half of common odors they encounter (e.g., Cain, 1979; Engen, 1987; Huisman & Majid, 2018; Sulmont-Rossé, Issanchou, & Köster, 2005). One potential explanation for this odor naming difficulty is that odor and language are weakly connected in the brain (Olofsson & Gottfried, 2015). Specifically, since olfactory information is only coarsely processed by the time it is integrated with language, language is left with underspecified odor representations. If odor and language are weakly connected, then comprehension of odor language should also be difficult. In particular, it should be difficult to mentally simulate olfactory aspects of word meaning. This is in line with reports that generating olfactory imagery is difficult (Crowder & Schab, 1995). Yet, it has been found that merely reading odor words (e.g., *cinnamon*) activates the primary olfactory cortex, the piriform cortex (González et al., 2006), and it has been proposed that odor labels can activate “odor object templates” (Olofsson, Bowman, Khatibi, & Gottfried, 2012) which can facilitate subsequent processing of odors. This would imply the weak link between odor and language is asymmetrical, so simply reading words activates perceptual representations of odor, as has been suggested for vision and audition.

Against this proposal, some studies have failed to find piriform cortex activation to odor language (Han et al., 2019; Joshi, Han, Faria, Larsson, & Hummel, 2020; Pomp et al., 2018), instead finding activation in higher-level brain regions more associated with hedonic value than odor

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quality (Pomp et al., 2018). However, strong conclusions cannot be drawn about the lack of piriform activation in some of these studies due to design constraints. For example, in a number of sentences used by Pomp et al. (2018) no specific odor was described, only a general negative olfactory experience (e.g., *The stench is unbearable*). Furthermore, Joshi et al. (2020) did not use a localizer task to identify the piriform cortex.

A recent behavioral study set out to test how odor and language are connected in comprehension (Speed & Majid, 2018). Participants smelled an odor while they held a word in mind. Words could match the odor (e.g., *cinnamon* and cinnamon odor), be a near-match to the odor (e.g., *nutmeg* and cinnamon odor), mismatch the odor (e.g., *garlic* and cinnamon odor), or be a word with no odor associations (e.g., *glitter*). Later, recognition memory for the odors was tested. The same study was conducted with sound words and sound clips for comparison. Although match and near-match words interfered with memory for sounds, there was no effect of words on odor recognition memory (Speed & Majid, 2018). This suggests although audition is simulated for sound words, olfaction is not simulated for odor words, consistent with the idea that the links between olfaction and language are symmetrical (Majid, 2021). It is, however, difficult to draw firm conclusions about a lack of mental simulation of odor because this finding relies on a null effect.

In the present study we directly assess the role of olfaction in the comprehension of odor language by exploring odor language in individuals who have lost their sense of smell—i.e., people with acquired anosmia. A similar patient-based approach has previously been used as a strong test of grounded action language. It has been shown, for example, that because of their action deficits, patients with Parkinson's disease and motor neuron disease have difficulty comprehending action-related language compared to control participants (Bak, 2013; Fernandino et al., 2013b, 2013a; Speed, van Dam, Hirath, Vigliocco, & Desai, 2017). This suggests action representations play a critical role in the processing of action language. These findings suggest that people who experience sensorimotor loss of any kind over their lifetime—be it an action deficit or an olfactory deficit—would be similarly impaired in language processing.

The overall picture appears more complex, however. Studies comparing blind and sighted individuals find no substantive differences in blind participants' general understanding of vision words (Bedny, Koster-Hale, Elli, Yazzolino, & Saxe, 2019), although admittedly fine-grained differences in visual knowledge have been reported (Kim, Elli, & Bedny, 2019a). Early blind participants also display the typical concreteness effect in lexical decision tasks, with faster processing times for concrete than abstract words, an effect previously thought to be driven by visual experience (Bottini, Morucci, D'Urso, Collignon, & Crepaldi, 2021). Critically, these studies involved congenital or early blind participants. Having never experienced a specific sensory modality may lead to fundamental differences in the format and content of conceptual representations, likely via compensation from other modalities (Trumpp & Kiefer, 2018; Trumpp, Kiese, Hoenig, Haarmeier, & Kiefer, 2013). So it is important to distinguish acquired and congenital sensory loss, and the role each may play in language processing. In our study, we specifically focus on the language processing of acquired anosmics and ask how they compare to those with an intact sense of smell.

Several recent studies have attempted to address this question. Han et al. (2019) compared neural processing of odor words and expectation of odor words in 14 patients with acquired anosmia and 16 control participants. They found brain activation did not differ between anosmics and controls when reading odor words. However, areas related to semantics and higher-order odor processing were activated during word expectation when anosmics were told to expect "words with smell", but not controls. This greater activation could reflect greater processing effort when expecting odor words (see also Joshi et al., 2020), but overall anosmics' response to odor language does not appear to be negatively impacted by their lack of smell perception. A recent case study by Reilly and colleagues also suggests losing the sense of smell

does not greatly impact odor language (Reilly, Finley, Kelly, Zuckerman, & Flurie, 2021). Although the early anosmic participant, P01, associated words more weakly with olfaction than a group of controls and produced unusual associations connecting smelling objects to odor-neutral words, their other associations (e.g., color, social) did not differ from controls, and neither did their narrations of pleasant and unpleasant odor scenes. Overall, there is weak evidence from people with anosmia that language comprehension relies on mental simulation of odors. However, to date, studies have tested only a small number of anosmic participants and no study has examined online processing of odor language.

In this pre-registered study, we measured four aspects of odor language processing in a group of anosmics and a group of matched control participants. We tested fifty-five individuals with acquired anosmia who lost their sense of smell as adults (median duration of anosmia, 8.5 years). They therefore have experienced odor in the past and are likely to have semantic associations with odor. However, they can no longer perceive odors at the point of testing. This makes them comparable to Parkinson's patients or late blind individuals who have lost motor ~ perceptual abilities later in life and who have been tested in comparable studies.

We included four tasks measuring language comprehension at different levels of processing, relying on relatively more implicit to explicit measures. First, we used a lexical decision task with priming which does not require explicit judgements about odor words, and therefore taps implicit processing. Previous studies have shown that lexical decision tasks are sensitive to semantic information, including sensorimotor associations (Lynott, Connell, Brysbaert, Brand, & Carney, 2020; Speed & Brysbaert, 2021). As an ancillary measure, we also tested memory for words in this task, since word recall is also sensitive to semantic information (Lau, Goh, & Yap, 2018).

The third task was a semantic similarity judgment task which involves explicit decision-making about meaning (cf., Fernandino et al., 2013a). Both the lexical decision task and the semantic similarity judgment task have been shown to be sensitive to mental simulation in other sensory modalities (e.g., Fernandino et al., 2013a; Lynott et al., 2020; Speed & Brysbaert, 2021). However, whether this would also be the case for olfaction was unclear. We sought to establish if mental simulation of odors is fairly automatic (lexical decision) or occurs only when deeper semantic processing is required (semantic similarity judgment).

Finally, we collected ratings of emotional associations for words previously rated as strongly associated with odor, taste, and vision (following Lynott et al., 2020). We measured emotional associations in terms of valence, dominance, and arousal (Moors et al., 2013) to the same set of words. As predicted by a grounded account of odor language and an asymmetrical relationship between language and olfaction, we predicted that in the lexical decision task, compared to control participants, anosmics would be slower, less accurate and show reduced priming for odor and taste words, but not vision words, and remember fewer odor and taste words than controls. We also predicted that in the semantic similarity judgments task, anosmics would be slower and less accurate for odor and taste trials compared to controls, but not for vision trials. Finally, because odors are linked to increased emotional processing (e.g., Yeshurun & Sobel, 2010), we expected emotional associations to odor and taste words would be weaker in anosmics compared to controls.

2. Method

This study was approved by the Radboud University Ethics Assessment Committee of the Faculty of Arts and the Faculty of Philosophy, Theology and Religious Studies (EACH). The study was pre-registered with the Open Science Framework (<https://osf.io/5pmw3/registrations>).

2.1. Participants

Anosmic participants were recruited via UK anosmia charities Fifth Sense and Abscent. Seventy-four participants completed the study successfully, but one participant was removed for having anosmia for < 2 years, one participant was removed for having a native language other than English, and due to miscommunication about the study components, 17 participants were removed for not completing the demographic questionnaire. Not completing the demographic questionnaire meant we did not have sufficient information about the participants' anosmia. This left 55 participants (38 female, 17 male, $M_{age} = 57.03$, $SD = 13.25$) with acquired anosmia¹ who lost their sense of smell at least two years ago. The median duration of anosmia was 102 months ($SD = 161.42$ months, range 25 – 660 months²). Seventy-six control participants were recruited via Prolific Academic, but 5 participants were removed for having a native language other than English, and due to miscommunication about the study components, 15 participants were removed for not completing the demographic questionnaire. This left 56 control participants (39 female, 16 male, 1 other, $M_{age} = 53.8$, $SD = 15.6$). All remaining participants were native speakers of English. The groups did not differ by age, $t(109) = 1.83$, $p = .18$, or gender, $\chi^2(1) = 0.043$, $p = .84$.

2.2. Stimuli

A set of 466 English nouns was rated by a group of native English speakers for their sensory associations in the five modalities of odor, taste, touch, audition, and vision (following Lynott, Connell, Brysbaert, Brand, & Carney, 2020). Based on average ratings, nouns were categorized into their dominant perceptual modality, leading to the selection of 21 odor (e.g., *lavender*), 21 taste (e.g., *basil*), and 42 vision (e.g., *brick*) nouns (see Table 1). To check our categorization of words by sensory modality, for each sensory word type we conducted a repeated measures ANOVA to compare average ratings of odor, taste and vision, and followed up main effects with paired t-tests. There was a significant effect of sensory modality for odor words, $F(2, 40) = 26.95$, $p < .001$, $\eta_p^2 = 0.57$, with significantly higher ratings on odor than taste ($p < .001$) and vision ($p < .001$). There was a significant effect of sensory modality for taste words, $F(2, 40) = 68.02$, $p < .001$, $\eta_p^2 = 0.77$, with significantly higher ratings of taste than odor ($p < .001$) and vision ($p < .001$). There was also a significant effect of sensory modality for vision words with significantly higher ratings of vision compared to odor ($p < .001$) and taste ($p < .001$).

We also compared ratings between sensory word types for each

Table 1

Modality ratings for odor, taste, and vision for sensory word types used in the study by mean (M) and standard deviation (SD).

Sensory word type	Modality rating					
	Odor		Taste		Vision	
	M	SD	M	SD	M	SD
Odor	3.83	0.62	1.40	1.49	2.63	0.84
Taste	3.36	0.67	4.44	0.53	2.93	0.56
Vision	0.31	0.65	0.10	0.33	3.97	0.46

¹ Here we only analyse data from acquired anosmics as we received responses from very few congenital anosmics ($n = 6$). We diverge from our pre-registered plan to combine data from acquired anosmics and congenital anosmics because initial visual inspection of the data suggested a different pattern of response.

² Four participants did not provide information about the duration of their anosmia.

sensory modality separately using a between items ANOVA, following up main effects with independent t-tests. There was a significant difference in odor ratings across sensory word types, $F(2, 81) = 271.31$, $p < .001$, $\eta_p^2 = 0.87$: odor words had significantly higher ratings on odor than taste ($p = .022$) and vision words ($p < .001$). There was a significant difference in taste ratings across sensory word type, $F(2, 81) = 195.39$, $p < .001$, $\eta_p^2 = 0.87$: taste words had significantly higher ratings on taste than odor words ($p < .001$) and vision words ($p < .001$). There was also a significant difference in vision ratings across sensory word type, $F(2, 81) = 43.04$, $p < .001$, $\eta_p^2 = 0.52$: vision words had significantly higher ratings on vision than odor words ($p < .001$) and taste words ($p < .001$).

Between items ANOVAs also confirmed there were no significant differences in word frequency ($p = .40$, Log frequency HAL, English Lexicon Project), word length ($p = .50$), number of orthographic neighbors ($p = .40$), number of phonological neighbors ($p = .76$), OLD20³ (similarity to other words, $p = .62$), or number of phonemes ($p = .75$) between the three sensory word types (see Table 2). Vision words however had significantly fewer syllables than smell ($p = .04$) and taste words ($p = .04$). We therefore opted to include number of syllables as a covariate in the analysis of lexical decision data.

In addition to the critical sensory words, 84 nonwords were generated for the lexical decision task by inputting the experimental words into the nonword generator Wuggy (Keuleers & Brysbaert, 2010), which generates nonwords that are legal words in English i.e., they follow the phonotactic constraints of English.

For the semantic similarity judgments, items were divided into 7 odor triplets, 7 taste triplets, and 14 vision triplets. In each triplet, there were two words that were more similar than the other (i.e., more similar taste, odor, or visual appearance) based on the modality ratings described above. In order to check the similarity triplets were matched in difficulty across triplets, we conducted a Qualtrics survey with a separate set of participants on Amazon Turk. Participants were instructed to click which of two words were most similar in meaning to a target word. If participants gave the intended response, they were given a 1; if they did not, they were given a 0. Based on nine responses, three triplets in the odor domain were rearranged due to low accuracy. The new set was then rated by a different set of 10 participants. There was no significant difference in accuracy across the three modalities, $F(2, 25) = 1.55$, $p = .23$, $\eta_p^2 = 0.11$; odor $M = 0.96$; taste $M = 0.91$; vision $M = 0.96$, showing the task difficulty was matched across odor, taste, and vision triplets.

Table 2

Word frequency, length, number of orthographic neighbors (Ortho_N), number of phonological neighbours (Phono_N), similarity to other words (OLD), number of phonemes and number of syllables, for odor, taste, and vision words by mean (M) and standard deviation (SD).

	Sensory word type						
	Odor		Taste		Vision		<i>p</i> -value
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	
Frequency	6.32	1.94	6.80	1.45	6.87	1.34	0.40
Length	7.24	1.92	6.95	1.92	6.64	2.02	0.50
Ortho_N	1.43	3.08	1.67	2.85	2.55	3.83	0.40
Phono_N	4.10	8.14	4.52	8.18	5.76	10.05	0.76
OLD	2.84	0.90	2.74	0.89	2.59	1.04	0.62
NPhon	6	1.45	5.76	1.51	5.67	1.78	0.75
NSyll	2.43	0.81	2.43	0.75	2	0.77	0.04

³ Two odor, two taste, and one vision word did not have OLD20 values.

2.3. Procedure

Participants completed all tasks via an online experiment in Labvanced and each task was conducted in a fixed order, as described below, beginning with the lexical decision task and ending with emotion ratings. Participants were then directed to a Qualtrics questionnaire where they were asked demographic questions, including background information about their anosmia.

2.3.1. Lexical decision task

Participants completed six practice trials before the experimental trials. Participants were first presented with a fixation cross for 500 ms (see Fig. 5). They then saw a mask of hash marks for 100 ms, a prime word for 50 ms, and another mask of hash marks for 100 ms. The prime word was either the target word presented in capitals or a random letter string, counterbalanced across participants. The target word was then presented and participants had to decide if it was a real word or not by pressing the right arrow on the keyboard for “yes” and the left arrow on the keyboard for “no”. They had a maximum of 4000 ms to respond. Participants saw each word once (21 odor words, 21 taste words, 42 vision words), either preceded by a prime word or a random letter string, which was counterbalanced across participants. Response time and accuracy were recorded.

2.3.2. Memory task

Immediately after the lexical decision task, participants were given one minute to remember as many words as they could from the lexical decision task. They typed their responses into a box on screen.

2.3.3. Semantic similarity judgment task

As with the lexical decision task, participants completed six practice trials before the experimental trials. In each trial, participants were first presented with a fixation cross for 500 ms, followed by three words presented simultaneously in a triangle formation (see Fig. 6). A target word was presented in bold above two words in regular font, with presentation on the left versus right side counterbalanced across participants. Participants were instructed to select which of the two words on the bottom was most similar in meaning to the top one. Participants had a maximum of 5000 ms to respond. Each item was only shown once to each participant (7 odor, 7 taste, 14 vision trials).

2.3.4. Emotion rating task

Finally, participants were given all words again and asked to rate each on valence, arousal, and dominance (following Moors et al., 2013). Participants made their ratings by clicking on a 7-point scale (valence, 1 = very negative/unpleasant, 7 = very positive/pleasant; arousal, 1 = passive/calm, 7 = active/arousing; dominance, 1 = very weak/submissive, 7 = very strong/dominant).

3. Results

As laid out in the pre-registration, data from the lexical decision task, semantic similarity judgment task, and emotion rating task was analyzed with logistic mixed effects analyses (accuracy) or linear mixed effect analyses (response time) in R (R Core Team, 2020) using the lme4 package (Bates, Maechler, Bolker, & Walker, 2014) with participants and items modelled as random effects, and ability to smell (anosmic, control), sensory word type (odor, taste, vision), and the interaction between ability to smell and sensory words type, as fixed effects. Memory counts were analyzed using linear regression models with by-participants intercepts. We compared models with and without the relevant factors using Maximum Likelihood Estimation with Chi-square, and provide R^2 values for the difference in variance explained between the two models using the r2glmm package (Jaeger, 2017). As planned in the pre-registration, we also ran analyses with smell and taste words combined into the category “flavor”. The results of these analyses are

included in Supplementary Material. Figures were made using the R package ggplot2 (Wickham, 2016). All data and analysis code can be found here at <https://osf.io/5pmw3/>.

3.1. Lexical decision task

Following the pre-registered criteria, trials were removed if they were < 250 ms or greater than 3000 ms, or outside 2.5 SD of the participant’s mean response time (2.4% of the data). Since items were not matched for number of syllables across sensory word types, and number of syllables could potentially affect performance in the lexical decision task, we added it as a covariate in our models although it was not included in our pre-registered statistical models. We note that results remain the same with and without the addition of this covariate.

3.1.1. Accuracy of lexical decisions

We predicted that compared to control participants, anosmics would be less accurate for odor and taste words, but not vision words, however we observed no interaction between the ability to smell and sensory word type for accuracy, $\chi^2(1) = 0.21, p = .90, R^2 < 0.001$. We did find a main effect of ability to smell on accuracy, $\chi^2(1) = 9.96, p = .002, R^2 < 0.001$, with anosmics more accurate than controls (see Fig. 1A). There was no main effect of sensory word type, $\chi^2(2) = 4.32, p = .12, R^2 < 0.001$.

3.1.2. Response times for lexical decisions

Compared to control participants, we predicted anosmics would have slower response times for odor and taste words, but not vision words. Again, we observed no interaction between ability to smell and sensory word type for lexical decision response time, $\chi^2(2) = 0.95, p = .62, R^2 < 0.001$ (see Fig. 1B). There was also no effect of sensory word type, $\chi^2(2) = 4.65, p = .10, R^2 = 0.002$, or ability to smell, $\chi^2(1) = 2.04, p = .15, R^2 = 0.008$. Although caution is required interpreting the effects of the masked priming because we did not control individual participants’ hardware, we nevertheless found a significant effect of priming, $\chi^2(1) = 374.75, p < .001, R^2 = 0.02$. As expected, responses were faster for primed compared to unprimed words. Fig. 1C depicts the priming effect which is the response time for primed trials subtracted from the response time for unprimed trials: positive scores indicate faster responses for primed trials. However, there was no interaction between priming and sensory word type, $\chi^2(2) = 1.82, p = .40, R^2 < 0.001$, nor a three-way interaction between ability to smell, sensory word type, and priming, $\chi^2(2) = 0.96, p = .62, R^2 < 0.001$.

3.1.3. Duration of anosmia and lexical decisions: Exploratory analyses

As exploratory analyses, we conducted separate models for anosmic participants only testing the effect of the duration of participants’ anosmia (in months), and the interaction between duration and sensory word type. If anosmia did affect responses to odor words, then it would be reasonable to predict that participants who have experienced anosmia longer would be less accurate and slower making lexical decisions to odor and taste words compared to vision words. However, there was no effect of anosmia duration on accuracy, $\chi^2(1) = 1.72, p = .19, R^2 < 0.001$. Since the model including the interaction term did not converge, we tested the effect of duration separately for each sensory word type. There was no effect of duration on lexical decision accuracy for odor, $\chi^2(1) = 3.62, p = .06, R^2 < .001$,⁴ or vision words, $\chi^2(1) = 0.10, p = .75, R^2 < 0.001$. The model with only taste words did not converge.

Similarly, there was no effect of anosmia duration on response time, $\chi^2(1) = 0.44, p = .51, R^2 = 0.005$. There was a significant interaction between duration and sensory word type on response time, $\chi^2(2) = 10.34, p = .006, R^2 = 0.002$; however when assessing the effect of

⁴ This R^2 value is estimated from the model without number of syllables as a covariate, because the model did not converge with it included.

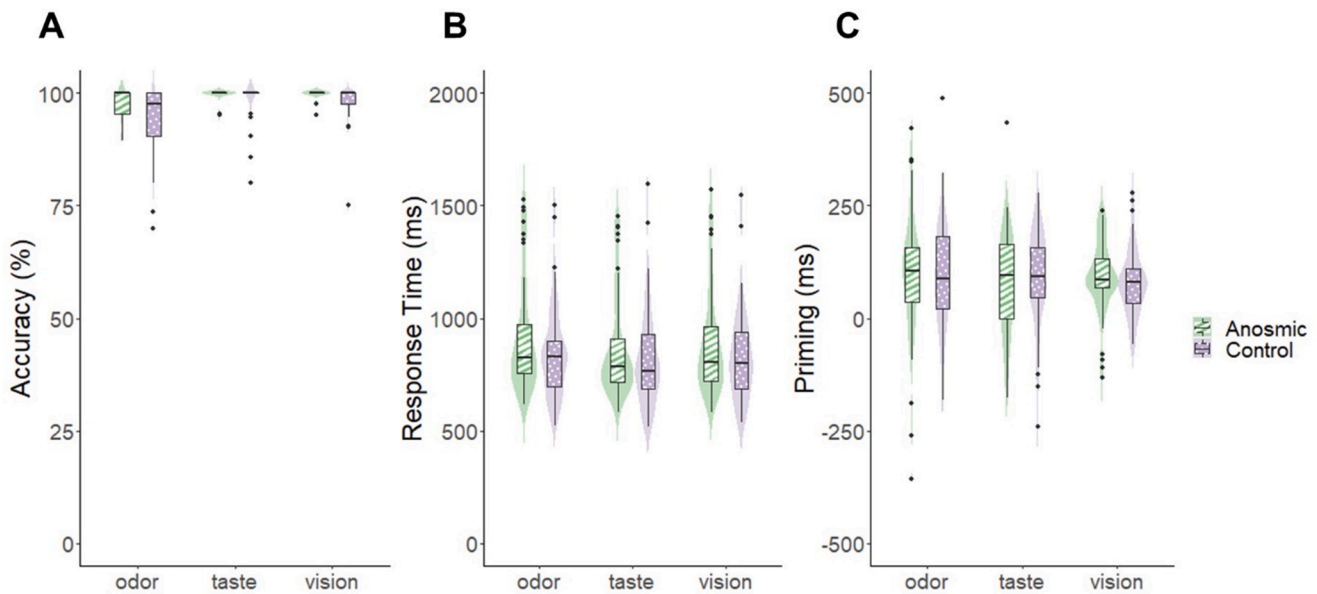


Fig. 1. Violin and boxplots of participants' (A) lexical decision accuracy, (B) response time, and (C) priming effect (response time unprimed trials minus response time primed trials) of odor, taste, and vision words.

anosmia duration on response time for each sensory word type separately, the direction of the effect was opposite to predicted: beta coefficients were always negative (odor words: $b = -0.25$, $t = -1.23$, taste words: $b = -0.11$, $t = -0.58$, vision words: $b = -0.07$, $t = -0.40$), which indicates faster responses for longer durations of anosmia.

To summarize, contrary to predictions, there was no evidence that ability to smell affected lexical decision accuracy or response time—i.e., losing the sense of smell does not impair the ability to process smell or taste words in comparison to vision words.

3.2. Memory task

The number of words recalled in each category was counted. Two anosmic participants did not recall any words and were not included in the analysis.

3.2.1. Recall of sensory words

We predicted anosmics would remember fewer odor and taste words compared to controls. We found a significant interaction between the ability to smell and sensory word type, $\chi^2(2) = 8.21$, $p = .02$, $R^2 = 0.016$, and followed this up by comparing anosmics and controls separately for each sensory word type using the emmeans package (Lenth, 2021), which conducts pairwise comparisons of estimated marginal means.

Contrary to predictions, anosmics remembered significantly more odor words than controls, $b = 0.59$, $t(258) = 2.1$, $p = .04$, but there was no difference between anosmics and controls for taste, $b = 0.32$, $t(258) = 1.13$, $p = .26$, or vision words, $b = 0.31$, $t(258) = -1.09$, $p = .28$ (see Fig. 2). There was also a significant effect of sensory word type, $\chi^2(2) = 6.21$, $p = .04$, $R^2 = 0.012$. Pairwise comparisons with the emmeans package indicated that significantly more taste words than odor words were remembered, $b = 0.39$, $t(216) = 2.37$, $p = .02$, but there was no difference between taste and vision words, $b = 0.30$, $t(216) = 1.87$, $p = .06$, nor between odor and vision words, $b = 0.08$, $t(216) = 0.51$, $p = .61$. There was no main effect of the ability to smell, $\chi^2(2) = 0.91$, $p = .34$, $R^2 = 0.004$.

3.2.2. Duration of anosmia and recall of sensory words: Exploratory analyses

We again conducted exploratory analyses testing for an effect of anosmia duration on recall of sensory words. There was no effect of

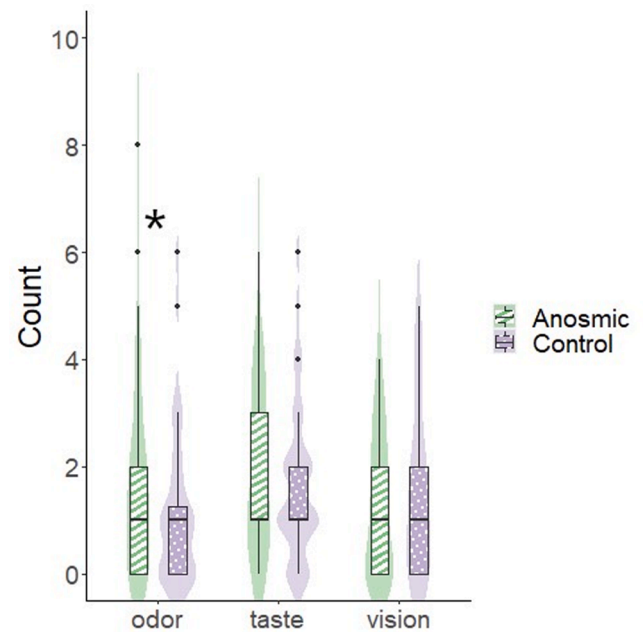


Fig. 2. Violin and boxplot of number of correctly recalled words per participant.

anosmia duration, $\chi^2(2) = .03$, $p = .87$, $R^2 < 0.001$, but there was a significant interaction between duration and sensory word type, $\chi^2(2) = 6.37$, $p = .04$, $R^2 = 0.024$. However, in follow-up tests, duration was not a significant predictor of memory for odor, $b = -0.002$, $t = -1.24$, $p = .22$, taste, $b = 0.001$, $t = 0.55$, $p = .58$, or vision words, $b = 0.002$, $t = 1.47$, $p = .15$.

Overall, the results do not support the predicted impairment in memory for odor and taste words in anosmics. If anything, memory for odor words tends to be slightly better compared to controls, opposite to what would be expected according to the grounded view of language.

3.3. Semantic similarity judgment task

Following the pre-registered criteria, trials in the semantic similarity judgment task were removed if they were < 250 ms or greater than 3000 ms, or outside 2.5SD of the participant's mean response time (8.9% of the data). We predicted anosmics would be slower and less accurate for odor and taste trials compared to controls, but not for vision trials, where accuracy is defined as correctly selecting the most similar word to the target.

3.3.1. Accuracy of semantic similarity judgments

We first looked at accuracy, and there was no interaction between sensory word type and ability to smell, $\chi^2(1) = 4.24$, $p = .12$, $R^2 < 0.001$. There was a significant main effect of sensory word type, $\chi^2(2) = 12.76$, $p = .001$, $R^2 = 0.005$. Follow-up tests with the emmeans package (Lenth, 2021) suggested lower accuracy for odor words compared to taste words, $b = 2.32$, $z = 3.04$, $p = .002$, and vision words, $b = 2.24$, $z = 3.55$, $p < .001$, but no difference between taste and vision words, $b = 0.09$, $z = 0.12$, $p = .91$. Ability to smell also affected overall accuracy, $\chi^2(1) = 7.32$, $p = .007$, $R^2 = 0.001$, with anosmics more accurate than controls. Contrary to predictions, then, anosmics were not specifically less accurate than controls when making explicit judgments about odor words (see Fig. 3A).

3.3.2. Response times to semantic similarity judgments

Looking at the response times for semantic similarity judgments, again contrary to predictions, there was no interaction between the ability to smell and sensory word type, $\chi^2(2) = 1.32$, $p = .52$, $R^2 = 0.001$. There was also no effect of sensory word type, $\chi^2(2) = 1.3$, $p = .52$, $R^2 = 0.005$. There was, however, a significant effect of the ability to smell, $\chi^2(2) = 12.43$, $p < .001$, $R^2 = 0.043$. Anosmics overall were slower than control participants (see Fig. 3B).

3.3.3. Duration of anosmia and semantic similarity judgments: Exploratory analyses

Once again, we conducted exploratory analyses to test whether duration of anosmia affects responses in the task. When analyzing accuracy however, models were nearly unidentifiable, most likely due to ceiling effects. We therefore tested the duration of anosmia on response

times only. There was no effect of anosmia duration, $\chi^2(2) = 0.08$, $p = .77$, $R^2 < 0.001$, and no interaction between anosmia duration and sensory word type, $\chi^2(2) = 0.31$, $p = .85$, $R^2 < 0.001$. Taken together, we find that losing the sense of smell does not impair semantic judgments about odor or taste words.

3.4. Emotion rating task

We analyzed ratings of valence, arousal, and dominance separately. For each measure, we expected anosmics and controls to differ for ratings of odor and taste words, but not vision words.

3.4.1. Valence

We found an interaction between the ability to smell and sensory word type in ratings of valence, $\chi^2(2) = 15.38$, $p = .005$, $R^2 = 0.001$, with a significant difference between anosmics and controls for odor words, $b = 0.24$, $z = 2.55$, $p = .01$, and taste words, $b = 0.40$, $z = 4.22$, $p < .001$, but not vision words, $b = 0.14$, $z = 1.60$, $p = .11$. Contrary to predictions however, odor and taste words were rated more positively by anosmics than controls.

There was also a main effect of sensory word type, $\chi^2(2) = 19.93$, $p < .001$, $R^2 = 0.078$. Pairwise comparisons with the emmeans package (Lenth, 2021) showed that taste words were rated more positively than odor, $b = 1.19$, $z = 4.04$, $p < .001$, and vision words, $b = 1.08$, $z = 4.23$, $p < .001$, but there was no difference between odor and vision words, $b = 0.11$, $z = 0.44$, $p = .66$ (see Fig. 4A). There was also a main effect of the ability to smell, $\chi^2(2) = 7.61$, $p = .006$, $R^2 = 0.004$, with ratings higher in anosmics than controls.

3.4.1.1. Duration of anosmia and valence: Exploratory analyses. We also explored whether the duration of anosmia affected ratings of valence. There was no significant effect of duration, $\chi^2(2) = 0.68$, $p = .41$, $R^2 < 0.001$. However, there was a significant interaction between duration and sensory word type, $\chi^2(2) = 11.17$, $p = .004$, $R^2 = 0.002$. To follow-up the interaction, we tested the effect of duration separately for each sensory word type and found duration was not a significant predictor of valence for any sensory word type. Overall, the results suggest that anosmics perceive odor and taste words as more positively valenced

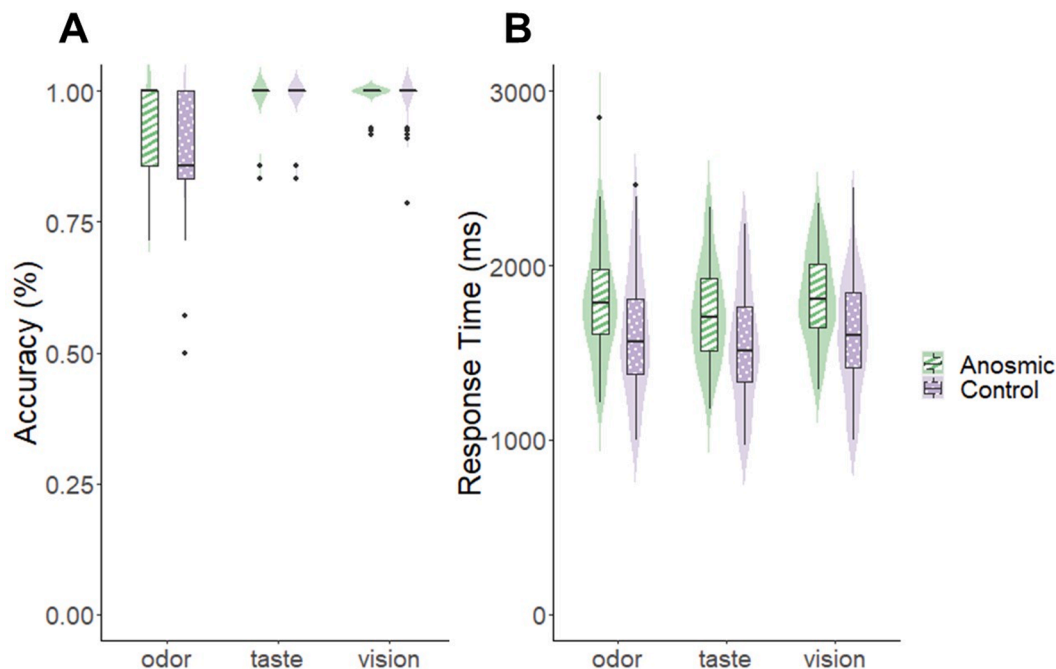


Fig. 3. Violin and boxplots of participant mean semantic similarity judgment (A) accuracy and (B) response time.

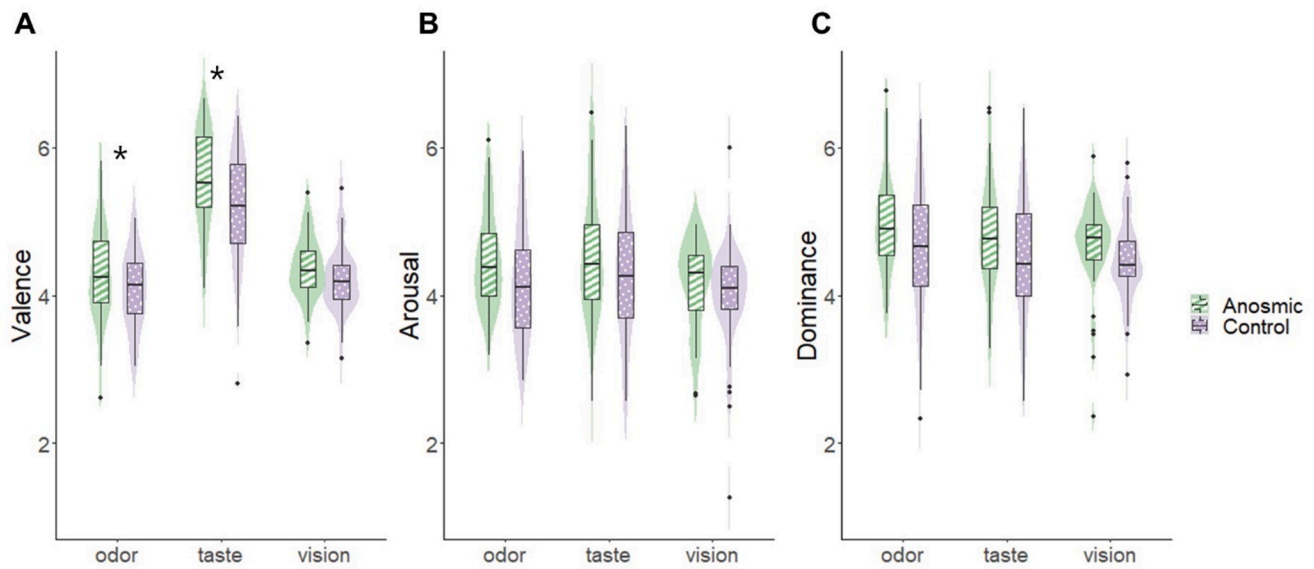


Fig. 4. Violin and boxplots of participant mean rating of (A) valence, (B) arousal, and (C) dominance.

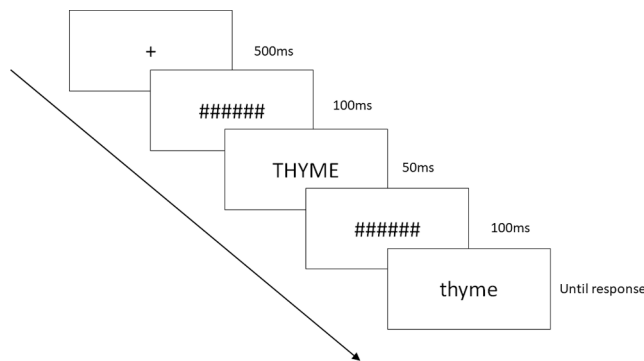


Fig. 5. Procedure for lexical decision task.

than controls do, but this does not apply to vision words.

3.4.2. Arousal

For arousal there was no interaction between the ability to smell and sensory word type, $\chi^2(2) = 5.81$, $p = .05$, $R^2 < 0.001$, nor an effect of sensory word type, $\chi^2(2) = 3.71$, $p = .16$, $R^2 = 0.007$. There was a significant effect of the ability to smell, $\chi^2(2) = 4.12$, $p = .04$, $R^2 = 0.005$, with higher ratings given by anosmics overall (see Fig. 4C).

3.4.2.1. Duration of anosmia and arousal: Exploratory analyses. Again, we explored whether duration of anosmia affected ratings, but there was no effect of duration, $\chi^2(2) = 0.74$, $p = .39$, $R^2 = 0.001$, and no interaction between duration and sensory word type, $\chi^2(2) = 1.17$, $p = .56$, $R^2 < 0.001$. In sum, the ability to smell had minimal impact on how smell and taste words are judged with respect to their arousal.

3.4.3. Dominance

For dominance there was no interaction between ability to smell and sensory word type, $\chi^2(2) = 3.26$, $p = .20$, $R^2 < 0.001$, and no main effect of sensory word type, $\chi^2(2) = 1.80$, $p = .41$, $R^2 = 0.005$. There was a main effect of the ability to smell, $\chi^2(2) = 6.46$, $p = .01$, $R^2 = 0.007$, with ratings higher in anosmics than controls (see Fig. 4C).

3.4.3.1. Duration of anosmia and dominance: Exploratory analyses. As an exploratory analysis, we also tested for the effect of anosmia duration on ratings of dominance. There was however no effect of anosmia duration, $\chi^2(2) = 0.08$, $p = .77$, $R^2 < 0.001$ and no interaction between duration and sensory word type, $\chi^2(2) = 2.89$, $p = .24$, $R^2 = 0.001$.

4. Discussion

We investigated the online processing of olfactory language in a large group of individuals with acquired anosmia. Following proposals that odor language is grounded in olfactory representations (González et al., 2006), we predicted participants with anosmia would be impaired in processing odor language compared to controls. However, we found no difference in lexical decision performance for odor and taste words in anosmics compared to controls, and no detriment in semantic similarity judgments for odor and taste words in anosmics compared to controls. We find no evidence that odor representations play a critical role in the comprehension of odor language. Although odor representations may be activated during explicit imagination or expectation tasks (Zhou et al., 2019), our results do not support the proposal that odor simulation is involved in odor language comprehension (Speed & Majid, 2018, 2019).

We also predicted anosmics would remember fewer odor and taste words than control participants. On the contrary, we found anosmics remembered more odor words. This suggests losing the sense of smell is not detrimental to odor language processing. The puzzling aspect here is

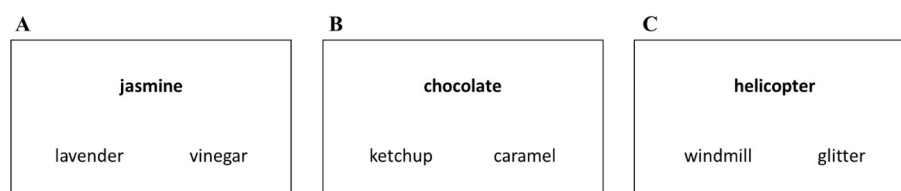


Fig. 6. Example triplets from the semantic similarity judgment task for (A) odor triplets, (B) taste triplets, and (C) vision triplets.

that we find the opposite pattern to the one predicted. It is possible that odor words are more salient to anosmics because they are aware these words are related to the perceptual sense they have lost. In particular, we recruited participants via two anosmia charities, whose members likely attach more importance to the sense of smell and their loss. Reading odor words may have left an emotional trace for these participants. fMRI studies with patients with acquired anosmia have shown extensive activation in higher-order olfactory regions of the brain in anticipation of odor words, suggesting increased effort or attention (Han et al., 2019; Joshi et al., 2020). Such an explanation is also compatible with the better memory for odor words we found: anosmics may have effortfully processed odor words, simultaneously strengthening memory traces. On the other hand, the lack of difference in lexical decision response time to odor words between anosmics and controls suggests an explanation in terms of processing effort is unlikely.

There are other possibilities to consider. Perhaps the anosmic participants were more motivated to perform the study than the control participants who we recruited via Prolific Academic. This could be tested in the future by replicating the study in a lab environment where motivation may be better equated. Whilst we agree there are limitations with collecting control data from participants online, there are also some benefits. It has been shown, for example, that participants recruited online are more diverse than typical university samples (Burhmaster, Kwang, & Gosling, 2011), and therefore may be a better comparison for the group of anosmic participants. Furthermore, research has shown that a number of classic psycholinguistic effects involving small differences in reaction time have been replicated with data collected online, and there are negligible differences in the quality of data between online studies and studies in the lab (Enochson & Culberston, 2015; Germine et al., 2012). We are therefore confident in the quality of the control data we collected. Another factor to consider is that we followed our pre-registered hypotheses and analyses, and did not correct for multiple comparisons when following up significant interaction and main effects (see Rothman, 1990). If we did apply a more conservative significance criterion, the difference in word recall and valence ratings between anosmics and controls for odor words would no longer be significant, whilst the difference in valence between anosmics and controls for taste words would remain. Future research should therefore aim to replicate such an effect.

It has been suggested that if odor simulation is unavailable during language comprehension, emotional simulation may become relevant for odor language (Speed & Majid, 2019). Our emotional ratings provide first support for this idea. Odor and taste words had more positive valence associations for anosmics than controls, but this was not the case for vision words. It is possible, then, that anosmics rely more strongly on emotional associations for odor-relevant words since they can no longer rely on odor experience. It is also possible, however, that odor and taste words are rated as more positive because the anosmics are aware their experience of the word referent is limited after losing their sense of smell. The words could be emotional because individuals know what they have lost. Another possibility is that in the absence of odor simulation, participants rely more heavily on linguistic co-occurrences (see, e.g., Connell, 2019; Reilly et al., 2021). For example, it has been shown that odor-related words occur in more emotional parts of the English lexicon than vision-related words (Winter, 2016). Anosmics may rely on the emotional content of odor-word neighbors to support word meaning. A similar argument has been made in the context of blind language processing and is a matter of on-going debate (Kim et al., 2019a; Kim, Elli, & Bedny, 2019b; Lewis, Zettersten, & Lupyan, 2019; Ostarek, van Paridon, & Montero-Melis, 2019).

The present investigation was limited to acquired anosmics, i.e., individuals who have previously been able to smell, and are likely to still possess memories and semantic associations to odors. So, in principle, these anosmics could mentally simulate odor via memory traces of previous olfactory experience, although it has been shown that acquired anosmics have weaker olfactory imagery than control participants

(Flohr et al., 2014), suggesting this is unlikely. To shed more light on the issue, the same study could be repeated with individuals who have congenital smell loss (i.e., people born without a sense of smell). Moreover, due to the online nature of the study, we were unable to conduct any physical testing of olfactory ability which could provide additional validation of the anosmic group. We also note the inherent difficulty in drawing conclusions based on null results. An obvious question is whether we had adequate statistical power to detect effects. In terms of sample size, we have twice as many participants as previous studies that have observed action language processing deficits in individuals with Parkinson's disease (Fernandino et al., 2013b, 2013a). In addition, such studies performed statistical analyses by participants only, whilst we used linear mixed effects models that take into account both participant- and item-level variance, and are therefore more powerful (Brysbaert & Stevens, 2018). At a minimum this suggests even if there are simulation effects they are incredibly small in size. It is possible, however, there are other contexts in which odor simulation is more relevant, such as when reading a menu or recipe. Critically, while there is no indication of impairment in odor language processing in anosmics, in some tasks the effects were even in the opposite direction to predictions (e.g., word recall, emotional valence).

It could be argued the tasks used in the present study were semantically shallow, meaning they could easily be completed without necessarily activating semantic information. However, previous studies using a lexical decision task have found that patients with Parkinson's disease are impaired comprehending action verbs compared to controls (Fernandino et al., 2013a). Furthermore, Reilly et al. (2021) did not find a difference between their anosmic patient and a group of controls in the narration of an olfactory event, which presumably requires deep semantic processing, lending further credence to our conclusions.

Taken together with previous studies of participants with an intact sense of smell (Pomp et al., 2018; Speed & Majid, 2018), as well as studies with anosmic patients (Han et al., 2019; Joshi et al., 2020; Reilly et al., 2021), the evidence so far does not support the proposal that mental simulation of odor occurs during odor language processing. The existing findings suggest the connection between language and olfaction is symmetric, with equally weak connections (for English speakers) between language and olfactory areas in comprehension as production (Majid, 2021; Speed & Majid, 2018). Instead, the evidence suggests odor language may involve high-level representations, such as hedonic information (Pomp et al., 2018; Speed & Majid, 2018). This contrasts with other behavioral paradigms that suggest single words can activate sensory odor information. Olofsson et al. (2012), for example, found responses to odors were facilitated after participants were presented with matching labels, suggesting labels activate odor templates. In their study, however, participants were familiarized with the odors and their labels first, and then presented with the same odor four times in the experimental trials. It is possible, then, that a label can activate an odor representation via short-term odor memory with repetition, but in everyday language processing olfactory activation is not automatic. This requires further exploration.

To conclude, we provide evidence suggesting that odor language is comprehended using high-level odor representations, rather than low-level simulations of odor. Embodied theories of language processing should be fine-tuned to account for differences in mental simulation across the sensory modalities.

Declaration of Competing Interest

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

Data availability

There is a link to the data in the manuscript.

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