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Olfactory language and semantic processing in anosmia: a neuropsychological case control study

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ABSTRACT
A longstanding debate within philosophy and neuroscience involves the extent to which sensory information is a necessary condition for conceptual knowledge. Much of our understanding of this relationship has been informed by examining the impact of congenital blindness and deafness on language and cognitive development. Relatively little is known about the "lesser" senses of smell and taste. Here we report a neuropsychological case-control study contrasting a young adult male (P01) diagnosed with anosmia (i.e. no olfaction) during early childhood relative to an age- and sex-matched control group. A structural MRI of P01's brain revealed profoundly atrophic/aplastic olfactory bulbs, and standardized smell testing confirmed his prior pediatric diagnosis of anosmia. Participants completed three language experiments examining comprehension, production, and subjective experiential ratings of odor salient words (e.g. sewer) and scenarios (e.g. fish market). P01's ratings of odor salience of single words were lower than all control participants, whereas his ratings on five other perceptual and affective dimensions were similar to controls. P01 produced unusual associations when cued to generate words that smelled similar to odor-neutral target words (e.g. ink → plant). In narrative picture description for odor salient scenes (e.g. bakery), P01 was indistinguishable from controls. These results suggest that odor deprivation does not overtly impair functional language use. However, subtle lexical-semantic effects of anosmia may be revealed using sensitive linguistic measures.

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Introduction

> What's in a name? That which we call a rose
>
> By any other name would smell as sweet …
>
> ~Shakespeare, Romeo and Juliet

The power of Juliet Capulet's metaphor lies in the strength of its associated sensory imagery. When reading this stanza, most of us cannot help but experience the odor of roses and the visual image of a garden. A longstanding philosophical question involves whether people with congenital sensory deprivation (e.g. blindness or deafness) are capable of experiencing such phenomena. The dogmatic answer from rationalist philosophy is a resounding no. From Aristotle to the modern era, philosophers and cognitive scientists have speculated that people who are born blind cannot possibly know the visual characteristics of a garden or the qualia of other predominantly visual concepts (e.g. glitter, glow) (Berkeley, 1709). It is only within the past century that rigorous empirical studies have unseated this assumption. An emerging consensus today holds that people with congenital blindness acquire, process, and use visual terms in remarkably analogous ways to people with normal vision (Bedny et al., 2019, 2009; Kim, Elli, Bedny 2019 ; Landau & Gleitman, 1985).

Landau and Gleitman (1985) argued that many assumptions about semantic representation in congenital blindness were justified by deduction rather than hard data. Folk intuition might support the conclusion that a person who has never experienced sight cannot possibly experience a richly developed sense of visual imagery for objects that are inaccessible through haptic means (e.g. clouds, colors, abstract visual art). However, Landau and Gleitman (1985) largely disproved these assumptions in their seminal research tracking language and conceptual development in a cohort of congenitally blind children. The principal finding was that by approximately the age of three, blind and sighted children are virtually indistinguishable in their language competencies. The authors specifically examined competence with visual verbs (e.g. look, see) and color terms. When cued to "look" at a specified target object, one of children (i.e. Kelli) showed reaching behaviors consistent with using her hands to inspect the item. Kelli also used the word "look" appropriately in spontaneous conversation, and she further demonstrated knowledge of the verb, "see", as requiring a direct line of sight between a person and an intended target.

Bedny and colleagues have amassed additional evidence for homogeneity in language processing between people who are congenitally blind and their sighted counterparts (Bedny et al., 2011; Bedny, 2017; Bedny et al., 2019; Kim et al., 219). Bedny et al. (2019) found similar characterization of visual verbs along dimensions such as intensity, duration, and stability between blind and sighted adults. In another study, blind and sighted adults appeared to show different grouping strategies across a variety of tasks including animal

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category sorting and ordering. Blind participants appeared to group animals by inferencing from taxonomic relations or other encyclopedic knowledge, whereas sighted participants appeared to rely more heavily on form-based visual cues (Kim et al., 2019). When task demands required indexing information about size, height, and shape, the groups were indistinguishable (Kim et al., 2019). In contrast, the groups diverged when cued for sorting by color and skin texture. Differences here were attributed to blind adults leveraging nonvisual information (e.g. encyclopedic knowledge) in their sorting strategies (Kim et al., 2019).

In summary, a growing body of evidence suggests that congenital blindness does not impair but may perturb conceptual processing in subtle ways that are only evident using sensitive, unconventional measures that force people to extrapolate beyond redundant information. For example, a person who lacks the ability to perceive odor may "know" that skunks are malodorous because they have been explicitly told so or have observed other peoples' reactions to skunks. In contrast, judgments of the odor of alcohol, steel, or ink would likely lack such experiential bases. People who are blind build rich representations of visually salient concepts. These representations are likely bolstered both by redundant sensory information and co-occurrence statistics (e.g. language embeddings) within the environment. The extent to which similar compensatory processes extend to other sensory disorders (e.g. anosmia) remains unclear.

Olfaction as a neglected perceptual and conceptual domain

Aristotle (c. 350 B.C.E.) postulated that human sensation and perception are governed by a hierarchy of the senses with vision and audition eclipsing the lesser senses of smell, taste, and touch (Slakey, 1961). Dominance of vision and audition is also evident in the sheer number of empirical studies investigating these modalities. Subsequently, much remains unclear about the complex interactions between odor, conceptual knowledge, and language. One possibility is that odor has a negligible impact on object knowledge. Landau and Gleitman (1985) reiterated this assumption in their remark that "neither taste nor odor seems to provide much information for learning about the objects, properties, and events that form the underlying conceptual layer supporting language learning" (pg. 14). A marginalized role of olfaction is also generally supported by corpus studies demonstrating that English has an impoverished smell lexicon relative to many other natural languages (Majid et al., 2018). There are relatively few English words that refer exclusively to odors or afford rich descriptions of odors. English speakers are, therefore, compelled to describe odors through general descriptors (e.g. Sulfur smells bad.) or through associations with odor emitters (e.g. Sulfur smells like a rotten egg.). A parallel body of psycholinguistic research has demonstrated that odors are notoriously difficult to name among English speakers and are susceptible to high levels of confusability relative to conventional elicitation tasks such as picture naming (Jönsson et al., 2005; Stevenson et al., 2007).

Experiential models of semantic knowledge

Odor is one feature among many that comprise word and object meaning (Martin, 2007; Tulving, 1972). Theories of semantic memory differ in their approach to semantic feature representation and integration. Experiential semantic models are premised upon the idea that word meaning can be decomposed into a high dimensional vector space (Binder et al., 2016; Crutch et al., 2013; Reilly et al., 2016). Such models have recently offered powerful advances in decoding brain imaging data and elucidating word processing deficits in stroke aphasia (Anderson et al., 2016; Anderson et al., ; Crutch et al., 2013). Such semantic models offer flexibility in accounting for individual differences. Consider, for example, a simplified three-dimensional semantic space composed of color, odor, and emotional valence. It is possible to derive pairwise distance metrics between any two words (e.g. dog, table) within such a space using simple Euclidean geometry (Troche et al., 2017). It may also be possible to "lesion" such a model by selectively eliminating individual dimensions and then recalibrating a new and correspondingly lower distance matrix. In reference to the previous example, one might model the impact of anosmia on semantic distances between *dog* and *table* by omitting the odor vector and recalculating a new set of distances based on color and emotion.

Study aims

To our knowledge, no prior research has investigated processing and representation of odor concepts in people who have never experienced olfaction. The prevailing assumption is that olfaction is of only marginal importance for acquiring and representing concepts. Moreover, anosmia has never been identified as a frank cause of language disorder or delay. Yet, these assumptions await empirical validation. Here we investigated the ways that a person with anosmia processes odor-salient words and scenes. We hypothesize that sensitive measures will identify lexical-semantic differences in a person with anosmia relative to olfactory-typical peers.

Method

Case description

P01 is a 24-year-old, right-handed, Caucasian male. He is a monolingual English speaker and college graduate who is currently completing a doctoral degree. P01 reports no past medical history for language learning disabilities (e.g. dyslexia, developmental language disorder). He also has no known neurological, facial, or sinus injuries. P01 initially discovered that he had no sense of smell while on a family vacation in the first grade. His parents asked him to close the car windows secondary to the odor of a skunk, which he failed to detect. After this incident, P01 reportedly followed up with an otolaryngologist who confirmed a diagnosis of anosmia but recommended invasive follow-up testing (e.g. biopsy) to determine an etiology. P01 did not pursue further testing or intervention.

P01 reports being a picky eater who believes that he has retained a sense of taste but has difficulty distinguishing between spices. P01 maintains some reactivity to noxious chemical odors (e.g. bleach) but notes that this might be related to taste (i.e. “I taste it in the back of my throat”).[1] When asked to account for how a lack of smell has affected his life, P01 reports a history of cooking with rotten milk and recently failing to detect a burning electrical cable. He relies on alarms for detecting gas leaks in his home. He explained that he primarily learns about odors by observing other peoples’ reactions and through explicit instruction.

P01 performed within the range of total anosmia (17 of 40) on the Smell Identification Test (R. Doty, 2013) and attained a perfect score (30 of 30) on the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). Figure 1 presents a structural MR image of P01’s rostral frontal cortex, demonstrating near absence of olfactory bulbs bilaterally. Since there is no prior pediatric comparison image, it is impossible to determine whether P01 was born without olfactory bulbs (i.e. aplastic) or alternatively whether his olfactory bulbs atrophied throughout

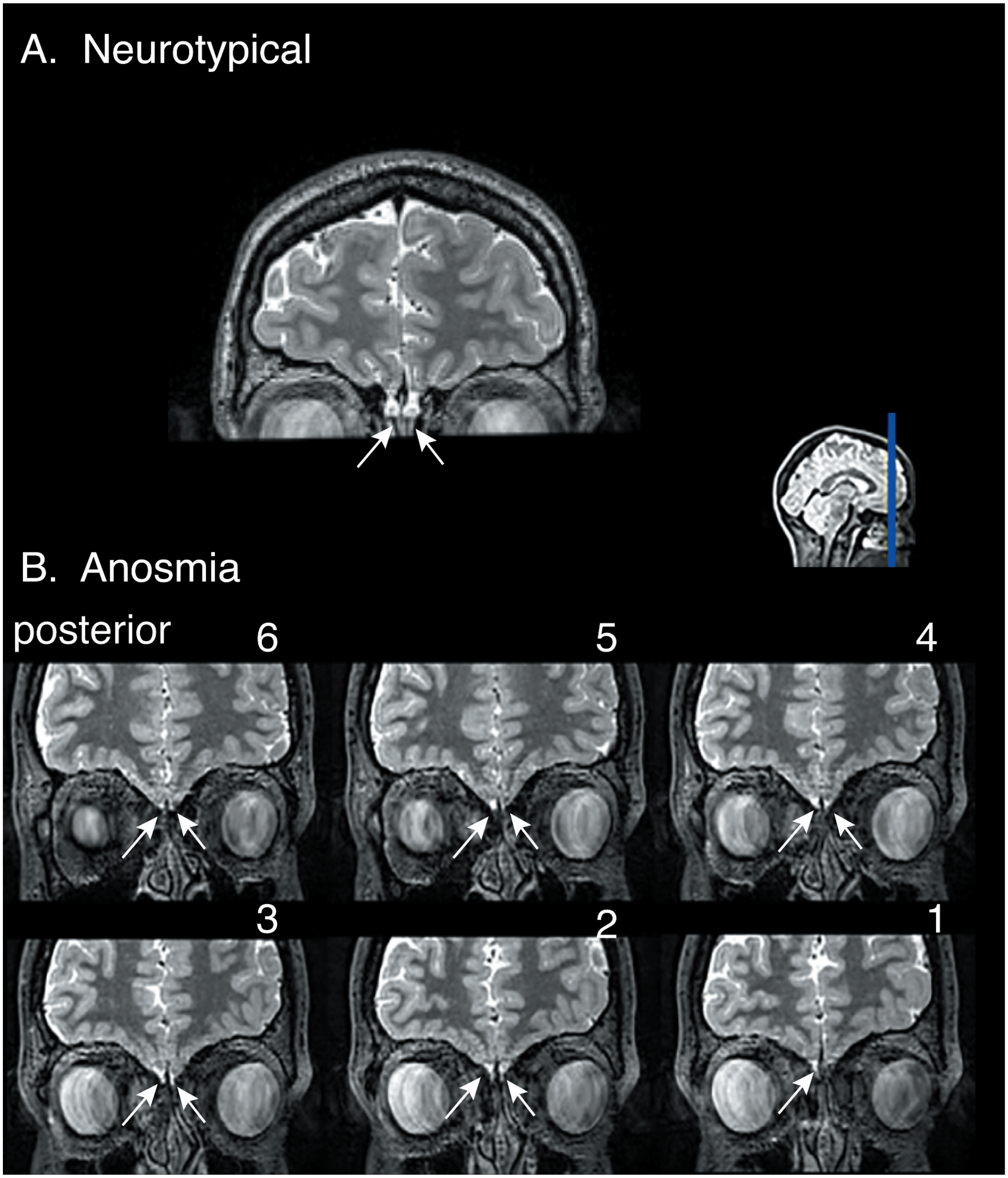


Figure 1. Coronal multislice image of P01’s olfactory bulbs. **Note**: Figure 1a represents a healthy neurotypical control participant. Figure 1b represents a multislice coronal view of P01 acquired via a Siemens 3-Tesla Magnetic Resonance scanner [Echo Time = 569 ms, Repetition Time = 3200 ms, Field of View = 220 mm, Slice Thickness = 0.90 mm].

childhood secondary to a peripheral disorder of his nasal epithelium. While prior research has reported olfaction in the absence of olfactory bulbs in a small subset of lefthanded women (Weiss et al., 2020); given the converging data derived from P01's smell testing, his self-reported history of absent olfaction, and MR imaging, we concluded that P01 presents with a case of true anosmia.

Experiment 1: lexical-semantic network structure

In the experiment to follow, we contrasted semantic distance and clustering properties between P01 relative to a sample of neurotypical control participants (N = 20) for a set of concrete nouns (N = 80) matched in lexical frequency but differing in odor salience. We specifically examined Euclidean semantic distance as rated on five cognitive dimensions: Color, Sound, Smell, Positive/Negative Feelings, and Social Interactions (see Appendix A).

Participants

Participants included P01 and a control group composed of sex- and roughly age-matched young adult males. The control group included master-level designated workers (N = 20, mean age = 29.75, range = 22–35) from the Mechanical Turk crowdsourcing platform (Amazon Inc.).

Stimuli & procedures

Stimuli included 80 concrete nouns spanning a wide spectrum of odor salience. We first queried the Lancaster Sensorimotor Norms (Lynott et al., 2019), isolating a subset of highly imageable English nouns (>3.5 on a 5-point Likert scale for visual salience). We sampled from the respective tails (low/high) of the olfactory rating distribution ($-1 > z > 1$) of these items, isolating two prospective item pools. We then sorted the low versus high odor salient words by word frequency (low to high) and eliminated lower frequency entries until attaining a final stimulus set composed of 40 items per condition. Stimuli are freely available for inspection and use on the Open Science Framework (OSF) at https://osf.io/ujwkm/.

P01 and MTurkers rated all words on a 0–7 Likert scale for salience on the following five dimensions: Color, Smell, Sound, Positive/Negative Feelings, and Social Interactions. Stimuli were presented in completely random order and responses recorded via Qualtrics survey software. Participants were given unlimited time to complete the task. Scale wording is reflected in Appendix A.

Data analyses

We converted perceptual ratings (80 words, 5 dimensions) to Euclidean distance matrices using the method of complete linkage, yielding an 80 × 80 pairwise semantic distance matrix reflecting the aggregate of the five cognitive dimensions for each individual participant. We then generated a group-level semantic distance matrix for the MTurk control participants by averaging their respective ratings for each word and dimension. We determined optimal cluster size for k-means partitioning using gap statistics as implemented within the "nbclust" package of R (Charrad et al., 2015; R Core Team, 2019). Once an optimal cluster size was determined, we subjected the semantic distance matrices to hierarchical clustering. We examined association strength of the distance matrices for P01 relative to controls via the Mantel statistic as implemented within the 'ade4' package of R (Dray et al., 2018) and contrasted P01 to controls on individual modalities (color, smell) using the Crawford-Garthwaite Bayesian test statistic (case vs. control) as implemented within the "psycho" package of R (Crawford & Garthwaite, 2007; Makowski, 2018).

Results

Figure 2 illustrates the distribution of experiential ratings for P01 relative to the MTurk controls. A Bayesian test for single case assessment indicated that P01's ratings of odor salience (Raw = 1.51, Z = −2.10, percentile = 1.78) were significantly lower than the MTurker distribution (M = 2.97, SD = 0.69, $p < .05$*). P01's ratings of odor salience of words were lower than 97.49% (95% CI [93.13, 99.97]) of the control group. In contrast, P01's subjective ratings across each of the remaining dimensions (color, emotion, sound, and social) did not differ from controls.[2]

Figure 3 represents hierarchical cluster dendrograms for P01 relative to the aggregate semantic distance of the MTurk control group. The raw semantic distance matrices for P01 and MTurk participants were uncorrelated (Mantel Statistic with 1000 iterations = 0.03, simulated $p = 0.26$), suggesting that pairwise Euclidean distances between words differed across the two groups. These differences are further apparent when referencing the clustering solutions for P01 relative to MTurkers (see Figure 3). We determined optimal cluster size (k-means) by calculating gap statistics for P01 and the control group. P01's word ratings best aggregated by a 3-cluster solution, whereas the MTurker data suggested a 5-cluster solution.

In a follow-up analysis, we evaluated the distribution of odor concepts within each of the clusters for P01 and the MTurk participants. We categorically coded each target word as: smells or not (0/1), smells pleasant or not (0/1), and smells unpleasant or not (0/1). We then conducted chi-squared tests of independence to evaluate whether cluster was independent of smell coding, with the null hypothesis that that cluster (k) is independent of the smell salience of the target words. Among P01's clusters ($k = 3$), there was no relationship between smell salience and cluster [$\chi^2(2) = 1.96$, $p > .05$], no relationship between pleasant odors and cluster [$\chi^2(2) = .04$, $p > .05$], and no relationship between unpleasant odors and cluster [$\chi^2(2) = 3.58$, $p > .05$]. In contrast, the MTurk clusters ($k = 5$) appeared to strongly differentiate by smell [$\chi^2(4) = 50.19$, $p < .0001$], fractionating further by pleasant odors [$\chi^2(4) = 18.21$, $p = .001$], and unpleasant odors [$\chi^2(4) = 27.68$, $p < .0001$].

Interim discussion: experiment 1

P01 demonstrates fluent language and above average academic achievement. There is no evidence to suggest a significant negative impact of anosmia on P01's conceptual or lexical

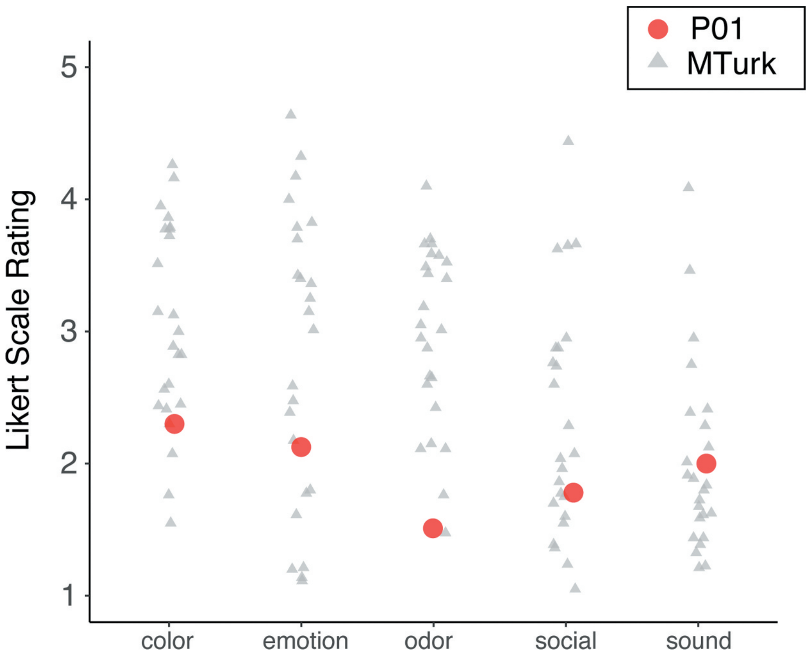


Figure 2. Scatterplot of P01 relative to MTurk participants across semantic dimensions.

development. Despite gross preservation of global cognition and language, P01 differed from MTurk controls in his perceptual salience ratings for single words, and these differences emerged when visualizing relative distances between words.

P01's subjective ratings of odor salience were lower than any control participant, in turn altering semantic distances between other rated words. These distances also translated to differences in how words clustered. For P01, his semantic clusters were not differentiated by odor salience. In contrast, control participants considered odor to be an important distinction marked by pleasantness. Thus, subtle differences in semantic representation related to odor salience emerged between P01 and control participants.

Experiment 2: narrative picture description

In Experiment 1, we examined semantic representation and processing of olfactory-salient language at the single word level. In the experiment to follow, we used a scene description task to gather more ecologically valid data on P01's olfactory language use. We examined macroscale elements of narrative production for scenes whose central themes involved odors (either pleasant or unpleasant) in order to capture potential differences between P01 and controls in (1) lexical diversity and (2) olfactory salience of words used when describing pictures. We hypothesized that P01 would demonstrate decreased lexical diversity and use words with lower olfactory salience relative to controls.

Method

Participants

Participants included P01 and 20 young adult males (mean age = 23.8, SD = 5.04, range = 18–34) recruited from a large public university campus. Participants were by self-report right-handed native English speakers with no history of neurological disorders, ocular damage, or eye surgery. All participants reported normal or corrected to normal vision.

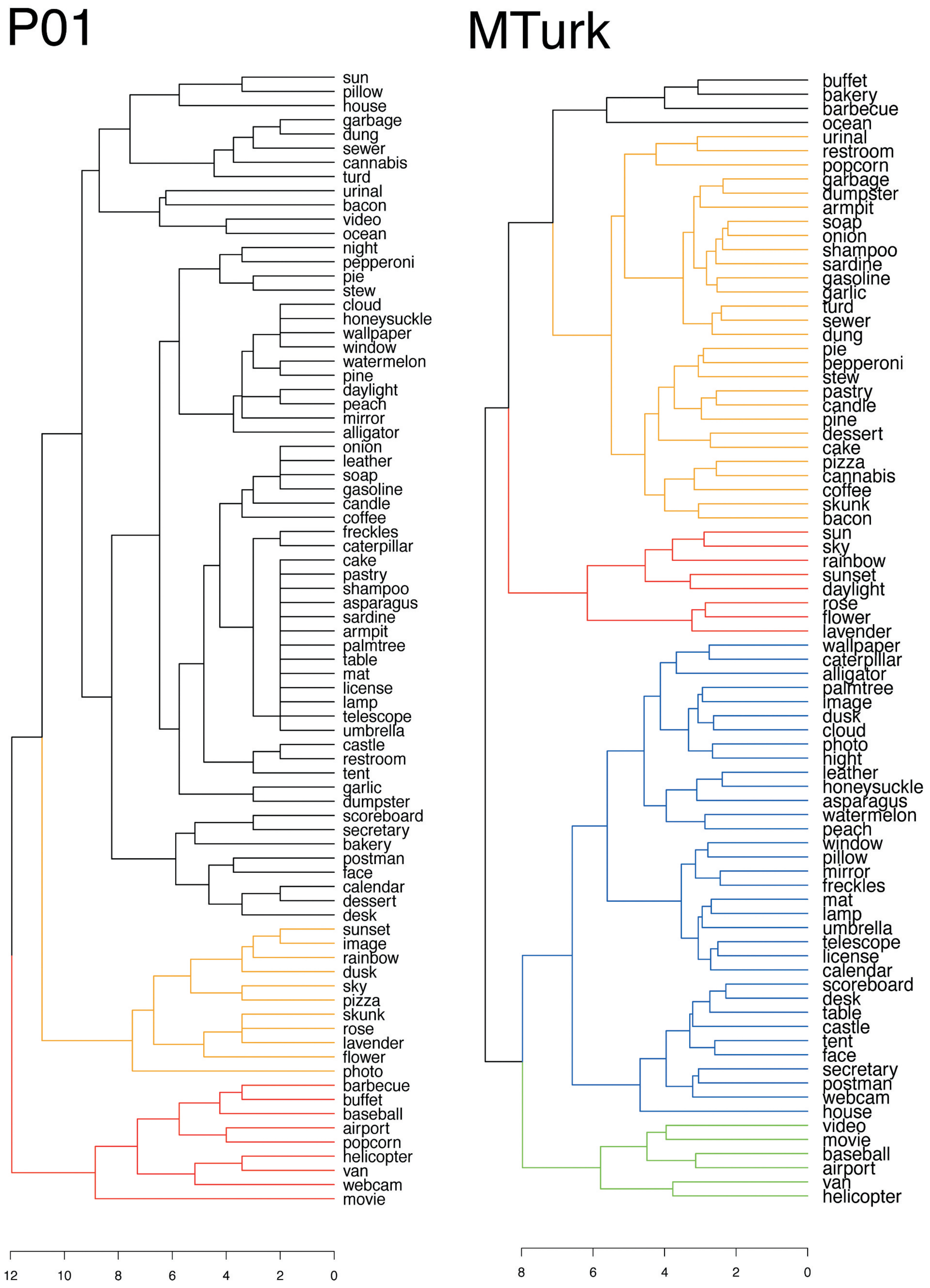
Stimuli

We first generated a candidate list of pleasant and unpleasant odor scenes (e.g. fish market, bakery). We then queried Google Images (Google Inc.) and compiled a set of six naturalistic scenes (color photographs) depicting people. Pleasant odor images included scenes of a bakery, a florist, and a barbecue scene. Unpleasant odor images included scenes of a fish market, a garbage pile, and a crowded smoking lounge.

Procedures

We standardized stimulus delivery using E-Prime 3.0 Professional software (Psychology Software Tools, Inc.). Picture stimuli were presented individually in random order on a Windows-based desktop computer. Prior to each picture presentation, written instructions were presented on the screen in conjunction with verbal instruction by the experimenter: "Pretend you are XX in this picture. Describe what they might be emotionally feeling and physically experiencing in this scene. Give us at least five sentences." After each picture appeared, the experimenter pointed to a predetermined person in each photo.

Participants were given unlimited time to respond. We digitally recorded oral responses and transcribed the narratives offline. All narratives were transcribed independently by two separate coders, and then compared using procedures adapted from Brennan et al. (2013). Inter-rater agreement was 98%. We removed word fragments, interjections/fillers, and unintelligible utterances from the transcripts.



P01

MTurk

Figure 3. Cluster Dendrogram of P01 relative to MTurk participants.

Table 1. Narrative contrasts.

	Lexical Diversity		Smell Salience of Content Words						
	MLUw	TTR	Baker	BBQ	Fish Market	Flowers	Smoking	Trash	Overall
Control	15.75	.38	1.02	1.29	1.02	.93	.97	1.39	1.05
P01	16.01	.30	.85	1.27	.80	1.38	.94	1.13	.96
P01 Percentile Rank	59.50%	86.28%	58.48%	57.26%	59.47%	64.12%	57.48%	59.16%	57.7%

Lexical Diversity: MLUw = Mean length of utterances (words), TTR = Type-Token Ratio, *Olfactory Salience of Content Words*: Mean olfactory salience of all content words used per picture narrative, *Percentile*: P01 score percent rank (e.g. <86.28% = P01 score is lower than 86.28% of control scores.)

We examined macro-level narrative discourse measures using a combination of manual coding and automated text mining. We derived Type Token Ratios (TTR) operationalized as the total number of unique words divided by the total number of words using the "koRpus" package in R (R Core Team, 2019; Michalke et al., 2018). We again used the "koRpus" package to derive mean length of utterance-words (MLUw) by dividing the total number of words in the narrative by the number of utterances (Michalke et al., 2018). In a second analysis, we employed a bag-of-words approach which involved extracting all open class words (e.g. nouns, verbs) from the unedited narratives. From these concatenated word lists, we eliminated function words, numbers, punctuation, and single letter words. We also edited plural nouns and past-tense verbs to their singular and present forms respectively. We then aligned olfactory salience ratings for each word with its corresponding entry from Lancaster Sensorimotor Norms (Lynott et al., 2019).

Results

Table 1 reflects narrative characteristics across participants. P01 did not differ from the control group by MLUw ($p > .1$), TTR ($p > .1$) or mean olfactory salience ($p > .1$) (see Table 1).

Interim discussion: experiment 2

In this experiment, we examined connected discourse for scenes thematically centered around odors. Contrary to our predictions, P01 and controls were indistinguishable on both macroscale measures and the distributions of content word odor salience across their narratives. Such homogeneity raises the question of whether compensatory mechanisms could account for P01's successful inferencing. More specifically, it is unclear how P01 "knows" about the salience of odor-laden scenes when he has never directly experienced smell.

P01's knowledge of olfactory-salient concepts may be moderated by a number of sources and alternate modalities. P01 may have gleaned knowledge about smell through implicit distributional cues from language, learned associations from directly observing other people's reactions, and inferencing from correlated feature detail. In real world ecological settings, odors are often accompanied by many correlated visually observable phenomena including excrement, corpses, or people wincing and retreating. Over a lifetime of accrued experience, non-olfactory detail may supplement conceptual knowledge even in the absence of direct experience. We revisit this possibility along with the potential contribution of diminished odor salience as a lexical property of English in the general discussion.

Experiment 3: word association for low-Olfaction words

In the previous experiments, P01 could have potentially accessed prior knowledge about odors gleaned from alternate modalities. For example, P01's knowledge of the odor of skunks could be informed by explicit instruction or direct observation. In contrast, P01 has no linguistic or experiential precedent upon which to judge the odor of chalk. Thus, by asking P01 to make judgments of words with very limited odor salience, we can reduce the contaminating effects of past experience or correlated feature knowledge.

We hypothesized that lack of a compensatory knowledge base for olfactory word meaning would compel P01 to "guess" about the odors of words he cannot directly experience. This strategy would result in P01 erroneously ascribing odor to words that do not smell. For example, when cued to identify a word that smells like a paper clip, P01 might produce a smelly associate such as a rose. In contrast, controls "know" that paper clips do not smell and will in turn index different attributes (e.g. lexical co-occurrence, material composition, contextual associates). Thus, we predicted that when asked to produce smell associates for low-smell stimuli, P01 would on average produce responses of higher olfactory salience than controls.

Method

Participants

Participants included the same sample described in Experiment 2. See method for demographics and inclusion criteria.

Stimuli

We generated a list of high frequency words with low olfactory salience by consensus among the authors, restricting stimuli to concrete nouns. The final set of stimuli included the following words: Chalk, Computer, Crackers, Diamond, Ink, Knife, Leash, Pen, Salt, Snow, Sweater, Syringe, Table, Tape, Wallet.

The average olfactory rating of the stimuli was 1.01 (SD = 0.57) on a 0–5 point scale (Lynott et al., 2019). Average word frequency was 29.08 (SD = 29.43) per million words (Brysbaert & New, 2009).

Procedures

Participants were seated in a quiet room in front of a computer monitor. Instructions and stimuli were presented using E-Prime 3.0 Professional software (Psychology Software Tools, Inc). The experiment initiated with a set of self-paced written instructions supplemented by verbal instructions from the experimenter. Participants were informed that they would view a target word on the screen and they were to, "Name two things that smell like XX."

Once the participant indicated comprehension, the stimuli appeared sequentially in random order. Participants were given unlimited time to respond. All responses were digitally recorded (Tascam DR-05) and transcribed offline by two independent coders. Inter-rater reliability was 99.94%. Discrepancies in response transcriptions were reconciled by consensus.

Data coding & analyses

We first obtained olfactory ratings for all responses using the Lancaster norms. One control participant failed to provide the specified number of two responses for one particular target word, bringing the total number of response items for the control group to 599, of which six items had no corresponding entry in the Lancaster norms. We then derived a mean olfactory salience by participant collapsing across stimuli, and contrasted these scores using the Crawford-Garthwaite case-control statistic as implemented in the "psycho" package of R (R Core Team, 2019; Crawford & Garthwaite, 2007; Makowski, 2018).

Next, we examined the similarity of participant responses and stimulus words using Latent Semantic Analysis (LSA; Landauer & Dumais, 1997). We completed a pairwise comparison of each response/stimulus word pair across participants to produce a cosine similarity value. We used the LSA@CU Boulder website to calculate cosine values based on word co-occurrence within the college-level General Reading Space corpus (http://lsa.colorado.edu). Five of the 599 queried words were not represented in the corpus, resulting in a total of 594 cosine values calculated across control participants. We collapsed cosine values across responses to derive a mean cosine value by participant. We used the resulting mean cosine values to compare P01 to control participants using the case-control test for single case assessment as implemented in the "psycho" package of R (R Core Team, 2019; Crawford & Garthwaite, 2007).

Results

The mean olfactory salience for P01's word associations (Raw = 2.99, Z = 2.94) was greater than the 99th percentile of the olfactory salience of the control participants (M = 1.64, SD = 0.46, p < .01**, 95% CI [97.95, 100.00]).

The average cosine similarity of P01's target and response word pairs (Raw = 0.19, Z = −1.32) did not differ from controls (M = 0.24, SD = 0.04, p > .1).

Interim discussion: experiment 3

We predicted that P01 would produce "smelly" responses in contrast to control participants who are well aware that the stimuli did not have odors. P01 strongly upheld this prediction with responses ascending the 99th percentile of olfaction from the control group. We reasoned that P01 would guess these associations using a somewhat random selection process drawing upon a relatively restricted bank of salient odor words. That is, rather than identify associates based on semantic or linguistic context, P01 would arbitrarily draw upon words he knows have strong odors. P01 might link associates using simple collocation information (e.g. rain and dog are linked because they co-occur in the context of a common idiom). To examine this possibility, we contrasted co-occurrence statistics (cosine distance) between all cue and response pairs (e.g. chalk-fart). P01's co-occurrence relations between word pairs did not differ from controls.

P01's word associations provide unique insight into his strategies for inferencing about smell when he cannot access prior knowledge. When processing single words and producing narratives, P01 was virtually indistinguishable from controls. However, the unusual task demands of this experiment elicited divergence between P01 and controls by eliminating the substrate for P01's compensatory scaffolding.

General discussion

Olfaction is believed to play a marginal role in language and conceptual development relative to vision and audition (Aristotle c.350 B.C.E., Landau & Gleitman, 1985). This implicit assumption of a sensory hierarchy is also mirrored within many Western languages (see Majid et al., 2018). For example, English has an impoverished odor lexicon which compels its speakers to describe odors using underspecified descriptors (e.g. bad, good), spontaneous adjectivizations (e.g. minty, musky), and similes (e.g. smells like _______). From a Whorfian perspective, it is tempting to conclude that the presence of a sparse odor lexicon in English and other Western languages reflects a correspondingly limited role of olfaction within semantic memory. However, recent sociolinguistic evidence has demonstrated numerous languages including Turkish, Cantonese, Farsi, and Malay have richly developed odor lexicons rivaling that of vision (Majid et al., 2018; Speed & Majid, 2020). The breadth of this cross-linguistic evidence demonstrates that a sparse odor lexicon is not a universal property of natural language.

Landau and Gleitman (1985) argued that smell and taste alone contribute little to the conceptual substrate that underlies language development. P01 generally confirms this hypothesis. He reports above average academic performance with no history of language or learning impairment. The characteristics of his oral narratives for highly odor salient situations were indistinguishable from control participants. In this respect, P01's behavior was consistent with a growing body of research in congenital blindness demonstrating a pattern of homogeneity between blind and sighted people. Yet, P01 also diverged from controls on finer-grained tasks of semantic knowledge. These differences primarily involved perturbation of semantic distances between words as revealed by cluster analyses and the qualitative nature of P01's associations to odor neutral words. These results illustrate that a person with anosmia describes odorous scenes comparably to people who can smell. Nevertheless, the data suggest that this homogeneity may have been attained through distinctive compensatory mechanisms.

Knowing about odors in the absence of smell

P01 expresses rich and complex ideas about odor despite never having experienced smell firsthand. In this respect, his behavior is analogous to the ways that congenitally blind adults process visually salient words such as gleam, glow, and glitter (Bedny et al., 2019). Bedny and colleagues argued that the acquisition and use of visual words (e.g. verbs, colors) is likely mediated by other domains, including linguistic metaphor (e.g. red is hot), haptic feedback, and statistical regularities that give rise to correlated feature knowledge (see also Kim et al., 2019). Consider the following illustrative example of how one might make inference about one sensory modality from an altogether different sense. There exists an inverse relationship between object mass and resonant sound frequency. This physical law gives rise to a regularity in our environment that elephants tend to rumble while bees buzz. Implicit knowledge of this physical law allows one to bypass vision to infer size (and by extension threat potential) directly from sound. We routinely make use of correlated sensory knowledge to make inferences about missing information. Statistical regularities nested in language offer a parallel source of inference about word meaning.

Semantic features act as a substrate for word and object meaning. A distributed network of features confers redundancy such that people can often spontaneously compensate for the loss of one feature by invoking others. Flexibility in semantic feature weighting is an essential component of object representation (Barclay et al., 1974). Whereas visual attributes are diagnostic features of fruits and vegetables, visual knowledge is minimally informative about environmental sounds. Thus, object knowledge involves a dynamic integration of different modalities. In our particular culture and language, olfaction does not appear to have significant weighting for most concepts. As such, the selective loss of smell would not be predicted to grossly perturb or impair semantic representation and processing. In everyday language tasks such as scene description, P01 generally upholds this prediction. He appears to make active use of many alternate sources of information to seamlessly convey information about a sense he has never directly experienced. Notably, while P01 does not experience what might be considered conventional firsthand olfaction, he does report the subjective experience of "tasting" caustic substances such as bleach in the back of his throat. This chemosensory phenomenon has been previously documented (Doty et al., 1984; Laska et al., 1997), and its neurophysiological substrate is thought to involve collateral inputs from the trigeminal nerve (Cranial Nerve (CN)V). It is,therefore, possible that P01 has gained some experience of olfaction for volatile odors mediated by CN V that could serve as a modality for acquiring knowledge about odors. However, these capacities were not evident in his performance on standardized smell testing, nor in P01's task performance as reported here (e.g. P01's perception and production of CN V and CN I mediated concepts did not differ).

P01 reports that language (e.g. description by others) is one of the dominant alternate sources of information he uses to learn about smells. On macroscale linguistic tasks, P01 behaves similarly to controls. There are several potential mechanisms by which he achieves this homogeneity. First, P01 may leverage information from language and other correlated features gleaned from direct experience (e.g. observing facial expression in the context of a smell). Another potential factor contributing to this apparent homogeneity between P01 and controls relates to a lexical-semantic property of P01's native language. English speakers rarely find themselves providing fine-grained descriptions of odors or tastes. Thus, P01 shows facile compensation for his loss of olfaction in a language with minimal olfactory demands. An unanswered question is whether similar levels of homogeneity would be observed in an anosmic speaker of languages such as Malay or Turkish that may have greater communicative pressures for describing smells.

Limitations and future directions

P01 is a single case study, whose language profile we attributed to anosmia. We cannot rule out the influence of idiosyncratic individual differences (e.g. education level) without a much larger sample size. In addition, we did not conduct standardized neuropsychological or smell testing on the control participants, instead relying on self-report of preserved cognition, language, and olfaction. A more rigorous comparison will involve comprehensive perceptual and cognitive testing across all participants with the goal of a continuous analysis of individual differences.

Another limitation of our approach was that we cannot rule out that P01 experiences acquired rather than congenital anosmia. That is, he could well have perceived odors as a young child only to lose olfaction later during development. There are many potential causes of acquired anosmia across the lifespan. Anosmia is a symptom of numerous neurological disorders including traumatic brain injury, Alzheimer's disease, and Parkinson's disease (Attems et al., 2015; R. L. Doty, 2012; Marin et al., 2018). In addition to central neurological causes of anosmia, peripheral conditions known to produce either transient or chronic anosmia include exposure to environmental toxins, smoking, seasonal allergies, non-allergenic rhinitis, and nasal obstructions (e.g. polyp, tumor, deviated septum). (Ajmani et al., 2017; Genter & Doty, 2019) In addition, viral conditions such as influenza and colds are commonly associated with anosmia and/or ageusia (i.e. loss of taste), and anosmia has been identified as an early clinical marker of the novel coronavirus disease (COVID-19) (Meng et al., 2020; Vaira et al., 2020).

The nature of semantic impairment associated with acquired versus congenital sensory loss remains unclear. One might predict that the loss of olfaction during early adulthood emerges within an established semantic substrate for odors. That is, we may "know" about odors from prior experience even though we cannot directly perceive such odors now. Another possibility is that the loss of a particular sensory channel gradually degrades the representation of objects salient in a given modality. Trumpp et al. (2013) presented evidence for this possibility in a young adult (patient J.R.) who experienced aphasia in his mid-twenties after being admitted to the hospital with seizures. Structural imaging revealed a unilateral abscess encompassing left hemisphere auditory association cortex (MTG/STG). Nine years after his initial brain injury, J.R. showed a remarkable pattern of performance in both verbal and nonverbal tasks including not only difficulties in identifying everyday environmental sounds, but also recognizing (i.e. lexical decision) and producing (i.e. verbal fluency) sound salient words. These findings suggest that semantic deficits impacting a single sensory modality can emerge in the context of previously intact semantic abilities.

We cannot be certain that P01 never experienced olfaction prior to his diagnosis of anosmia in early childhood. However, given the relatively brief time period in which P01 may have experienced olfaction and the scarcity and infrequency of smell words in English, any early olfactory sensation would likely have only a small impact on P01's smell salient concept formation.

Future investigations will benefit from neuroimaging measures to elucidate neurophysiological mechanisms supporting the observed behaviors (e.g. fMRI, EEG). Future investigations will also benefit from examining the impact of anosmia on speakers of a more smell salient language (e.g. Malay), in which differences related to anosmia may be more difficult to obscure.

Concluding remarks

To our knowledge, P01 represents the first single case examining the effects of anosmia on language and semantic processing. A general finding was that P01 demonstrates no overt language or cognitive impairment as a result of smell deprivation. However, sensitive measures revealed subtle differences in P01's semantic processing relative to controls. These findings are grossly consistent with prior research in the domain of congenital blindness (see Bedny et al., 2019, 2011; Landau & Gleitman, 1985). This investigation adds to a growing body of literature demonstrating plasticity of object knowledge in the context of early sensory deprivation.

Notes

1. P01's report of reactivity to noxious chemicals is consistent with at least partially preserved trigeminal chemoreception via cranial nerve V (CN V). Whereas the first cranial nerve (CN I) provides direct olfactory input to neural sensory regions, CN V responds to painful or irritating compounds by inducing changes to intranasal tissue, secretions, and respiratory patterns (see Doty et al., 1978 for details on trigeminal chemoreception in people with anosmia).
2. The supplemental data include an additional scatterplot reflecting a more granular depiction of olfactory ratings as a function of the olfactory salience (low/high) of the stimulus words. Visit https://osf.io/ujwkm/.

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Appendix

APPENDIX A

You will rate how much each word in the lists below makes you think of 5 different qualities. Make sure to read the question before each block carefully so you know what quality you should be thinking about.

How much does this word make you think of color?

How much does this word make you think of odors or smell?

How much does this word make you think of sound(s)?

How much does this word make you think of positive or negative feelings?

How much does this word make you think of social relations or situations where people might interact with one another?