

Running head: Visual load induces prolonged inattentional anosmia

“What smell?” Temporarily loading visual attention
induces a prolonged loss of olfactory awareness

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Word count

Abstract: 150

Introduction and discussion: 1845

Methods and results: 4486

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Abstract

The human sense of smell is highly sensitive, often conveying important biological signals. Yet, anecdotal evidence suggests that we commonly fail to notice supra-threshold environmental olfactory stimuli. The determinants of olfactory awareness are, as yet, unknown. Here, we adapted the ‘inattention blindness’ paradigm, to test whether olfactory awareness is dependent on attention. Across three experiments, participants performed a visual search task with either a high or low perceptual load (a well-established attentional manipulation) while exposed to an ambient coffee aroma. Consistent with our hypothesis, task load modulated olfactory awareness: 42.5% fewer participants in the high (vs. low) load condition reported noticing the coffee aroma. Our final experiment demonstrates that, due to unique characteristics of olfactory habituation, the consequences of inattentional anosmia can persist even once attention becomes available. These findings establish the phenomenon of inattentional anosmia, and have applied implications for predicting when people may miss potentially important olfactory information.

KEYWORDS: INATTENTION; ANOSMIA; SMELL; PERCEPTUAL LOAD.

The sense of smell is thought to have evolved before other senses (Kaas, 2013) and plays an important role in alerting us to biologically important signals such as potential dangers (e.g., a gas leak, rotten food), and rewards (e.g., foods, potential mates). Human olfaction is capable of high levels of acuity (see McGann, 2017; Sela & Sobel, 2010, for review). For example, humans can detect the scent of fear in sweat, find their own t-shirt among 100 visually identical t-shirts worn by others, and discriminate between the smells of close friends or relatives (Ackerl et al., 2002; Chen & Haviland-Jones, 2000; Lord & Kasprzak, 1989; Mallet & Schaal, 1998; Porter & Moore 1981). If such human olfactory feats sound surprising, however, then you are not alone – we humans typically show low confidence in our olfactory abilities, rating smell as being substantially less important than the other senses (e.g., Classen, 1994; Sela & Sobel, 2010).

One explanation for our lack of appreciation of this important and powerful sense is that we may often simply not notice olfactory information (cf. Sela & Sobel, 2010). The fact that individuals often fail to notice unexpected supra-threshold odors is likely why, as Sela and Sobel note, the warning agent for propane gas is added at 57,000 times the detection threshold. This phenomenon resembles the visual phenomenon of ‘inattention blindness’, whereby participants fail to notice an unexpected stimulus that appears in plain sight (Mack & Rock, 1998, see also Macdonald & Lavie, 2011, and Murphy & Dalton, 2016, for similar phenomena in the auditory and tactile modalities). As the term ‘inattention blindness’ suggests, this phenomenon is thought to occur when attentional capacity is otherwise engaged by another task.

To date, no study has directly tested for an olfactory analogue of inattention blindness – inattention anosmia (i.e., ‘smell blindness’). However, suggestive evidence for this phenomenon comes from studies of unconscious olfactory influences on mood or performance. In these studies, only a very small minority of participants were able to correctly answer

questions about their olfactory experience such as recalling the location where they had previously encountered a particular smell (Degal & Koster, 1999), or guessing that the olfactory sense had been manipulated during an earlier phase of an experiment (Lorig, 1992).

If inattentional anosmia exists, it could have more profound consequences than other forms of inattentional unawareness due to the unique characteristics of olfaction. Perhaps due to its earlier evolution, olfactory processing differs both functionally and anatomically from the other senses. Olfaction has limited representation on the more recently evolved neocortex – it has been argued that the olfactory bulb serves as the functional equivalent to primary visual cortex, with olfactory cortex being an associative rather than primary sensory cortex (Haberly, 2001). Claims that olfaction is the only sense in which the pathway from sensory receptor to cortex does not allow for thalamic gating have led to debate as to whether selective attention is possible within the olfactory modality (Keller, 2011; Sela & Sobel, 2010, although see also Tham, Stevenson & Miller, 2011).

A key functional difference between olfaction and other senses is the uniquely powerful nature of olfactory habituation. The cortical response to ongoing olfactory stimulation rapidly diminishes (Sobel et al, 2000), and a recent study found that after 22.5 minutes exposure to an ambient smell participants were no longer able to detect it even when directly asked to do so (Mahmut & Stevenson, 2015). A striking implication here is that there may be a limited time window in which to detect ambient smells. If inattentional anosmia occurs during the initial period that a smell is encountered, it may never be detected.

Despite these functional and anatomical differences, some evidence exists of olfactory attentional processes resembling those of other senses. Directing endogenous attention to the olfactory modality can speed olfactory decision-making (Spence, Kettenmann, Kobal & McGlone, 2000, 2001a, b), and amplify olfactory cortical processing (Zelano et al., 2005). However, the role of attention in spontaneous olfactory awareness has never been tested.

Here we sought to establish the phenomenon of inattentional anosmia, testing the hypothesis that awareness of olfactory stimuli is, like other forms of sensory awareness, critically dependent on the availability of attentional capacity. To this end, we adapted an inattentional blindness paradigm first introduced by Cartwright-Finch and Lavie (2006), using a well-established perceptual load manipulation of attention. According to the Load Theory (Lavie, 1995, 2010), the availability of attentional capacity is determined by the perceptual load of the current task, with high load tasks exhausting capacity and hence preventing additional processing. Cartwright-Finch and Lavie (2006, Experiment 2) had their participants search for a target letter (X or N) either among small circular placeholders (low load condition) or among five heterogeneous angular non-target letters (high perceptual load). On the sixth and final trial, an unexpected critical stimulus (a small shape) was presented alongside the task stimuli. The participants were then immediately asked whether they noticed anything appearing onscreen in the final trial that had not appeared in the previous trials. Consistent with the predictions of Load Theory, awareness of the critical stimulus was modulated by perceptual load: While nearly all (16/18) participants performing the low load task noticed the stimulus, only half of those performing the high load task noticed it. Visual perceptual load has also been found to modulate awareness of auditory stimuli, with high visual load inducing ‘inattentional deafness’ (Macdonald & Lavie, 2011).

To test whether visual load also modulates olfactory awareness, participants were presented with the same visual search task used by Cartwright-Finch and Lavie, while exposed to the ambient aroma of coffee. Immediately upon completion of the task, participants were taken to a different room and given a series of probes designed to elicit report of the olfactory stimulus, before being asked directly if they had noticed it. We predicted that the visual load of the task performed by the participants would predict awareness of the coffee aroma, with those in the high load condition having increased susceptibility to inattentional anosmia.

Experiment 1

Method

Participants. A sample size of 20 participants per condition of load was selected based on the effect sizes from previous demonstrations of perceptual load effects on awareness (Cartright-Finch & Lavie, 2006; Macdonald & Lavie, 2011) – this sample size was associated with power of .85 to detect the mean proportional group differences found across previous studies. Participants were recruited at the University of Sussex. Forty volunteer participants (5 male) aged 20-34 years ($M = 22$) took part in Experiment 1. All studies were approved by the University of Sussex Sciences & Technology Cross-Schools Research Ethics Committee.

Stimuli and Procedure. In order to create an odor stimulus, 180g of coffee beans were placed in the small and windowless testing room overnight prior to each day of testing (the beans were replaced each day). The beans were distributed between three open plastic containers, placed out of participants' sight. They remained in the testing room during the testing sessions.

Upon entering the dimly-lit testing room, the participants were seated at a computer and presented with a visual search task with either a high or low visual load. To minimize the risk of participants noticing the smell during the time between entering the room and starting the task (~90 seconds), the experimenter was careful to deliver the task instructions in an efficient manner, avoiding opportunities (e.g. pauses) for the participant's attention to wander. Note that a supplementary experiment (Experiment S1) clarified that only a minority (15-25% depending on the type of prompt) of participants report noticing the smell during this instruction period.

In order to control for any fluctuation in the level of olfactory stimulation across conditions, participants were allocated to load conditions in an alternating manner throughout the day and the daily order of testing (i.e., which condition was tested as the first session of the day) was counterbalanced with load. In both Experiments 1 and 2, the high and low load conditions did not significantly differ with respect to the time of the experimental testing session or the daily order of testing (all p s $> .250$). Furthermore, neither of these variables differed significantly for those participants who noticed the olfactory stimulus versus those who did not (all p s $> .250$). The visual search task was created and presented using E-Prime software (Version 2.0; Psychology Software Tools, Pittsburgh, PA). All of the stimuli were presented in light grey (RGB values 200, 200, 200) against a black background, on a 15 inch monitor at a viewing distance of approximately 57cm. Each trial began with a 500ms fixation point, immediately followed by a 100ms presentation of the stimulus display consisting of a target letter (either X or N, subtending $0.6^\circ \times 0.4^\circ$ of visual angle) arranged with five non-target letters in a circular formation around fixation (radius 1.6°). In the high load condition, the non-target letters were heterogeneous angular letters of similar dimensions to the target (selected in a pseudo-random manner from the set W, M, K, H, Z, V). In the low load condition, the non-target letters were all small Os (subtending $0.15^\circ \times 0.12^\circ$). Participants were instructed to search among the circle of letters for the target letter, and respond by pressing '0' for X and '2' for N.

In order to compare any effect of perceptual load on olfactory processing with previously established load effects, measures of both external distraction and mind wandering were also included in Experiment 1. To measure external visual distraction during the search task, a distractor letter (also either X or N, 0.8° by 0.5°) was presented to either the left or right of the circular search array, 1.4° from the nearest circle letter. This distractor letter was equally likely to be compatible (e.g., X when the target was X) or incompatible (e.g., X when the target was N) with the target. The participants were instructed to ignore the distractor, and to respond

as rapidly as possible without compromising on accuracy. A 90ms beep was heard either on incorrect responses, or when no response was detected within 3000ms. The participants completed three slow practice trials (stimuli onscreen until response) and two 24 trial practice blocks with the timing specified above, followed by 16 blocks of 48 trials. All combinations of target identity, distractor identity, target position, and distractor position were fully counterbalanced.

In order to measure mind wandering during the search task, participants were prompted at the end of each task block to report (by pressing A or Z, respectively) whether their thoughts were currently task-related or task-unrelated. Definitions and examples of both task related (e.g., “Where is the target letter?”) and task-unrelated (e.g., “I must stop by the supermarket on the way home.”) thoughts were given during task instructions. Participants were advised that there was no correct or incorrect response to these thought probes and that, in contrast to the search task, these responses did not need to be made under any time pressure.

Upon completing the computerised visual search task, the participants went into a different room where they were verbally asked to “describe the room you just completed the task in. Try and describe it using all of your senses”. The experimenter noted whether or not the description of the room included any mention of the olfactory stimulus. In order to be able to test for the possibility that the participants might have been aware of the olfactory stimulus yet not included it in their room description, the participants were then asked two more direct questions: First “Did you notice any odors in the room, if so what?”, and then “Could you smell coffee in the room?”. The participants were then asked to rate on five-point scales the extent to which their task-unrelated thoughts were related to odors in the room; how distracting, noticeable, and pleasant they found the odor, and how much the odor made them desire coffee. Next, they completed four questions about their general experiences of coffee: “Do you generally like the smell of coffee?” (responding on a scale from “not at all” to “very much so”),

“Do you drink coffee?” (on a scale from ‘never’ to ‘daily’), “Do you feel that you need coffee to feel at your best?” (responding from “not at all” to “very much so”), and “Have you had any coffee today (yes or no)?” A subset of participants (16, evenly distributed among load conditions) were then taken back to the testing room to confirm that they were able to detect the olfactory stimulus under conditions of full attention, when asked ‘What can you smell now?’

Results

Data for all experiments can be downloaded at

https://osf.io/27h68/?view_only=740f63bc2ebe459aa91dd2b05e1485fc.

Participant characteristics. All of the participants were able to detect the olfactory stimulus when taken back to the room during debriefing. Examination of the final questionnaire ratings confirmed that participants allocated to the high and low load condition did not differ in terms of their habitual coffee consumption, liking of the smell of coffee, or feelings of needing coffee ($p > .250$; see Table 1), nor in terms of whether they had yet consumed coffee that day (8 participants in high load, seven in low load, $p > .250$).

		High load		Low load	
		Mean	<i>S.E.</i>	Mean	<i>S.E.</i>
Expt 1	Do you generally like the smell of coffee? (1 = Not at all, 5 = Very much so)	4.20	0.25	4.35	0.21
	Do you drink coffee? (1 = Never, 5 = Daily)	3.30	0.40	3.50	0.36
	Do you feel that you need coffee to feel at your best? (1 = Not at all, 5 = Very much so)	2.15	0.30	2.25	0.35

Expt 2	Do you generally like the smell of coffee? (1 = Not at all, 5 = Very much so)	3.15	0.36	3.75	0.25
	Do you drink coffee? (1 = Never, 5 = Daily)	2.30	0.39	2.85	0.35
	Do you feel that you need coffee to feel at your best? (1 = Not at all, 5 = Very much so)	1.75	0.30	1.65	0.23
Expt 3	Do you generally like the smell of coffee? (1 = Not at all, 5 = Very much so)	3.40	0.29	3.65	0.25
	Do you drink coffee? (1 = Never, 5 = Daily)	2.25	0.36	2.50	0.34
	Do you feel that you need coffee to feel at your best? (1 = Not at all, 5 = Very much so)	1.35	0.15	1.90	0.32
Expt 4	Do you generally like the smell of coffee? (1 = Not at all, 5 = Very much so)	4.5	0.18	-	-
	Do you drink coffee? (1 = Never, 5 = Daily)	3.25	0.39	-	-
	Do you feel that you need coffee to feel at your best? (1 = Not at all, 5 = Very much so)	2.85	0.33	-	-

Table 1. Participant characteristics within each condition of perceptual load in Experiments 1-4.

Critical stimulus (CS) awareness. Participants were considered to be aware of the CS if they mentioned the smell of coffee in their description of the testing room. As can be seen in Figure 1, 60% of the participants who performed the low visual load task reported the olfactory stimulus. However, only 20% of those who performed the high visual load task reported the olfactory stimuli, representing a significant decrease in their olfactory awareness under high visual load, $\chi^2(1, N = 40) = 6.67, p = .010$, (two-tailed, as in all other experiments reported), $\phi = .41$. Note that participants in the low load condition were also significantly more likely to report the stimulus than those participants who were exposed the olfactory stimulus only during the instruction period during our Experiment S1, $\chi^2(1, N = 40) = 8.64, \phi = .46, p = .003$. On the other hand, the high load participants were no more likely to report awareness than participants in Experiment S1 ($p > .250$), suggesting that awareness of the olfactory stimulus increased during the course of the low load task, but not the high load task.

In response to the more specific questions: “Did you notice any odors in the room?” and “Could you smell coffee in the room?” three additional participants reported detecting the olfactory stimulus (one under high load and two under low load). Critically, the participants were significantly less likely to mention the smell of coffee in response to either question under high load as compared to low load (see Table 2). Strikingly, even when specifically asked whether they had smelled coffee 75% of those in the high load condition said no.

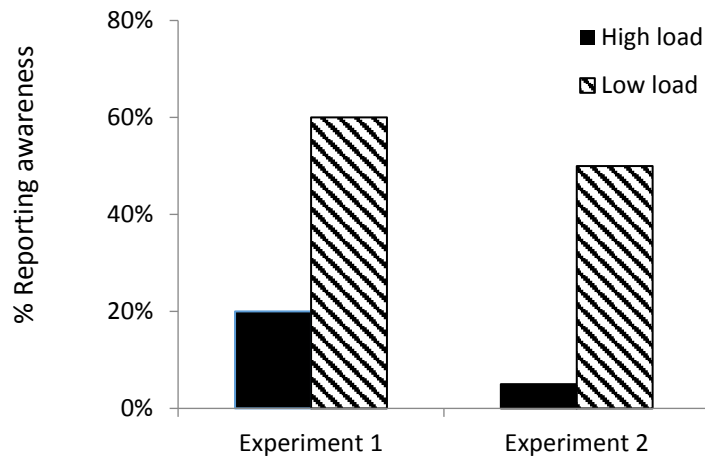


Figure 1. Percentage of participants indicating awareness of the olfactory stimulus in high and low load groups in Experiments 1 and 2 (N = 40 in each).

		High load	Low load	χ^2	p	ϕ
Expt 1	Did you notice any odors?	25%	60%	5.01	.025	.35
	Did you smell coffee?	25%	70%	8.12	.004	.45
Expt 2	Did you notice any odors?	5%	55%	11.91	.001	.55
	Did you smell coffee?	25%	60%	5.01	.025	.35

Table 2. Percentage of participants in high versus low load conditions who reported olfactory stimulus in response to follow up questions.

Visual search task performance, external distraction and mind wandering.

Reaction Times (RTs) under 100ms or over 1500ms were excluded from all analyses in all experiments. Mean RTs to correct responses and percentage error rates as a function of distractor condition and load are presented in Table 3. These measures were entered into two 2 x 2 mixed model Analyses of Variance (ANOVAs) with the within-participants factor of

distractor compatibility (compatible, incompatible) and the between-participants factor of load. For RTs, there was a main effect of load, $F(1, 38) = 21.96$, $p < .001$, reflecting slower RTs in the high load search task versus the low load search task. A main effect of compatibility was also found, $F(1, 38) = 52.34$, $p < .001$, indicating that the incompatible distractors (compared to compatible distractors) significantly slowed RTs. Replicating prior findings (e.g., Forster & Lavie, 2007; Lavie & Cox, 1997), this distractor effect was significantly reduced by the level of load in the visual search task, as reflected in an interaction between load by distractor compatibility, $F(1, 38) = 32.73$, $p < .001$, see Figure 2. Percentage error rates were also significantly slower in high versus low load, $F(1, 38) = 13.28$, $p = .001$; and in the incompatible versus compatible distractor condition, $F(1, 38) = 28.50$, $p < .001$. No load x distractor compatibility interaction was observed on the error measure, $F < 1$.

	High load				Low load			
	Incompatible		Compatible		Incompatible		Compatible	
	Mean	<i>S.E.</i>	Mean	<i>S.E.</i>	Mean	<i>S.E.</i>	Mean	<i>S.E.</i>
RT (ms)	732	18	727	18	615	26	567	22
% Errors	20	2	17	2	12	2	8	1

Table 3. Mean reaction times (RTs) and percentage error rates as a function of distractor compatibility and load in Experiment 1.

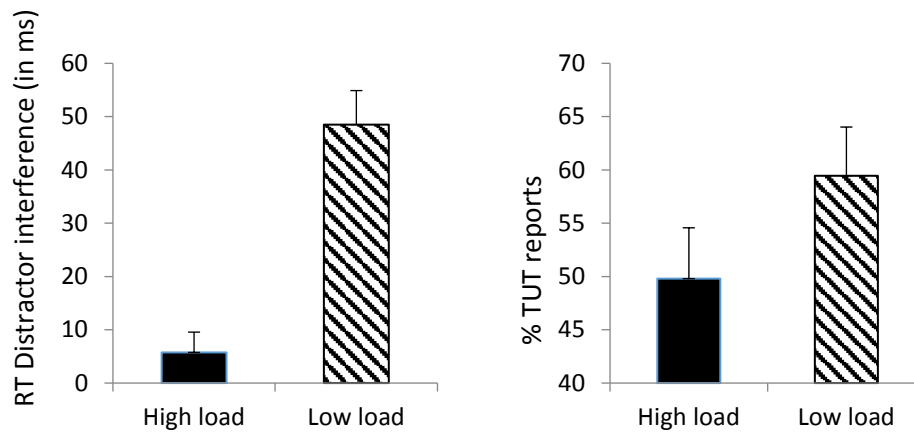


Figure 2: Reaction time (RT) distractor interference (Mean RT incompatible distractor – mean RT compatible distractor) and task-unrelated thoughts (TUT) in the high and low load groups in Experiment 1.

The percentage of thought probes at which participants reported mind-wandering (i.e., task-unrelated thoughts) varied between participants from 0-100%. The level of mind-wandering in each condition was similar to that observed in Forster and Lavie’s (2009) most similar previous experimental demonstration of visual load effects on mind-wandering (mean difference in the present study = 10%, mean difference in Forster and Lavie’s Experiment 4 = 11%). However, in contrast to the latter results (using a within-participant load manipulation), and perhaps due to the high between-participant variation in mind-wandering, this difference did not reach significance in the present between-participant manipulation of load, $t(38) = 1.46$, $p = .153$, 95% CI [-23.03-3.74].

Experiment 2

Experiment 1 demonstrates that a task with high visual load can reduce people’s awareness of olfactory stimuli, inducing a state of ‘inattentional anosmia’. Experiment 2 sought to replicate this finding with two changes. First, to rule out any potential interaction between load modulation of olfactory awareness and the additional measures of visual distraction and

mind wandering, these additional measures were removed. Second, to avoid any possible influence of the experimenter's tone of voice or facial expression on the awareness test, this test was presented in a written format.

Method

Participants. Forty participants (seven male) aged 19-26 years ($M = 21$) years took part.

Stimuli and procedure. All stimuli and procedure were identical to Experiment 1 with the following exceptions. No response competition distractors or thought probes were included in the visual search task. Participants performed 8 blocks of the main task. After the computer task, the first two follow-up questions were administered in written rather than verbal format: Participants first wrote down their description of the testing room, before being asked on a new sheet of paper whether they noticed any odors in the room. Participants were then verbally asked whether they had smelled coffee. Finally, participants rated their liking of the smell of coffee, frequency of coffee consumption, and need for coffee ("Do you feel that you need coffee to feel at your best?") as in Experiment 1, and indicated whether or not they had drunk coffee on the day of testing. All of the participants were then taken back to the testing room for the full attention test, which confirmed whether they could detect the olfactory stimulus.

Results

Participant characteristics. All participants indicated that they were able to detect the olfactory stimulus upon returning to the room during debriefing. As in Experiment 1, participants allocated to the high and low load conditions did not differ with respect to their habitual coffee consumption, liking of the smell of coffee, or feelings of needing coffee

($p > .250$, see Table 1), nor whether they had yet drunk coffee today (three low load, four high load, $p = .68$).

Visual search task performance. Mean RTs to correct responses and percentage error rates as a function of load are presented in Table 4. As in Experiment 1, participants performing the high load visual search task had higher RTs and higher % error rates compared to those in the low load condition: For RTs, $t(38) = 5.44$, $p < .001$; for errors, $t(38) = 5.49$, $p < .001$.

		High load		Low load	
Experiment		Mean	<i>S.E.</i>	Mean	<i>S.E.</i>
2	RT	717	24	543	22
	% Error rate	13	2	4	1
3	RT	647	26	497	10
	% Error rate	29	4	14	2

Table 4. Mean reaction times (RTs) and percentage error rates as a function of load in Experiments 2 and 3.

CS awareness. As can be seen in Figure 1, Experiment 2 replicated the key finding of significantly reduced olfactory awareness amongst those participants who performed the high visual load search task, compared to those who performed the low visual load search task, $\chi^2(1, N = 40) = 10.16$, $p = .001$, $\phi = .51$. As in Experiment 1, rates of awareness in the low load condition, but not the high load condition, were significantly higher than those among participants exposed to the stimulus only during the instruction period (control Experiment S1): For low load, $\chi^2(1, N = 40) = 5.58$, $p = .018$, $\phi = .37$, for high load $p > .250$.

As in Experiment 1, the two more specific follow-up questions also elicited significantly fewer reports of the olfactory stimulus in the high versus low load condition (see Table 2), confirming that participants had not simply failed to recognise or omitted to mention the olfactory stimulus.

Experiment 3

Experiments 1-2 demonstrate that an experimental manipulation of perceptual load can substantially reduce the likelihood that participants report awareness of an olfactory stimulus in a subsequent awareness test. Experiment 3 sought to test an alternative account of these findings in terms of load effects on memory rather than on awareness. It might be argued that participants in the high load condition noticed the smell during the initial instruction period, but that the high load task interfered with the consolidation of this memory. To test whether this account could explain our findings, Experiment 3 replicated the previous procedure with a key difference – the perceptual load task was administered in a different room to the olfactory stimulus, following initial exposure. If perceptual load interferes with memory consolidation, the high load group should exhibit reduced memory for the odor.

Method

Participants. Fifty-one participants (eight male) aged 18-25 ($M = 19$) years took part. As outlined below, in this experiment the awareness test and final full attention test were modified in order to clarify how many participants were able to independently identify the smell as coffee during the full attention test. The ability to independently identify the smell as coffee was an inclusion criterion for the load analysis, and the stopping rule was based on testing twenty participants in each condition who fulfilled this criterion.

Stimuli and procedure. All stimuli and procedure were identical to Experiment 2 with the following exceptions. Upon entering the first testing room, in which the olfactory stimulus was present as in previous experiments, participants were left alone for a short period corresponding to the duration of the instruction period in previous experiments (~ 90 seconds, see Experiment S1 for further examination of levels of awareness during this instruction period). Participants were then taken to a second room in which they completed either the high or low load visual search task. Two awareness test questions were then presented onscreen. As in previous experiments, the first question asked participants to describe the room that they sat in before moving into the present room, using all of their senses. Participants typed their response to this question before proceeding to a new screen that displayed the second question, which asked participants to describe any smells or odors that they noticed. Given that both previous experiments demonstrated consistent effects of perceptual load on all three of the awareness questions, the third question ('did you smell coffee?') was omitted from Experiment 3 – this allowed us to test whether participants could identify the smell of coffee in the final detection test without having been primed by this question. Following the awareness test questions, participants were prompted to get the experimenter who took them back to the first room (containing the olfactory stimulus), in which they completed a series of computerised questions testing whether they were able to detect and recognise the coffee odor when explicitly directed to do so under conditions of full attention. The first question asked 'Do you notice any smells or odors in the room now? If so please state what they are'. The next question asked 'Do you smell coffee now?'. Participants were then asked to rate the intensity of the odor by clicking on a labeled magnitude scale (Green et al, 1996). Finally, as in previous experiments, participants rated their liking of the smell of coffee, frequency of coffee consumption, need for coffee ("Do you feel that you need coffee to feel at your best?"), and indicated whether or not they had drunk coffee on the day of testing.

Results

Participant characteristics. During the final ‘full attention’ test, 78% participants independently identified the smell as demonstrated by typing the word ‘coffee’ in response to the prompt to report any smells or odors in the room. Of the eleven participants (two males, six high load, five low load) who did not independently identify the smell as coffee, eight reported some kind of food or smoke smell (for full qualitative responses see Supplement 2). Although all of these participants answered in the affirmative to the more specific subsequent question ‘Do you smell coffee?’, these participants were excluded from further analysis as they could presumably not have identified the coffee smell during the awareness test. We note that their exclusion did not change the results pertaining to the effects of load.

As in previous experiments, participants in the high and low load condition did not differ with respect to their habitual coffee consumption, liking of the smell of coffee, or feelings of needing coffee ($p > .250$, with the exception of needing coffee for which $p = .124$, see Table 1), nor whether they had yet drunk coffee today (5 low load, 3 high load, $p > .250$). They also rated the smell as of similar intensity ($M = 44\%$ low load, 50% high load, $p > .250$ – these ratings fall between the verbal labels of ‘strong’ and ‘very strong’, which are at 30% and 53% respectively).

Visual search task performance. Mean RTs to correct responses and percentage error rates as a function of load are presented in Table 4. As in previous experiments, both RTs and percentage error rates were significantly increased in the high load condition: For RTs $t(38) = 3.72$, $p = .001$; for errors, $t(38) = 5.35$, $p < .001$.

CS awareness. In sharp contrast to previous experiments, participants in the high load condition were no less likely to report the coffee smell in response to either of the awareness test questions – in fact the numerical trend was in the opposite direction: In response to the

first question, 25% of participants in the high load and 15% of participants in the low load mentioned the coffee smell ($p > .250$). In response to the second question, 40% of high load participants and 20% of low load participants reported awareness ($p = .168$). Hence, the data are clearly inconsistent with any alternative account in terms of the high load task interfering with the consolidation of olfactory memories formed during the short period before the task commenced.

As with previous demonstrations of inattentional blindness for unexpected stimuli, our findings cannot entirely rule out the possibility that the high load might have interfered with the consolidation of memories encoded during the task itself. However, if any such disruption of consolidation by the high load task was sufficiently powerful to explain the 42.5% drop in reporting rates between load conditions in the previous experiments, one might expect to observe some decrease in reporting rates among those participants who performed the high load condition compared to those tested immediately following initial exposure in Experiment S1. In contrast to this prediction, and as in the two previous experiments, noticing rates in the high load condition (40%) were not in any way diminished compared to those of participants tested immediately following initial exposure in the control condition of Experiment S1 (30%) – in fact they were numerically higher (although this difference was not significant, $p > .250$).

Experiment 4

As noted previously, the uniquely powerful nature of olfactory habituation suggests that the consequences of inattentional anosmia might well be more prolonged than those of inattentional blindness, with awareness diminished even beyond the period that attention is occupied. This possibility depends on the assumption that olfactory habituation can occur even while attention is engaged in a demanding task. Given that olfactory habituation occurs at the

cortical level, in the absence of any changes at receptor level (Mahmut & Stevenson, 2015), it was important to confirm this assumption. Experiment 4 therefore repeated the high load condition of previous experiments, but administered the awareness test while the participant was still exposed to the olfactory stimulus.

Method

Participants. 20 participants (five male) aged 18-33 ($M = 21$) years took part. Data from a further two participants (1 male, 1 female) were excluded due to their failure to detect the coffee smell even after having left and returned to the room.

Stimuli and procedure. The stimuli and procedure were similar to the high load condition of Experiment 2 with the following exceptions. Immediately following the visual search task (which took approximately 21 minutes), participants remained seated in the same room. The series of awareness test questions were presented onscreen (as in Experiment 3). The first two questions were as in previous experiments, except that participants were first asked to describe the room *they were currently in*, and next asked whether they noticed any smells or odors *in the room now*. The third question probed whether the participants remembered noticing smells or odors at any point during the computer task. In order to dishabituate to the olfactory stimulus, the participants then left the room to meet the experimenter and complete a payment form (for the first participant only, the question ‘Do you smell coffee now?’ was inadvertently included before leaving the room – the response was no). Participants then returned to the room where a further onscreen question asked whether they noticed any smells or odors in the room – correctly identifying the smell as coffee at this point was an inclusion criterion for analysis. Other questions were ‘Do you smell coffee now?’ and ‘Do you remember noticing the smell of coffee while performing the computer task?’ Finally, as in previous experiments, the participants rated their general liking

for the smell of coffee, frequency of coffee consumption and need for coffee, and indicated whether or not they had consumed coffee that day.

Results

Participant characteristics. Mean ratings of general liking and consumption of coffee are displayed in Table 1. Seven of the 20 participants had consumed coffee that day.

Visual search task performance. Visual search task performance was similar to the high load condition of previous experiments: mean RT to correct responses = 747 ms (S.E. = 23), mean percentage error rate = 15% (S.E. = 1).

CS awareness. Only a minority (30%) of the participants in Experiment 4 mentioned the coffee aroma in their room description, even though they were describing the room while still exposed to this smell and (as in previous experiments) were asked to use all of their senses in the description. When asked more specifically whether they noticed any smells or odors in the room, only one further participant reported the coffee smell. One additional participant responded that she did not notice a smell, but looked under the table and discovered the coffee beans which led her to ‘feel like’ she smelt them (although she indicated verbally after leaving the room that she was not sure whether or not she could actually smell them, and exclaimed in surprise upon re-entering the room at how strong the smell was). Regardless of how the response of this last participant is interpreted, the majority (either 60 or 65%) of participants appeared to have habituated to the olfactory stimulus despite their attention having been engaged in the high load search task.

In response to the additional question about memory of smells during the task, five of the seven participants who detected the coffee smell indicated that they also remembered noticing the smell during the task. Hence, while the majority of participants failed to notice the coffee smell, those who did notice it mostly reported having been aware throughout the

experiment rather than only in response to the smell prompt. One additional participant gave an ambiguous answer to the memory question: ‘around block I thought I noticed a smell of coffee’ – given that this participant did not report coffee when asked specifically about current smells this response seems to refer to an olfactory stimulus encountered outside of the testing room (a cafe was located ‘around the block’ from the testing lab).

Discussion

The results of the present study establish the phenomenon of inattentional anosmia for the first time – an olfactory analogue of inattentional blindness. Across three experiments, more than half of the participants failed to report having noticed the smell of coffee in their testing room. This was the case even when they were directly asked whether or not they had smelled coffee. Critically, the likelihood that a participant would notice the smell of coffee was significantly, and substantially, influenced by the visual demands of the search task that they performed: Across Experiments 1-2, 42.5% fewer participants in the high load condition, compared to the low load condition, reported awareness of the smell. As such, we demonstrate using a well-established attentional manipulation (perceptual load) that awareness of unexpected olfactory stimuli depends on the availability of attention.

In real-world terms, our study implies that people are significantly less likely to notice ambient smells in their surroundings when they are engaged in a visually-demanding task. Furthermore, Experiment 4 confirms that olfactory habituation can occur while attention is occupied, with the result that inattentional anosmia can lead smells to go undetected even once attention becomes available. As such, the potential consequences of inattentional anosmia appear more profound than those of inattentional blindness.

This study builds on the small but growing research field of olfactory attention, by demonstrating that attention not only enhances olfactory processing in a top-down manner, but also acts as a critical gateway to awareness of unexpected olfactory stimuli. There are

conflicting views regarding the similarity of olfactory attention to visual and auditory attention (Keller, 2011; Sela & Sobel, 2010). The present study reveals that olfactory attention shares a key common characteristic with visual and auditory attention, in terms of the effect of perceptual capacity limits on irrelevant processing. We also extend the Load Theory of attention to the olfactory domain for the first time.

Our finding of a powerful determinant of olfactory awareness has implications for a number of research/application fields. Given the central role of olfaction in eating behaviours, the present findings have implications for this literature. For example, engagement in visually-demanding tasks may be helpful for individuals wishing to avoid temptation by enticing smells. Inattentional anosmia could also be dangerous in certain situations (e.g., failing to notice the smell of gas or smoke). A valuable direction for future work would be to test whether visually demanding tasks can also impede detection of unpleasant or threat-signalling odors (cf. Baus & Bouchard, 2016; Boesveldt et al., 2010; Brauchli et al., 1995 for important differences between the processing of pleasant and unpleasant odors). Such a finding would have critical implications for accident prediction and prevention.

In summary, in the present study, we establish the phenomenon of inattentional anosmia, and clarify that olfactory awareness is dependent on the availability of attentional capacity. These findings create an important new link between the study of olfactory attention and the large existing literature on visual attention. Our results demonstrate a task-load based framework which can be adapted for predicting and manipulating olfactory awareness in both applied settings and future research.

Author contributions

S. Forster was responsible for the overall study concept and design, overseeing data collection, and performing all analyses. C. Spence suggested the concept for Experiment 4 with both authors contributing to data interpretation. S. Forster drafted the manuscript and C. Spence provided critical revisions. Both authors approved the final version of the manuscript.

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