Journal of Neuroradiology 53 (2026) 101529

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Original Article

Smelling decides: fMRI evidence reveals the influence of olfactory stimuli on risky decision-making

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ARTICLE INFO

Keywords:
Risky decision-making
fMRI
Functional connectivity
Olfactory stimuli
Gambling

ABSTRACT

Background and purpose: Olfactory stimuli are known to have a significant effect on cognitive functions. However, their effect on risky decision-making remains unclear. The present study aimed to investigate this effect, using functional magnetic resonance imaging (fMRI) and a novel mixed gambling task.
Materials and Methods: Twenty-nine healthy participants with normal olfactory function underwent fMRI scanning while performing a gambling task under exposure to pleasant and unpleasant odors, as well as fresh air and a neutral condition without any olfactory stimulation. ROI-to-ROI functional connectivity analyses were conducted, focusing on regions involved in olfactory processing and risky decision-making, including dorsolateral prefrontal cortex (DLPFC), ventromedial prefrontal cortex (vmPFC), orbitofrontal cortex (OFC), insula, anterior cingulate cortex (ACC), piriform cortex, and uncus.
Results: Pleasant odors, compared to the neutral condition, enhanced connectivity between OFC and vmPFC. Fresh air, compared to neutral, reduced connectivity between the DLPFC, OFC, vmPFC, piriform and insula, while increasing connectivity between the piriform and uncus. Unpleasant odors, compared to neutral, increased connectivity between the vmPFC, OFC, and ACC. Unpleasant odors, compared to fresh air, enhanced connectivity between the DLPFC and insula but reduced connectivity between the insula and OFC. Pleasant odors, compared to unpleasant odors, increased connectivity between the insula and OFC (p-FDR < 0.05).
Conclusion: Olfactory stimuli modulate neural networks underlying risky decision-making during a mixed gambling task. These findings highlight the clinical relevance of olfactory modulation for addiction research and the potential of functional connectivity analyses to provide a foundation for personalised interventions aimed at reducing maladaptive risk-taking behavior and cue-driven vulnerability.

Introduction

Decision-making is a complex cognitive function influenced by factors such as individual traits, demographic characteristics, beliefs, and past experiences.[1–4] Among the various aspects of decision-making, those associated with risks (i.e., risky decision-making) are a common part of our daily interactions. Risky decision-making refers to choices made between alternatives with uncertain outcomes that depend on changing circumstances and their probabilities.[5]

While the influence of social and cultural factors on risky decision-making has been widely studied, the role of intrinsic sensory factors and their effect on neural correlates of risky decision-making remains less understood. One such overlooked factor is olfaction. Olfaction has been shown to strongly influence a wide range of cognitive processes.[6–14] Evidence indicates that certain odors enhance cognitive functions, including memory, attention, pain perception, self-perception, and alertness.[10–19] Yet, the influence of olfactory stimuli on risky decision-making remains underexplored.[20–22]

Current literature has provided partial insights into how odors influence decision-making. For instance, exposure to mint aroma has been shown to reduce risk-taking behaviors[23], whereas a gambling study found that participants exposed to pleasant odors were more likely to engage in gambling behavior.[24] Neuroimaging findings show that olfactory information is initially processed in primary olfactory regions, including the piriform cortex and uncus, which play a key role in encoding odor identity and affective significance and maintain strong anatomical and functional connections with limbic and prefrontal regions.[25–28]

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https://doi.org/10.1016/j.neurad.2026.101529
Available online 5 February 2026

Beyond primary olfactory processing, the left orbitofrontal cortex (OFC) has been consistently implicated in value-based decision-making during exposure to olfactory stimuli.[29] Additionally, olfactory stimulation can increase activation in the anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (DLPFC) during decision-making tasks.[30] Another study found that unpleasant odors were associated with increased activation in the ventromedial prefrontal cortex (vmPFC) during moral decision-making tasks.[31] Further studies revealed an increase in the activation of DLPFC, and insula when participants were assessing the intensity and pleasantness of olfactory stimuli.[32] However, these studies primarily examined localised activation patterns and offer limited understanding of how olfactory stimuli alter the functional interactions between brain regions involved in olfactory processing and risky decision-making.

Functional magnetic resonance imaging (fMRI) is a widely used technique to study the neural processes involved in decision-making.[33] While traditional task-based fMRI analyses identify region-specific activations, they do not fully capture the dynamic connectivity between regions that supports complex cognitive processes. Functional connectivity analyses, provide a means to assess coordinated activity across distributed neural networks during cognitive processes, including risky decision-making.[34] Importantly, the sensitivity of task-based fMRI to such network dynamics depends not only on the analytical approach but also on the behavioral paradigm employed. While some tasks like the Monetary Incentive Delay (MID) task are widely used for isolating the neural correlates of reward anticipation and outcome processing, they primarily engage incentive-motivational circuitry rather than the active evaluative processes required for risky decision-making.[35, 36] In contrast, gambling paradigms directly engage decision-making under uncertainty by requiring explicit evaluation of potential gains and losses at the moment of choice, and recruiting neural systems involved in risk appraisal and value comparison.[37–39]

We sought to address the current gaps by developing a novel fMRI paradigm that integrates a gambling task with olfactory stimulation to investigate how different olfactory stimuli (pleasant, unpleasant, and fresh air) modulate patterns of functional connectivity within brain regions involved in olfactory processing and risky decision-making.

Method and material

Participants

Thirty-four healthy individuals aged 18–40 were initially screened for participation in this study. Eligibility was determined by two primary criteria: (1) a minimum of twelve years of formal education and (2) normal olfactory function. Exclusion criteria were defined as follows: (1) broncho-pulmonary or neurological conditions, (2) chronic pain, (3) pregnancy or breastfeeding status, (4) current cold or allergy symptoms, (5) an allergy to perfumes, (6) current use of analgesic medication including non-prescription drugs, (7) failure in an olfactory assessment, (8) MRI incompatibilities such as metal implants or claustrophobia, (9) a history of head trauma leading to neurological consequences, or (10) any neurological disorder that might influence the outcome of the study. Participants were also instructed to avoid wearing scented products on the day of testing. All procedures adhered to the Declaration of Helsinki guidelines, with data anonymised prior to analysis. Ethical approval was obtained from the Iran University of Medical Sciences, under the code IR.IUMS.FMD.REC.1400.101.

Measures and questionnaires

Potential participants underwent a medical evaluation by a physician. Demographic data were collected prior to any scanning procedures. Before the imaging session, participants familiarised themselves with the gambling task at the Iran University of Medical Sciences laboratory, emphasising both speed and accuracy of task performance. Olfactory function was assessed using the Sniffin Sticks test kit (Burghart Instruments, Wedemark, Germany). This kit comprises three subtests, measuring odor threshold, odor discrimination, and odor identification. Odors were presented using pen-like instruments, following standardised protocols.[40–42] For determining odor detection thresholds, a single-staircase, three-alternative forced-choice procedure was employed. The odor discrimination subtest consisted of 16 trials, each presenting participants with three different odorants. Within each set, two odorants were identical, and one was different. Participants were asked to identify the distinct odorant. In the odor identification subtest, participants were exposed to 16 common odors and asked to select the correct descriptor from four possible options. Scoring was based on established guidelines: the odor detection threshold ranged from 1 to 16 points, while the discrimination and identification subtests each ranged from 0 to 16 points. The sum of all three subtests produced the Threshold–Discrimination–Identification (TDI) score. A TDI score of 30.5 or above indicated normosmia; scores between 16.5 and 30 suggested hyposmia; and scores below 16 were indicative of functional anosmia.[43]

fMRI gambling task

Fig. 1 shows the experimental design of the fMRI task and the study protocol. Participants underwent two consecutive fMRI runs implementing a block-design gambling task, followed by resting blocks displaying a fixation cross. Within each run, four 60-second blocks were presented, and in each block, participants performed four gambling trials. In each trial, participants were presented with four selectable values ($A = 0$, $B = 5$, $C = 15$, $D = 25$) and were asked to combine these values in any way they preferred, such as choosing multiple instances of the same value or mixing different ones, to calculate a total sum within 13 s using a button box. Each trial was followed by a jittered interstimulus interval (ISI), which averaged 1 s. When the calculated sum was within 10 units of a computer-generated target, the feedback "You won!" appeared; otherwise, "You lost!" was displayed. The task consisted of four experimental conditions: The first, neutral condition, exposed participants to the ambient air in the scanner without added scents or airflow modulation. The second, pleasant odor condition, introduced a vanilla scent (vanilla diluted in a solution of ethanol and water (200gr per liter)), through an olfactometer described in the section below. The third, fresh air condition, delivered an increased flow of unscented air, distinguishing it from the neutral state. The final, unpleasant odor condition, presented the odor of phenol glycerin (6.4 % phenol in glycerin base, $C_9H_{12}O_3$). Each task block was separated by an 87-second rest period indicated by a white cross on a black background. Each run lasted 9 min and 48 s.

Olfactometer setup

Olfactory stimuli were delivered using a custom-built olfactometer comprising an air supply, control unit, and airflow distribution system (Fig. 1). Filtered and odorless air (30 L/min) was regulated and divided into eight channels, each connected to an odor reservoir via solenoid valves. During stimulation, the air stream (4 L/min) passed through the selected odor chamber (vanilla or phenol glycerin) and was conveyed via a 4-meter silicone tube (inner diameter = 4 mm [mm]) to a nasal mask fitted on the participant's face in the scanner. The olfactometer was deactivated during the neutral condition.

Scanning parameters

Scanning was conducted in a 3.0 Tesla (Siemens, MAGNETOM Prisma; Germany) MR-system at the National Brain Mapping Laboratory, Tehran, Iran. Structural T1-weighted images were acquired in a sagittal orientation employing a magnetisation-prepared rapid gradient-echo (MP-RAGE) sequence with the following parameters: Repetition Time = 1830 milliseconds (ms), Echo Time = 3.5 ms, field of view (FOV) = 256 cm × 256 cm, flip angle (FA) = 7°, 1 mm3 voxels. A

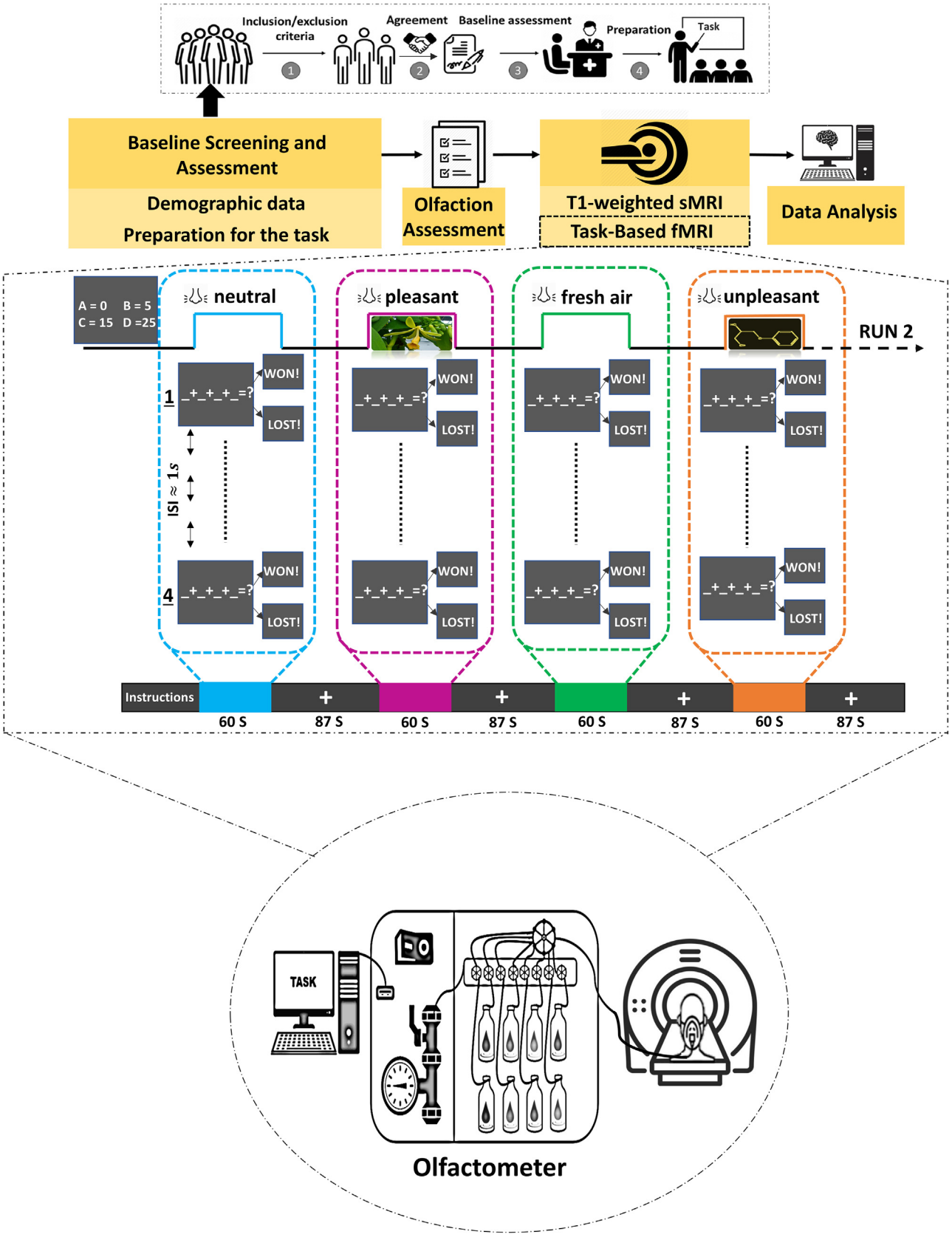

Fig. 1. Task design and study protocol.

gradient-echo-planar imaging (GRE-EPI) sequence with the following parameters was used to obtain functional MRI data: TR = 2000 ms, TE = 30 ms, FOV = 192 192, FA = 80, and in-plane voxel size of 2 mm.

fMRI data analysis

Initial preprocessing of functional images was performed using the fMRI Expert Analysis Tool (FEAT), a component of the FMRIB Software Library (version 6.0.3), while subsequent denoising and all functional connectivity analyses were conducted in the CONN toolbox. The preprocessing procedure, using FEAT, consisted of the following steps: (1) skull-stripping to remove nonbrain tissue from structural T1-weighted images using the Brain Extraction Tool (BET) with default values; (2) interleaved slice-timing correction; (3) motion correction with 6 degrees of freedom (DOF); (4) registration of the functional images to individual structural images using FMRIB's Linear Image Registration (FLIRT) and Boundary Registration (BBR) cost function; (5) normalization of structural images to MNI standard space; (6) spatial smoothing with a Gaussian kernel with a full-width at half maximum (FWHM) of 4 mm; (7) multiplicative normalization of the volume's mean intensity at each time point; (8) high-pass temporal filtering (Gaussian weighted least-squares straight-line fitting, with an Inverse of = 120.0 s). Analyses of functional connectivity were conducted with the CONN toolbox (version 20.b, www.nitrc.org/projects/conn, RRID:SCR 009,550)[44] in Statistical Parametric Mapping toolbox (SPM8, Wellcome Centre for Human Neuroimaging, University College London, UK; www.fil.ion.ucl.ac.uk/spm). In accordance with the standard scrubbing procedures for the removal of confounders in the CONN toolbox, the nuisance regression included motion parameters, linear detrending, and aCompCor components derived from white matter and cerebrospinal fluid signals.[45] Time series were temporally filtered using a band-pass filter of 0.008−0.09 Hz.[46]

Regions of interest (ROIs) were defined based on their established involvement in olfactory processing and decision-making networks and included the dorsolateral prefrontal cortex (DLPFC), orbitofrontal cortex (OFC), anterior cingulate cortex (ACC), insula, ventromedial prefrontal cortex (vmPFC), piriform cortex, and uncus. The DLPFC mask was extracted using the Brainnetome Atlas[47], specifically targeting subregions A9l (lateral Area 9) and A46 (Area 46) in line with previous studies.[48–51] Anatomical masks of OFC, insula, and ACC were defined bilaterally using the Automated Anatomical Labeling (AAL) atlases[52], and extracted using the WFU PickAtlas toolbox (http://fmri.wfubmc.edu/software/PickAtlas) in MATLAB 2021a (https://www.mathworks.com/products/matlab.html) and FSLeyes (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/FSLeyes). The bilateral mask of vmPFC was created by combining bilateral orbital frontal regions and rectus regions from the AAL atlas.[53, 54] The bilateral mask of piriform cortex was defined as 10 mm radius spheres centered at MNI coordinates [−22, 0, 14] and [22, 2, 12], which have been previously reported to show activation during olfactory stimulation.[55–57] The bilateral mask of uncus was defined as 10 mm radius spheres centered at MNI coordinates [14, −12, −22] and [−16, −12, −24].[58]

Condition-specific regressors (neutral, pleasant odor, fresh air, unpleasant odor) were modeled using their respective onsets and durations and convolved with a canonical hemodynamic response function. ROI-to-ROI functional connectivity was computed using Fisher z-transformed correlation coefficients between ROI time series for each condition.

At the second level, ROI-to-ROI connectivity analyses were performed using general linear models (GLMs) implemented in the CONN toolbox. To account for potential gender-related effects on functional connectivity, gender was included as a covariate of no interest in all second-level analyses. Connectivity differences between conditions were assessed using contrast-based *t*-tests, with statistical significance determined using false discovery rate (FDR) correction across ROI-to-ROI connections at p-FDR < 0.05.

Results

Participants characteristics

Out of the initial thirty-four participants, four participants did not meet the inclusion criteria, and data from one additional participant were excluded due to excessive motion during scanning. Consequently, data from 29 participants (16 females; mean age = 24.76 years) were included in the final fMRI analysis (Table 1).

Olfaction assessment

Results of the Sniffin' Sticks test indicated normal olfactory function across all participants, with comparable performance between males and females (Table 1).

ROI-to-ROI functional connectivity

pleasant odor > neutral

In the pleasant odor > neutral contrast, increased connectivity was observed between the OFC as the seed region and vmPFC (t-value = 3.30, p-FDR = 0.0165) (Fig. 2, Table 2).

fresh air > neutral

This contrast revealed increased connectivity between piriform and uncus (t-value = 2.93, p-FDR = 0.0204), OFC and vmPFC (t-value = 3.47, p-FDR = 0.0053), and between vmPFC and insula (t-value = 2.57, p-FDR = 0.0321). In addition, decreased connectivity was observed between DLPFC as seed region and OFC (t-value = −3.73, p-FDR = 0.0053), piriform (t-value = −3.10, p-FDR = 0.0136), vmPFC (t-value = −2.89, p-FDR = 0.0151), and insula (t-value = −2.25, p-FDR = 0.0495) (Fig. 3, Table 2).

unpleasant odor > neutral

This contrast showed an increased connectivity between vmPFC as seed region and ACC (t-value = 2.80, p-FDR = 0.0284), and OFC (t-value = 2.79, p-FDR = 0.0284) (Fig. 4, Table 2).

unpleasant odor > fresh air

This contrast revealed increased functional connectivity between DLPFC and insula (t-value = −3.89, p-FDR = 0.0035) and decreased connectivity between insula and OFC (t-value = −2.96, p-FDR = 0.0190) (Fig. 5, Table 2).

pleasant odor > unpleasant odor

This contrast showed increased connectivity between insula and OFC (t-value = 3.04, p-FDR = 0.0309) (Fig. 6, Table 2).

Discussion

This study investigated how different olfactory stimuli modulate neural connectivity underlying risky decision-making, using a novel mixed

Table 1
Demographic characteristics and olfactory performance of participants (n = 29).

Variables	Male (n = 13)	Female (n = 16)
Age (years)	25.15 (3.31)	23.81 (3.56)
Education (years)	17.38 (1.60)	17 (2.12)
Smelling Threshold	9.41 (2.39)	9.27 (2.05)
Smelling Detection	13.47 (1.51)	13.35 (1.64)
Smelling Identification	13.91 (1.91)	13.83 (1.43)
TDI	36.79 (1.51)	36.45 (1.71)

Note: values are denoted as mean (SD).

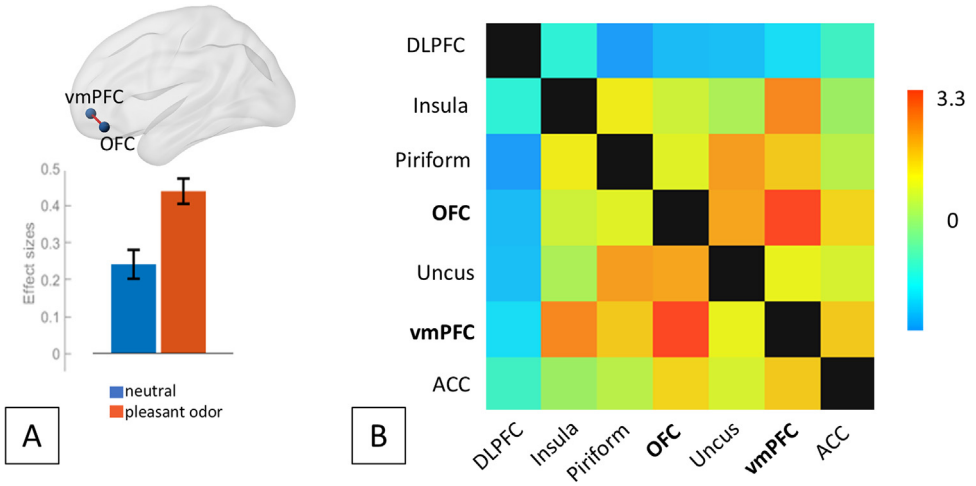

Fig. 2. pleasant odor > neutral contrast.

(A) Effect-size plot showing Fisher z−transformed ROI-to-ROI connectivity across conditions (p-FDR < 0.05). Error bars indicate standard error of the mean.

(B) ROI-to-ROI correlation matrix showing correlation coefficients for each of the 7 × 7 ROI correlations in pleasant odor > neutral contrast. Significant increased connectivity was observed between OFC and vmPFC (p-FDR < 0.05). Colors indicate the magnitude of the T statistic.

fMRI gambling paradigm in healthy participants with normal olfactory function.

pleasant odor > neutral

Results of this contrast revealed enhanced connectivity between the OFC and vmPFC. The increased interaction between the OFC and vmPFC observed here reflects the integration of affective value and sensory information, consistent with evidence that both regions contribute to the evaluation of odor pleasantness.[58–60]; This pattern of connectivity further supports the validity of the task in engaging affective aspects of olfactory processing. vmPFC is also involved in value-based and risky decision-making processes[61–65], suggesting that its engagement here may also show it's involvement in reward valuation and outcome anticipation. In parallel, OFC plays a key role in evaluating stimulus value (e.g., reward) and learning stimulus-outcome associations, and disruption in its function have been linked to the risky decision-making and challenges in outcome anticipation.[66–79] Enhanced connectivity between these regions suggests stronger integration of affective and evaluative processes when participants were exposed to pleasant odor.

Table 2
Results of ROI-to-ROI connectivity analyses across participants (n = 29).

Contrast	Seed region	Target region	t-value	p-FDR
pleasant > neutral	OFC	vmPFC	3.30	0.0165
fresh air > neutral	DLPFC	OFC	−3.73	0.0053
		Piriform	−3.10	0.0136
		vmPFC	−2.89	0.0151
		Insula	−2.25	0.0495
	Piriform	Uncus	2.93	0.0204
	OFC	vmPFC	3.47	0.0053
	vmPFC	Insula	2.57	0.0321
unpleasant > neutral	vmPFC	ACC	2.80	0.0284
		OFC	2.79	0.0284
unpleasant > fresh air	DLPFC	Insula	3.89	0.0035
	Insula	OFC	−2.96	0.0190
pleasant > unpleasant	Insula	OFC	3.04	0.0309

Notes: The table lists significant ROI-to-ROI connectivity effects (p-FDR < 0.05). The p-FDR column indicates FDR-corrected p-values across connections. The t-value column reports the second-level t-statistic associated with each connectivity effect. Seed and target regions refer to the predefined regions of interest included in the ROI-to-ROI analysis. Contrasts indicate the experimental condition comparisons.

fresh air > neutral

This contrast revealed a pattern of decrease in connectivity between the DLPFC and OFC, piriform, vmPFC, and insula. Previous research indicated that activation of DLPFC associates with decision-making abilities.[80–83] Reduced functional connectivity between the DLPFC and other cortical regions observed under the fresh air condition may indicate a more optimized engagement of prefrontal control networks during the risky decision-making process.[84]

In contrast, increased connectivity was observed between the OFC and vmPFC, between the vmPFC and insula, and between piriform and uncus. Increased connectivity between the vmPFC and insula underscores the role of the insula in relaying sensory information, including olfactory inputs, from somatosensory regions to the vmPFC.[85] The insula is also recognised for its involvement in diverse decision-making functions, including attention, value evaluation, choice determination, and reward processing.[86–91] Moreover, prior studies have highlighted the role of the insula in activating representations of homeostatic states related to the perception of risk, which subsequently impacts decision-making processes.[92]

The piriform cortex, a key region of the olfactory network, processes information derived from olfactory stimuli and is associated with tasks like odor categorisation and identification.[93] Uncus covers the anterior part of the parahippocampal gyrus known as the entorhinal cortex[94], which is part of the primary olfactory cortex. The observed connectivity between the piriform and uncus, supports prior evidence that the piriform cortex receives top-down modulatory input from the entorhinal cortex, reflecting their role in integrating olfactory information.[95]

unpleasant odor > neutral

Results of this contrast revealed increased connectivity between the vmPFC, taken as the seed region, and both the right OFC and right ACC. As discussed earlier, the increased connectivity between vmPFC and OFC, serves as a marker of odor recognition. Notably, there was an increased connectivity between the right ACC and vmPFC. Previous studies suggest that activation of ACC correlates with proficient decision-making, effective action-outcome learning, and efficient reward processing.[32,96–102] Activation of ACC has also been shown to increase in relation to the difficulty of decision-making, potentially induced by

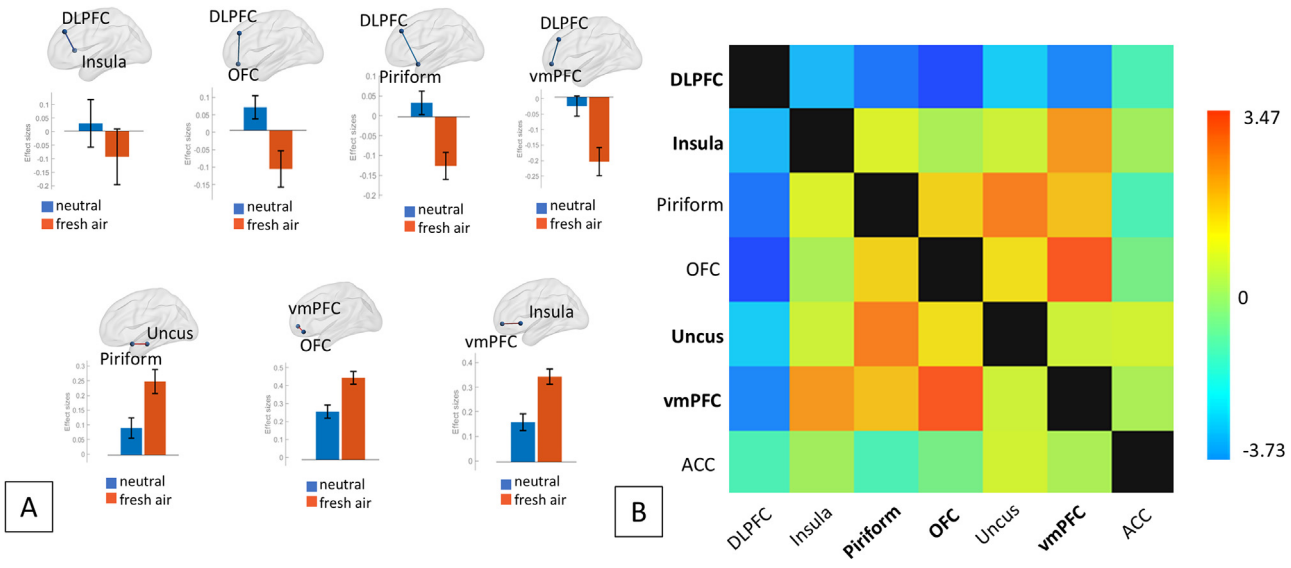

Fig. 3. fresh air > neutral contrast.

(A) Effect-size plot showing Fisher z−transformed ROI-to-ROI connectivity across conditions (p-FDR < 0.05). Error bars indicate standard error of the mean.

(B) ROI-to-ROI correlation matrix showing correlation coefficients for each of the 7 × 7 ROI correlations in fresh air > neutral contrast. Significant increased connectivity was observed between piriform and uncus, OFC and vmPFC, and between vmPFC and insula (p-FDR < 0.05). Significant decreased connectivity was observed between DLPFC and OFC, piriform, vmPFC, and insula (p-FDR < 0.05). Colors indicate the magnitude of the T statistic.

unpleasant odors.[103] The observed increase in functional connectivity may reflect heightened cognitive demand or decision-making difficulty, consistent with prior evidence that stronger functional connectivity might occur under greater task complexity.[104,105]

unpleasant odor > fresh air

This contrast showed enhanced connectivity between the DLPFC and the left insula, but decreased connectivity between the insula and left OFC. As previously discussed, both the DLPFC and insula are recognised as key regions for decision-making.[83,106–108] In addition, some previous research suggests a notable positive correlation between the activation of DLPFC and the complexity of decision-making.[80–82] The insula has also been shown to increase its activity with greater difficulty of decision-making.[109] Given this, the increased connectivity between the insula and DLPFC when exposed to unpleasant odors, compared to fresh air, suggests an increased challenge in risky decision-making. In contrast, reduced connectivity between the insula and left OFC might reflect the impaired integration between value perception, risk assessment and outcome prediction.[110,111]

pleasant odor > unpleasant odor

This contrast revealed enhanced connectivity between the insula and right OFC. Previous literature has shown that both insula and OFC are more activated during risky decision-making.[112–116] As discussed earlier, the OFC is involved in value perception, and its increased connectivity with the insula, which is involved in risk assessment, may reflect a more integrated evaluation of reward value and potential risk, which facilitates risky decision-making.[68,69,83,117]

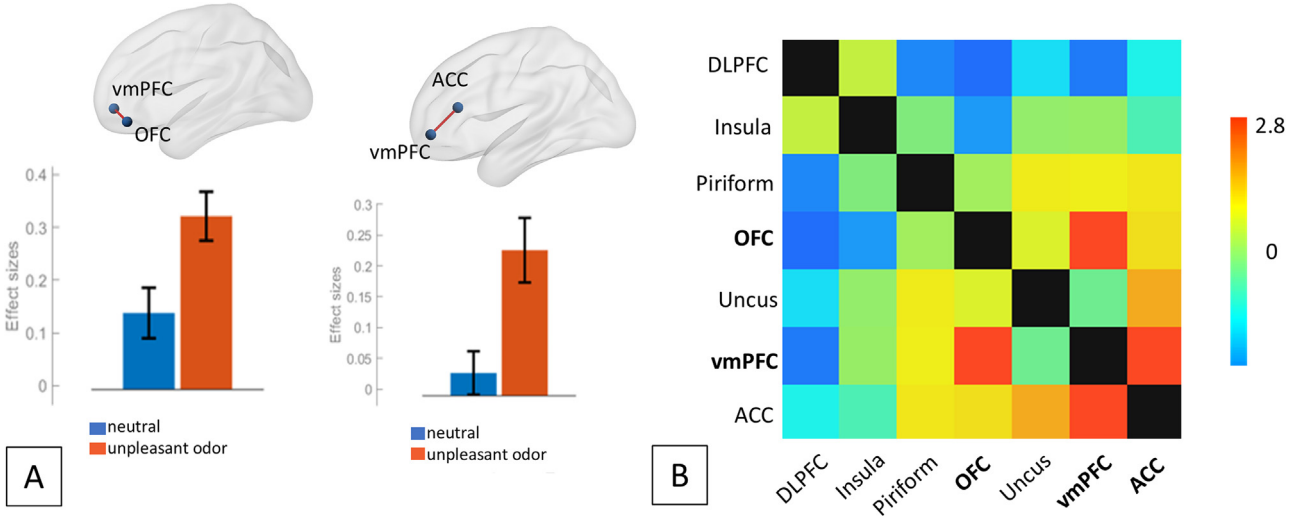

Fig. 4. unpleasant odor > neutral contrast.

(A) Effect-size plot showing Fisher z−transformed ROI-to-ROI connectivity across conditions (p-FDR < 0.05). Error bars indicate standard error of the mean.

(B) ROI-to-ROI correlation matrix showing correlation coefficients for each of the 7 × 7 ROI correlations in unpleasant odor > neutral contrast. Significant increased connectivity was observed between vmPFC and ACC, and between vmPFC and OFC (p-FDR < 0.05). Colors indicate the magnitude of the T statistic.

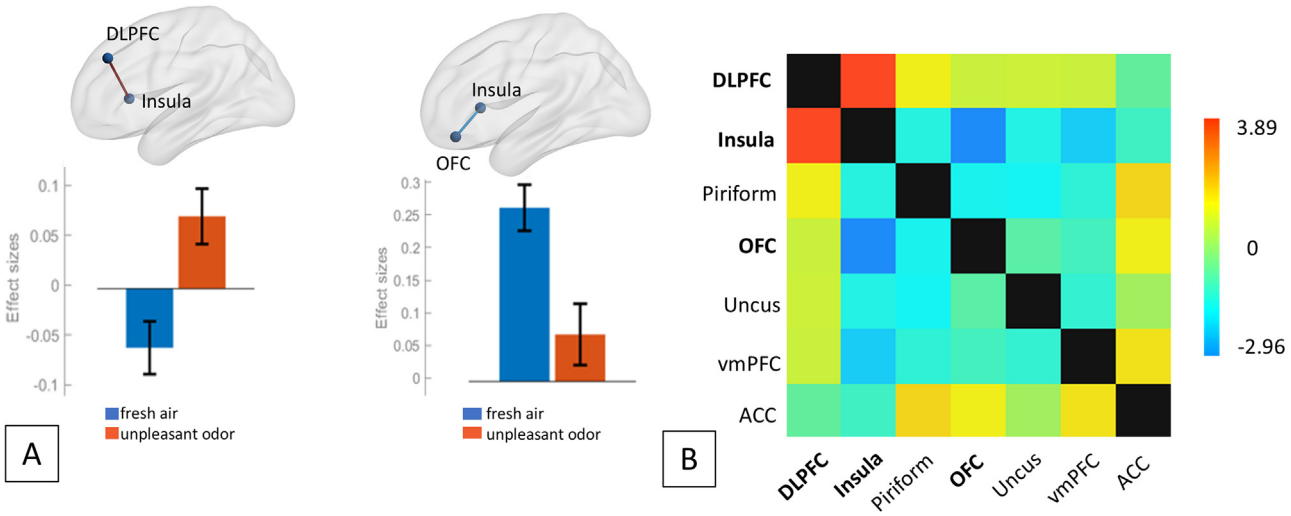

Fig. 5. unpleasant odor > fresh air contrast.

(A) Effect-size plot showing Fisher z−transformed ROI-to-ROI connectivity across conditions (p-FDR < 0.05). Error bars indicate standard error of the mean.

(B) ROI-to-ROI correlation matrix showing correlation coefficients for each of the 7 × 7 ROI correlations in unpleasant odor > fresh air contrast. Significant increased connectivity was observed between DLPFC and Insula (p-FDR < 0.05). Significant decreased connectivity was observed between Insula and OFC (p-FDR < 0.05). Colors indicate the magnitude of the T statistic.

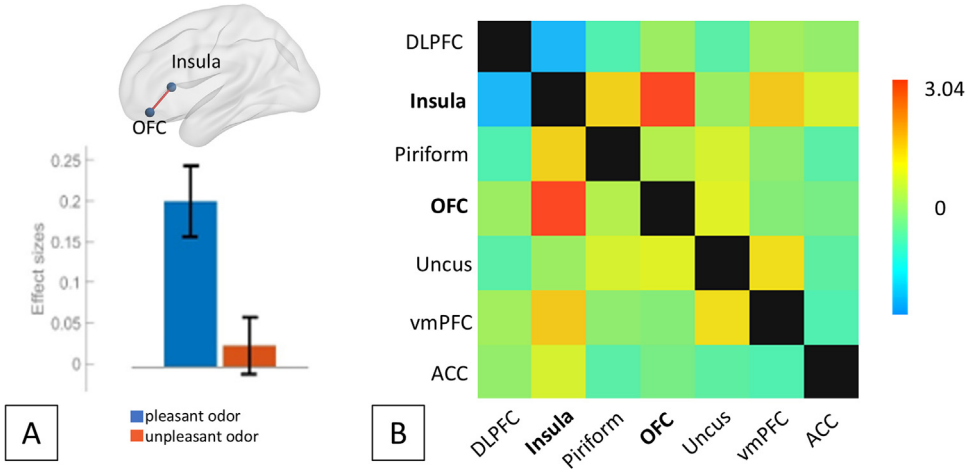

Fig. 6. pleasant odor > unpleasant odor contrast.

(A) Effect-size plot showing Fisher z−transformed ROI-to-ROI connectivity across conditions (p-FDR < 0.05). Error bars indicate standard error of the mean.

(B) ROI-to-ROI correlation matrix showing correlation coefficients for each of the 7 × 7 ROI correlations in pleasant odor > unpleasant odor contrast. Significant increased connectivity was observed between Insula and OFC (p-FDR < 0.05). Colors indicate the magnitude of the T statistic.

Conclusion

This is the first fMRI study to investigate how olfactory stimuli influence neural networks underlying risky decision-making, using a novel mixed gambling task. The findings demonstrate the sensitivity of decision-related networks to sensory environmental cues and highlight the clinical relevance of olfactory modulation for addiction research, including gambling disorder. Moreover, this study highlights the potential of functional connectivity analyses to characterise how sensory cues bias neural networks of risky decision-making and provides a foundation for future research into targeted, personalised interventions aimed at reducing maladaptive risk-taking behavior and cue-driven vulnerability in addiction.

Limitations

This study has several limitations that should be considered when interpreting the findings. First, real-time subjective ratings of odor perception (e.g., intensity, valence, and arousal) were not collected during scanning. As a result, individual differences in perceptual experience could not be directly assessed during task performance. Future studies would benefit from incorporating subjective odor ratings using Likert or visual analogue scales to provide behavioral context and validate perceptual effects alongside functional connectivity measures. Second, the present analyses focused on connectivity between predefined ROIs and did not examine subregional interactions, which may reveal additional specificity within olfactory and decision-making networks. Finally, future research should explore a wider range of pleasant and unpleasant odors, vary odor intensity levels, and include behavioral measures such as reaction time to better characterise how olfactory stimuli influence risky decision-making.

Role of funding source

Iran University of Medical Sciences approved and provided the funding for this study under the code IR.IUMS.FMD.REC.1400.101. This

funding source had no role in the design of this study and will not have any role during its execution, analyses, interpretation of the data, or decision to submit results.

Funding

This work was supported by the Iran University of Medical Sciences [Grant number 19540].

CRediT authorship contribution statement

All authors have contributed significantly to the work. The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

AHD: Writing – original draft, Methodology, Software, Conceptualization, Investigation, Data curation, Formal analysis, Visualization, Writing – review & editing.

AZS: Methodology, Software, Conceptualization, Investigation, Supervision, Resources, Funding acquisition, Writing – review & editing.

SKK: Investigation, Writing – review & editing.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Human and animal rights

The authors declare that the work described has been carried out in accordance with the Declaration of Helsinki of the World Medical Association revised in 2013 for experiments involving humans as well as in accordance with the EU Directive 2010/63/EU for animal experiments.

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.

Acknowledgment

We thank the National Brain Mapping Laboratory for their support in MRI data acquisition and the Department of Medical Physics at Iran University of Medical Sciences for their assistance with the olfactory testing procedures.

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