

## Original Article

# Odor-induced sound localization bias under unilateral intranasal trigeminal stimulation

Kun Liang<sup>1,2</sup>, Wu Wang<sup>1,2</sup>, Xiao Lei<sup>3</sup>, Huanke Zeng<sup>1,2</sup>, Wenxiao Gong<sup>1,2</sup>, Chunmiao Lou<sup>1,2</sup> and Lihan Chen<sup>1,2,4,\*</sup>

<sup>1</sup>School of Psychological and Cognitive Sciences, Peking University, Beijing, China

<sup>2</sup>Beijing Key Laboratory of Behaviour and Mental Health, Peking University, Beijing, China

<sup>3</sup>Academy for Advanced Interdisciplinary Studies, Peking University, Beijing, China

<sup>4</sup>Key Laboratory of Machine Perception (Ministry of Education), Peking University, Beijing, China

\*Corresponding author: Lihan Chen, School of Psychological and Cognitive Sciences, Peking University, Beijing, China. E-mail: [CLH@pku.edu.cn](mailto:CLH@pku.edu.cn)

As a stereo odor cue, internostril odor influx could help us in many spatial tasks, including localization and navigation. Studies have also revealed that this benefit could be modulated by the asymmetric concentrations of both influxes (left nose vs right nose). The interaction between olfaction and vision, such as in object recognition and visual direction judgment, has been documented; however, little has been revealed about the impact of odor cues on sound localization. Here we adopted the ventriloquist paradigm in auditory–odor interactions and investigated sound localization with the concurrent unilateral odor influx. Specifically, we teased apart both the “nature” of the odors (pure olfactory stimulus vs. mixed olfactory/trigeminal stimulus) and the location of influx (left nose vs. right nose) and examined sound localization with the method of constant stimuli. Forty-one participants, who passed the Chinese Smell Identification Test, perceived sounds with different azimuths (0°, 5°, 10°, and 20° unilaterally deflected from the sagittal plane by head-related transfer function) and performed sound localization (leftward or rightward) tasks under concurrent, different unilateral odor influxes (10% v/v phenylethyl alcohol, PEA, as pure olfactory stimulus, 1% m/v menthol as mixed olfactory/trigeminal stimulus, and propylene glycol as the control). Meanwhile, they reported confidence levels of the judgments. Results suggested that unilateral PEA influx did not affect human sound localization judgments. However, unilateral menthol influx systematically biased the perceived sound localization, shifting toward the odor source. Our study provides evidence that unilateral odor influx could bias perceived sound localization only when the odor activates the trigeminal nerves.

**Key words:** multisensory, odor, olfactory, trigeminal, sound localization

## Introduction

Humans often use visual cues to navigate the environments and localize the objects, overlooking the otherwise comparable odor function. We usually regard olfaction as an alternative when other functions of specific sensory modalities deteriorate or even are disabled, e.g., in blind individuals (Dunglison, 1856). However, odors render immediate vital information for survival—approaching food sources and life partners but avoiding predators and other forms of danger. Odor localization is ubiquitous in nearly all forms of creatures throughout the evolution, from unicellular organisms, which climbed the nutrients’ gradient to “make a living (Adler, 1966), to multicellular organisms, creatures developed multisensory strategies to navigate, as seen in birds’ odor plume (Papi et al., 1971), shrimps’ diving strategy according to gravitational information (Hamner and Hamner, 1977), and sharks’ stereo olfaction (Gardiner and Atema, 2010; Gardiner et al., 2015).

More complicated than we imagined, odors could activate the olfactory and trigeminal systems, clustering odors into pure olfactory stimuli or mixed trigeminal/olfactory stimuli. As shown in a large body of literature, there are 2 types of odor localization (allocentric and egocentric; Welge-Luessen

et al., 2014) that the odors type might influence. Allocentric localization refers to navigating the target in a limited but open space. It is independent of the odor type when 2 nostrils are involved (Welge-Luessen et al., 2014). Using odor cues, humans can successfully scent-track along the odor path on the ground and improve their performances by boosting the sensitivities of internostril comparisons (Porter et al., 2007). Egocentric localization refers to the discrimination of odors in one of the nostrils (left vs. right). It has been revealed to be dependent on the trigeminality of the odor. Humans could fulfill egocentric odor localization tasks upon trigeminal stimuli, which activate the trigeminal nerve (cranial nerve V, CN V), such as isoamyl acetate (Kleemann et al., 2009). Nevertheless, humans cannot discriminate which nostril receives the pure olfactory stimuli that solely activate the olfactory nerve (Cranial Nerve 1, CN I) when compared with other senses, e.g., vision and audition (Frasnelli et al., 2010; Kleemann et al., 2009; Kobal, 1994; except Porter et al., 2005). Those findings suggested the constraint of “trigeminality” in egocentric odor localization.

Although humans could not localize pure olfactory stimuli explicitly in an egocentric manner, it has been revealed to influence the crossmodal perception “implicitly” and resolve

the otherwise ambiguous directional perception in other sensory modalities. This influence was achieved by a top-down fashion of sensory association or by a bottom-up manner of crossmodal perceptual integration. After being paired (associated) with dots which move in a specific direction, odors could shift the perceived direction of ambiguous visual dot motion towards their paired pattern (Kuang and Zhang, 2014). Moreover, odor influxes with asymmetric concentrations could trigger a biased directional perception of visual stimuli. Wu (2020) used apparent optic flow with a centrifugal center to test odor-induced visual localization bias. This bias was mediated by the internostril ratio of odor concentrations instead of the absolute odor concentration discrepancies.

The above crossmodal capture in localization has been found in various sensory combinations (Mateeff et al., 1985; Soto-Faraco et al., 2004). Not only did olfaction-related stimuli involve in multisensory spatial judgment, but somatosensory-related stimuli could also bias the localization in another sensory modality, such as affecting the perceived auditory localization. Receptors for somatosensory are distributed all over the skin and inside the body. Such receptors are responsible for conveying the information of physical forces (e.g., touch), chemical environment (e.g., intranasal trigeminal odors) or temperature to the brain. Previous research suggested that spatial-incongruent tactile stimuli could influence sound localization in an external coordinate system (Bruns and Röder, 2010; Caclin et al., 2002), representing that tactile stimulation could bias the apparent location of a synchronous sound (Caclin et al., 2002). However, whether another form of somatosensory stimuli (intranasal trigeminal odors) could bias perceived sound localization remains unknown.

In our daily life, sound localization is as vital as the visual one. It is even more decisive in conveying critical location information when the accompanying visual object is uncertain for recognition or not available for immediate sight (e.g., an approaching car towards the rear of a pedestrian). On many occasions, visual cues could bias/facilitate the concurrent sound localization due to the functional superiority of visual modality over the auditory one in spatial tasks (Jiang and Chen, 2013; Sanabria et al., 2007; Welch and Warren, 1980), as realized in the ventriloquist effect. The ventriloquist effect has been initially demonstrated in audiovisual interaction in which the concurrent visual cues could bias perception of sound location toward the position of the visual distractor, even subjects trying to ignore them (for a review, see Chen and Vroomen, 2013). This illusion has been extended to the interaction between vision and other senses like touch (Merz et al., 2020) and chemical senses (Kuang and Zhang, 2014; Wu et al., 2020), providing an effective tool to study the interaction among various sensory modalities.

Notably, the previous research provided great possibilities that odors (both pure olfactory odor and mixed trigeminal/olfactory odor) might bias sound localization judgment. To assess the potential bias of chemosenses (i.e., odor) upon sound perception and the underlying constraints, we exploited the ventriloquism between odor and audition and aimed to answer (i) whether unilateral odor input (both pure olfactory stimuli and trigeminal stimuli) could bias perceived sound location; (ii) if so, whether/how pure olfactory stimuli and trigeminal stimuli imposed differential effects upon the sound localization. Given the trigeminality of the odor contributes

prominently to fulfilling localization, we anticipated that the efficacy of odor-sound interaction in localization is contingent on the specific odor stimulations (pure olfactory stimuli vs. trigeminal stimuli), and the trigeminal odors would play an upper hand in “capturing” sound localization than the pure olfactory stimuli achieve.

## Materials and methods

### Participants

According to the calculation by GPower, 34 participants were required to reach a power of 0.8 (Faul et al., 2007). Forty-one participants (40 right handed, 15 males and 26 females, age:  $22.6 \pm 3.2$  [SD] years) from Peking University attended the experiments. They did not have a history of nasal operation or suffer from common cold, rhinitis, or any neurological and psychiatric conditions. Before experiments, they had to pass the Chinese smell identification test to exclude olfactory dysfunction (Feng et al., 2019), in which they should correctly identify at least 34 of 40 odor items using a 4-alternative forced-choice paradigm. This study was proved by the Academic Affairs Committee of the School of Psychological and Cognitive Sciences at Peking University and complied with the Declaration of Helsinki. Participants read and signed the informed consent before formal experiments.

### Materials

The experimental program was written with Psychtoolbox (Brainard, 1997; Pelli, 1997) and conducted on MATLAB R2020b (Mathworks, Natick, MA, USA).

### Apparatus

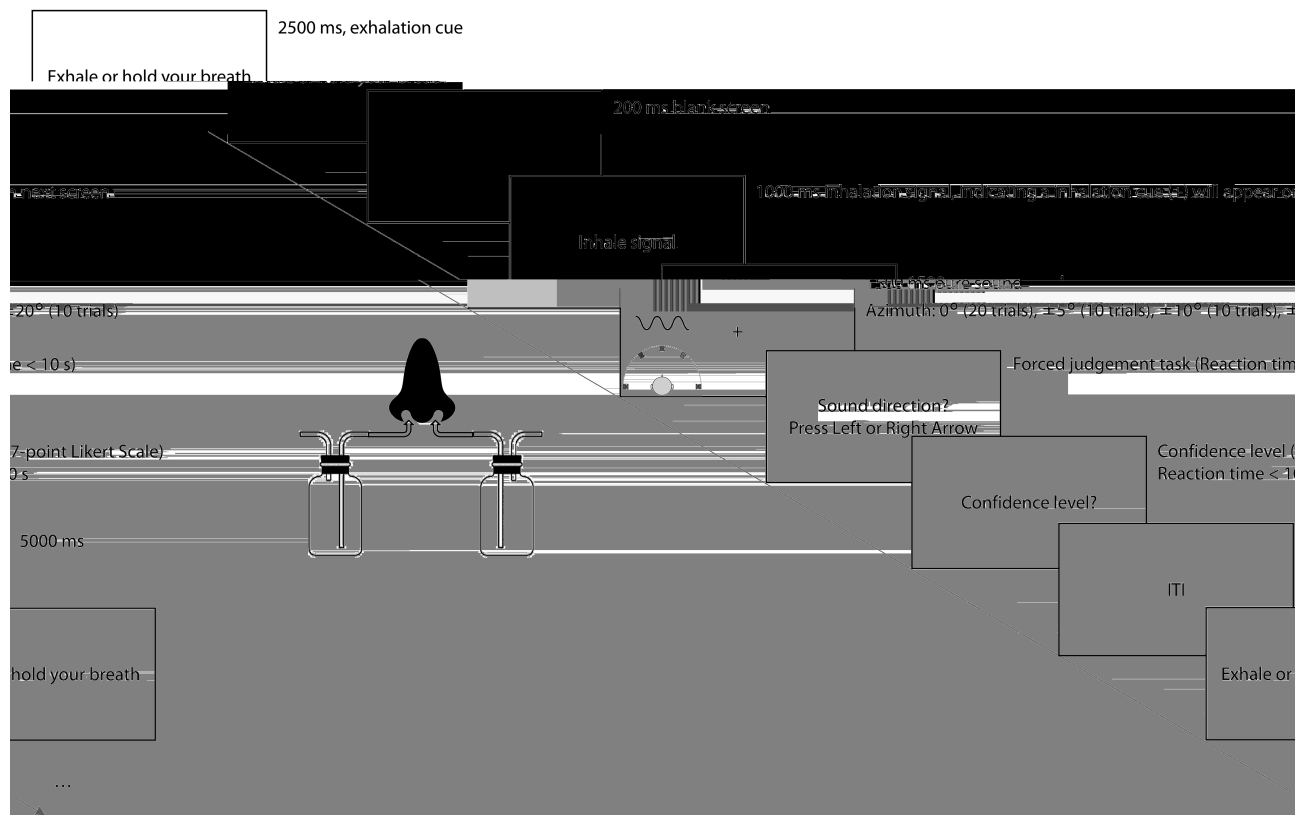
A pure sound (250 Hz, 50 dB, 1,500 ms) was generated by MATLAB and delivered to a headset (AirPods Pro, China). Sound azimuth control was achieved by the head-related transfer function (HRTF) generated from the MIT dataset (Gardner and Martin, 1994), which provided the necessary parameters of sound azimuths (e.g., interaural time difference, interaural level difference, etc.) as physical sounds did.

### Odorants

Phenylethyl alcohol (PEA, rose smell, D&B, 99% for analysis) and menthol (mint smell, Heowns, 98% for analysis) were dissolved in propylene glycol (odorless, Amethyst, 99% for analysis), respectively, to get 10% v/v PEA and 1% m/v menthol (Kobal et al., 1989). PEA is regarded as a pure olfactory stimulus, while menthol is regarded as a mixed olfactory/trigeminal stimulus (from here on, referred to as trigeminal stimulus). Propylene glycol was also used as the control group in the formal experiment. All 3 stimuli (30 mL each) were placed in identical 250-mL glass jars. Participants sniffed the odorants from the glass jars via odorless silicone tubes.

### Procedure

In our study, we implemented a ventriloquism paradigm with sound localization under the presence of odors. Meanwhile, we asked participants to rate their confidence in sound localization to check their attention and avoid potential response bias. To start the localization task, participants sat in front of a table and were required to keep their heads still



**Fig. 1.** Schematic illustration of one trial of the sound localization task. Participants inhaled the odor and heard the sound simultaneously. Sound azimuth was defined as the angle deflected from the sagittal plane (“-” means leftward, “+” means rightward). ITI, intertrial interval; response: Left or Right. Confidence: from 1 to 7 (1 means “just guess,” 7 means “very confident.” The higher, the more confident).

in a ventilated room. Participants could freely breathe unless there was a specific instruction. The complete paradigm is shown in Fig. 1. A typical trial began with the visual presentation of a breathing instruction for 2,500 ms, indicating that participants should exhale or just hold their breath at this stage. Then it went a 200-ms blank screen, followed by a 1000-ms inhalation pre-cue. After that, participants inhaled/smelt the odors and meanwhile heard a 1,500-ms pure sound (azimuths:  $-20^\circ$ ,  $-10^\circ$ ,  $-5^\circ$ ,  $0^\circ$ ,  $+5^\circ$ ,  $+10^\circ$ ,  $+20^\circ$ ; minus refers to left field while plus refers to right field). The sound azimuth setting was based on the resolution of the HRTF and the approximate difference limen (DL) ( $\theta$ ) (Mills, 1958). The simulated sound was unilaterally deflected from the sagittal plane in 7 logarithmic steps (i.e.,  $0^\circ$ ,  $\pm\theta$ ,  $\pm 2\theta$ , and  $\pm 4\theta$ ). Participants finally made a 2-alternative forced-choice judgment of whether the sound came from the left or right field and reported their confidence level (the 7-point Likert scale, 1 means “just guess,” while 7 means “extremely confident”) of the response within 10 s consecutively. The intertrial interval (ITI) was 5,000 ms. The experiment consisted of 5 blocks containing 5 odor-nostril conditions (bilateral propanediol as control, left PEA, right PEA, left menthol, and right menthol). The orders of conditions were counterbalanced among participants. To purge the leftover of previous odor, we turned on the air conditioner between blocks. Each block was divided into 2 sub-blocks, each having 40 trials. There was a 2-min forced break between sub-blocks. Therefore, one block consisted of 80 trials with 20 trials for  $0^\circ$  and 10 trials each for other sound azimuths. All trials were pseudo-randomly given in order.

## Da a a a

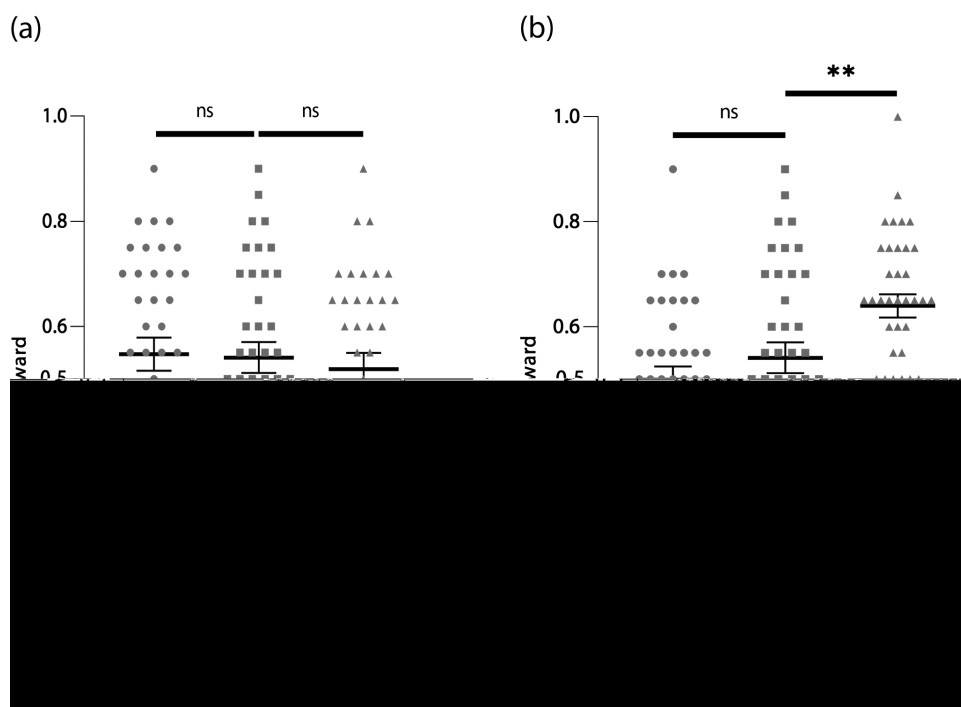
Psychophysical curves were fitted with Boltzmann sigmoid function,  $f(x) = 1/(1+e^{-(x-x^*)})$  in Origin (OriginLab Corp., Northampton, MA, USA), where  $x$  refers to the sound azimuth and  $x^*$  refers to the point of subjective equivalence (PSE), at which sound azimuth participants reported 50% rightward judgments. DL, or just noticeable difference, refers to the minimum azimuth that participants could discriminate different sound azimuths. DL for each participant was calculated according to the interquartile range of the function. Furthermore, we conducted a series of repeated measures analysis of variance (ANOVAs), multivariate analysis of variance, and paired sample  $t$ -tests using IBM SPSS Statistics 27 (SPSS Inc., Chicago, IL, USA) and JASP (Love et al., 2019). All statistical approaches were 2-tailed and set at the significant level of 0.05.

## Results

Three participants were excluded from statistical analysis due to the ill-fitting of the Boltzmann sigmoid function ( $R^2 < 0.4$ ) or initial rightward bias of sound localization (i.e., 100% of rightward judgments at sound azimuth =  $0^\circ$ ).

## L a a a a a a a a a a

We assessed whether unilateral odor influx influenced perceived sound at azimuth =  $0^\circ$ , where the sound direction information was most ambiguous (Fig. 2). For PEA, no significant effect of sound localization bias was found ( $F_{2,74} = 0.555$ ,



**Fig. 2.** The proportion of rightward judgments at azimuth = 0 under different odor-nostril conditions. (a) Unilateral PEA influx did not pose a significant rightward response difference compared with the control group at azimuth = 0. (b) Right menthol influx caused an increased rightward judgment compared with the control group at azimuth = 0. All error bars stand for standard error mean (SEM),  $**P < 0.01$ .

$P = 0.576$ , partial  $\eta^2 = 0.015$ , Bayes factors of  $H_0$  over  $H_1$ ,  $BF_{01} = 7.691$ ). However, unilateral menthol influx imposed a significant effect on perceived sound localization ( $F_{2,74} = 13.922$ ,  $P < 0.001$ , partial  $\eta^2 = 0.273$ ). Further paired sample  $t$ -tests revealed that this significant effect was contributed by the right menthol influx ( $t_{37} = 3.396$ ,  $P = 0.002$ , Cohen's  $d = 0.608$ ), with a 9.87% more report of rightward judgments at sound azimuth =  $0^\circ$  compared with the control group, instead of left menthol influx ( $t_{37} = -1.449$ ,  $P = 0.156$ , Cohen's  $d = 0.248$ ,  $BF_{01} = 2.192$ ).

At every sound azimuth, we calculated Bayesian factors  $H_0$  over  $H_1$  ( $BF_{01}$ ) of odor effect on sound localization perception to test whether there were more (or less) rightward judgments with odor influx at specific sound azimuth (see [Supplementary Tables 1 and 2](#)). The results from Bayesian ANOVA showed all  $BF_{01}$  values of odor conditions were higher than 3 at every azimuth and even higher than 10 when the sound azimuth was larger than  $10^\circ$ , which gave evidence that odor influx did not influence the sound localization judgment at a large azimuth input.

### PSE

To examine the performance of sound localization, we fitted a series of psychophysical curves that delineated the proportions of rightward judgment as a function of the sound azimuth under different odor-nostril conditions ([Fig. 3a and b](#)). PSEs for the individuals were shown in [Figs. 3c and 4d](#). PSE under control group is shifted rightward with an approximate angle of  $1.13^\circ$  ( $t_{37} = -2.590$ ,  $P = 0.014$ , Cohen's  $d = 0.420$ ). Intriguingly, PSE shifted discrepantly under different odor-nostril conditions. As shown in [Fig. 3e and f](#), unilateral PEA influx did not cause a significant PSE shift ( $F_{2,74} = 0.106$ ,  $P = 0.900$ , partial  $\eta^2 = 0.003$ ,  $BF_{01} = 11.234$ ). However, unilateral

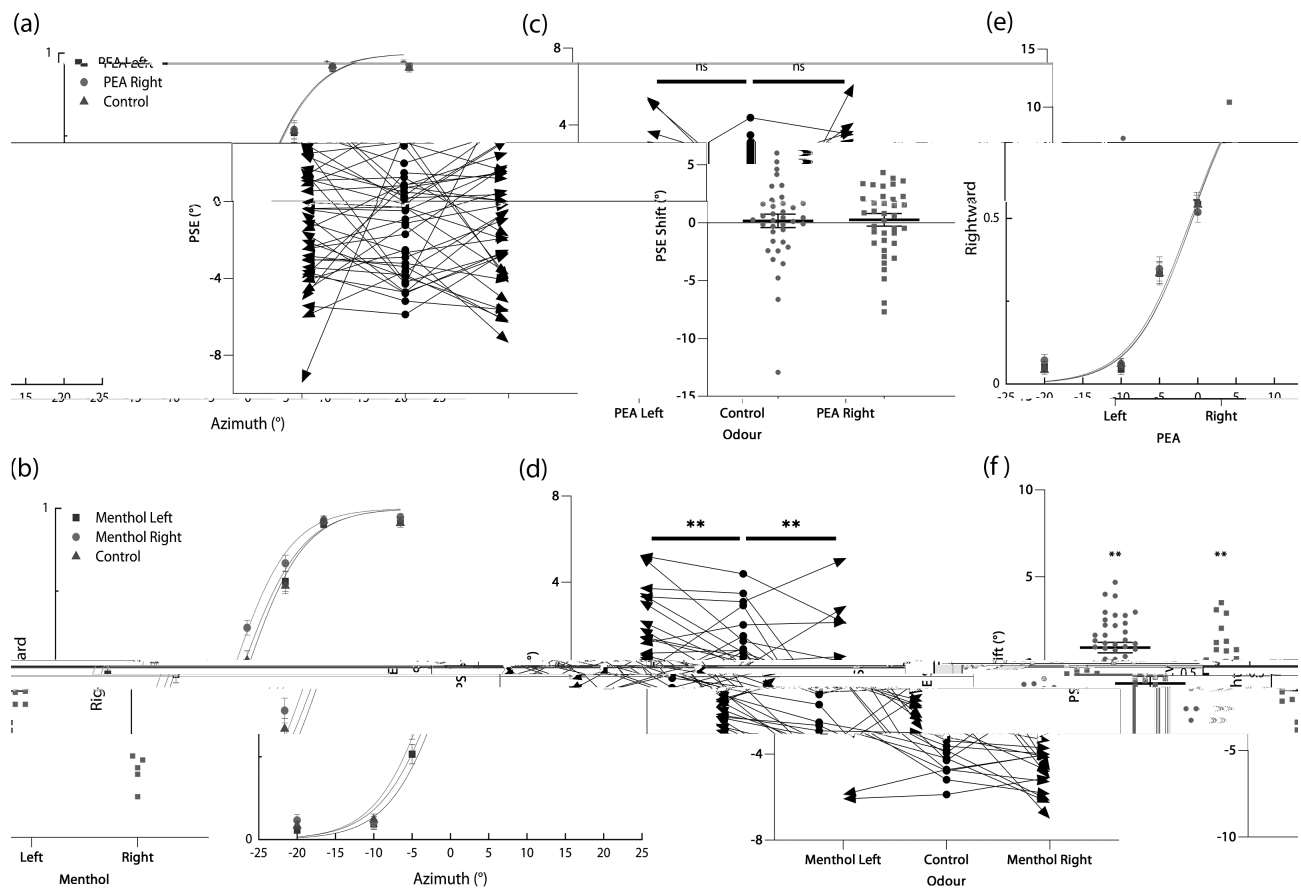
menthol influx systematically biased the perceived sound localization ( $F_{1,808,66,897}$  [Huynh–Feldt adjusted degree of freedom] = 17.000,  $P < 0.001$ , partial  $\eta^2 = 0.315$ ), shifting toward the odor side with the PSE shift of approximate a quarter of the DL (PSE shift of right menthol influx:  $-1.15 \pm 0.42$  [SEM]; PSE shift of left menthol influx:  $0.91 \pm 0.30$  [SEM]; DL at control group:  $-4.45 \pm 0.32$  [SEM]). That was, right menthol influx made PSE shifted rightward ( $-1.146^\circ \pm -0.417^\circ$  [SEM], 95% CI [ $-2.191^\circ$ ,  $-0.101^\circ$ ]), and vice versa ( $0.918^\circ \pm 0.301^\circ$  [SEM], 95% CI [ $0.163^\circ$ ,  $1.673^\circ$ ]). Confidence curves ([Fig. 4](#)) were U-shaped and were not different among different odor-nostril conditions ( $F_{28,716} = 0.458$ ,  $P = 0.993$ , partial  $\eta^2 = 0.018$ ), showing that participants were well-instructed and responded to the perceived sound direction as required.

### D

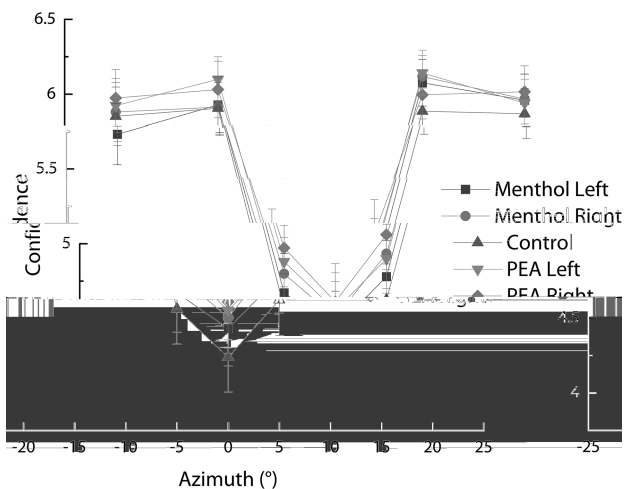
Different limen (DL) revealed participants' discrimination of sound azimuth (the higher DL, the lower the discriminative ability/sensitivity to the sound azimuth of the participant). DL at control group was not significantly different from  $5^\circ$  ( $t_{37} = -1.726$ ,  $P = 0.093$ ,  $BF_{01} = 1.948$ ), which was the initial  $\theta$ . Results suggested that all main effects and interactions regarding odor-nostril conditions were insignificant ( $F_{4,37} = 0.830$ ,  $P = 0.508$ ,  $BF_{01} = 17.688$ ), showing that participants had comparable sensitivities of sound localization in the presence of all given odor conditions.

## Discussion

The current study supported our hypothesis that unilateral odor influx, with binasal odor discrepancy, could bias human perceived sound localization to the odor side. Moreover, this odor-induced ventriloquism depends on the trigeminality of



**Fig. 3.** PSE shift of unilateral odor influx on sound direction perception. (a, b) Psychophysical curves of sound direction judgment under different odor-nostril conditions (control, left PEA influx, right PEA influx, left menthol influx, and right menthol influx). Negative values on the horizontal axis mean leftward sound stimuli, and positive values on the horizontal axis mean rightward sound stimuli. (c, d) individual PSE under different odor-nostril conditions. Middle dots and 2 arrows represent one participant. Unilateral menthol influx led to a systematic bias in perceived sound direction, shifting towards the odor side. (e, f) PSE shift of individual data. All error bars stand for standard error mean (SEM),  $**P < 0.01$ .



**Fig. 4.** The confidence level (the 7-point Likert scale, 1 means “just guess,” while 7 means “extremely confident”) of the sound direction judgment under different odor-nostril conditions (control, left PEA influx, right PEA influx, left menthol influx, and right menthol influx). Negative values on the horizontal axis mean leftward sound stimuli, and positive values on the horizontal axis mean rightward sound stimuli. All error bars stand for standard error mean (SEM).

the odor. Only odors that activate trigeminal nerves (in our study, it is menthol instead of PEA) could bias the sound localization.

This odor-induced ventriloquism could be interpreted by either the crossmodal capture effect of odor upon sound (Millot et al., 2016), or the modality precision/appropriateness hypothesis. The modality precision hypothesis suggests that the modality which is more precise in specific functioning (e.g., localization) dominates when the information from 2 sensory modalities is conflicting (Welch and Warren, 1980). Compared with the audition, olfaction outperformed the relocation task with a higher absolute correct rate (Schifferstein et al., 2010). From this point of view, odor containing olfactory and/or trigeminal properties is at least not weaker or better than audition in localization. Therefore, the concurrent but spatially discrepant odor inputs could combine and integrate with the sound to convey reliable spatial representation, influencing the sound localization judgment. Essentially, the prerequisite is that odors should convey directional information (Croy et al., 2014; Kikuta et al., 2010), which was satisfied through activation in the trigeminal-related cortex (i.e., somatosensory cortex and intraparietal sulcus) under unilateral trigeminal odor stimulus (Croy et al., 2014).

In our study, we found differential bias effects between PEA and menthol. The functional divergence associated with those stimuli had led to the observed difference in the bias effect. Menthol activates the trigeminal system that can convey directional information, whereas PEA activates only the olfactory nerve. The current observation that intranasal trigeminal stimuli could bias perceived sound localization was in line with the previous research that tactile stimuli to the fingertips bias auditory localization toward tactile stimulation (Caclin et al., 2002). The only difference was that trigeminal odor contained intranasal somatosensory stimuli instead of direct tactile stimulation. Trigeminal stimuli (e.g., menthol) could provide directional information, which is an essential factor of binasal odor localization. The reason trigeminal activation is fundamental in odor localization could be well interpreted by the high trigeminal sensitivity and olfactory degeneration during evolution. The trigeminal system involves nociceptive input, which is highly related to alerting and humans' survival. However, as for the olfactory system, the size of the human olfactory lobe decreased compared with other highly developed animals, which could be explained by successful bipedal movement (Raithel and Gottfried, 2021). Under such circumstances, the chemotaxis strategy, using concentration gradient to navigate, is enough. Human olfaction then becomes less vital in keeping a living compared with other animals.

In addition, the stereo olfaction of humans is constrained by objective physiological factors, for instance, neuronal pathway, interpreting the relative reliability of the olfactory localization and trigeminal localization. Although odors activate ipsilateral mitral and tufted cells (M/T cells), the primary olfactory cortex (POC) could receive afferent signals as well from contralateral M/T cells rapidly in the direct pathway through anterior commissure (Dalal et al., 2020) or in the indirect pathway through activating mirror-symmetric M/T cells (Dalal et al., 2020; Grobman et al., 2018; Kermen et al., 2020). Directional information of pure olfactory stimuli might dissipate in the higher olfactory cortex since odor perception united before that. This dissipation provides some explanation as to why humans do not have reliable stereo olfaction. However, the intranasal trigeminal system maintains directional information for a longer path (Croy et al., 2014; Doty et al., 1997; Iannilli et al., 2008) compared with olfaction before the POC, providing the neural possibilities to integrate with sound.

As mentioned above, our study highlighted that unilateral menthol influx could bias perceived sound localization. To analyze the potential mechanism of the menthol-induced bias, we proposed 2 possible pathways (direct and indirect) of this trigeminus-sound integration. Overall speaking, we suggested that 3 integration regions in the brain were involved in such trigeminus-sound integration through the direct and indirect pathways, including superior temporal gyrus/sulcus (STG/STS) (Beauchamp, 2005; Beauchamp et al., 2004), intraparietal sulcus (IPS) (Beauchamp et al., 2010; Regenbogen et al., 2018), and prefrontal cortex (PFC) (Zimmerman and Lahav, 2012). For the direct pathway, we speculated that directional information from the trigeminal cortex (e.g., somatosensory cortex) and sound information integrated in IPS near the somatosensory cortex, or STG/STS, which involves sound-related integration. For the indirect pathway, we conceived that trigeminal odor influenced sound localization by transmitting directional information to the olfactory cortex, finally integrating with sound in STS/STG and PFC, which were involved in olfactory processing. Furthermore, we

tended to explain the biological feasibility of the indirect pathway. From the neuronal perspective, although trigeminal nerves and olfactory nerves projected to the higher cortex independently, information from the trigeminal cortex was found to project to the olfactory cortex. Previous research discovered that even pure trigeminal stimulus (e.g., CO<sub>2</sub>) could activate the olfactory cortex (Carlson et al., 2013). Moreover, trigeminal information and olfactory information were reported in a preprint to integrate in the POC and the superior temporal cortex. This trigeminal-olfactory costimulation could also enhance POC-OFC (orbitofrontal cortex) connectivity (Karunanayaka et al., 2021). These findings showed the trigeminal and olfactory nerves were not isolated from each other and were functionally connected. From this point of view, directional information from trigeminal odor should be biologically possible to be conveyed to the primary or higher olfactory cortex and then integrated with sound.

Notably, a recent comparable study from Wu reported success in ventriloquism of PEA-induced optic flow bias (Wu et al., 2020). Our divergent results might result from the nature of sensory modalities and different experimental operations. Although we both used PEA as the inducer, vision and audition are distinct senses in terms of localization robustness. Since ventriloquism depends on the relative reliability of the 2 stimuli (Alais and Burr, 2004), the effect should vary from vision to audition. Moreover, Wu did not pledge the synchronization of visual and olfactory stimuli. However, an appropriate short stimuli-onset asynchrony (or time window) should be controlled since it is one of the fundamental constraints for successful multisensory integration (Otto et al., 2013). Putting breathing as a free factor might cause various sampling frequencies and odor influx volumes of the participants. In our experimental setting, we required participants to inhale/smell when the sound was given to keep the odor and auditory stimuli simultaneously presented.

Admittedly, breath regulation (when to exhale and when to inhale) not only ensured the synchronism of the odor stimuli, but might attract participants' attention to odor information (although they were required to neglect it). Extra attention to olfaction in localization tasks (Spence et al., 2000; Spence, Kettenmann, et al., 2001; Spence, McGlone, et al., 2001) or potential response bias to the odor might become an inevitable contributor to the ventriloquism that participants might use odor information to judge the sound localization. However, selective attention or response bias cannot explain well the results of our study. The confidence-azimuth curves were distinctly U-shape, showing the participants indeed judged the sound direction as we required. Furthermore, the results of Bayesian factors  $H_0$  over  $H_1$  ( $BF_{01}$ ) of odor effect on sound localization perception suggested that odor influx did not influence sound localization judgment when the azimuth was larger than 10°, whose pattern was in accordance with the principle of inverse effectiveness in multisensory integration (the stronger/more reliable the unimodal stimulus is, the weaker the integration benefits), supporting our interpretation of odor-sound integration (Stein and Meredith, 1993).

However, there are still some limitations in our study. We found a systematic rightward bias at azimuth = 0 in the control group, which might be interpreted by the participants' handedness or the innate bias of the HRTF. Although this bias did not interrupt our main findings, it still could be balanced by selecting participants and using real speakers in future research. Another limitation is that we only employed one pure

or trigeminal odor in the present study due to the pragmatic difficulties of implementing more stimulants and recruiting more participants, so we should remain cautious in drawing the conclusion. However, we anticipate the effects would also be observed among other intranasal trigeminal agonists. Additionally, we tried to control participants' breath to ensure synchronism of the stimuli but at the cost of the potential extra attention during inhalation. Besides, we compressed the ITI into 5 seconds to prevent severe olfactory fatigue in late trials. However, too short ITI might lead to a situation where the previous trial condition influences participants' present judgment due to the order effect. The optimal ITI could be tested in further studies.

Overall, our study unveiled the ventriloquism that unilateral trigeminal odors could bias perceived sound location, shifting towards the odor side. This bias is prevalent and with a stable sensitivity of sound localization judgment, bolstered by the fact that the DL did not change with the odor. The exact neural mechanism and the potential gender-specific differences under such ventriloquism could be explored in further research.

## Funding

This research was supported by grants from the Ministry of Science and Technology of China (2021ZD0202601) and the Natural Science Foundation of China (62061136001, T2192932).

## Author contributions

K.L.: idea formation, experimental design, data acquisition, statistical analysis and graphing, draft the article; W.W.: experimental design, graphing, and revising article; X.L.: experimental design, revising article; H.Z.: experimental design, statistical analysis; W.G.: experimental design, revising article; C.L.: statistical analysis; L.C.: experimental design, critically revising the manuscript.

## Conflict of interest

None declared.

## References

- Adler J. Chemotaxis in bacteria: motile *Escherichia coli* migrate in bands that are influenced by oxygen and organic nutrients. *Science*. 1966;153(3737):708–716.
- Alais D, Burr D. The ventriloquist effect results from near-optimal bimodal integration. *Curr Biol*. 2004;14(3):257–262.
- Beauchamp MS. See me, hear me, touch me: multisensory integration in lateral occipital-temporal cortex. *Curr Opin Neurobiol*. 2005;15(2):145–153.
- Beauchamp MS, Argall BD, Bodurka J, Duyn JH, Martin A. Unraveling multisensory integration: patchy organization within human STS multisensory cortex. *Nat Neurosci*. 2004;7(11):1190–1192.
- Beauchamp MS, Pasalar S, Ro T. Neural substrates of reliability-weighted visual-tactile multisensory integration. *Front Syst Neurosci*. 2010;4:25.
- Brainard DH. The psychophysics toolbox. *Spatial Vis*. 1997;10:433–436. <https://color.psych.ucsb.edu/psychtoolbox>.
- Bruns P, Röder B. Tactile capture of auditory localization: an event-related potential study. *Eur J Neurosci*. 2010;31(10):1844–1857.
- Caclin A, Soto-Faraco S, Kingstone A, Spence C. Tactile “capture” of audition. *Percept Psychophys*. 2002;64(4):616–630.
- Carlson KS, Xia CZ, Wesson DW. Encoding and representation of intranasal CO<sub>2</sub> in the mouse olfactory cortex. *J Neurosci*. 2013;33(34):13873–13881.
- Chen L, Vroomen J. Intersensory binding across space and time: a tutorial review. *Attention Percept Psychophys*. 2013;75(5):790–811.
- Croy I, Schulz M, Blumrich A, Hummel C, Gerber J, Hummel T. Human olfactory lateralization requires trigeminal activation. *Neuroimage*. 2014;98:289–295.
- Dalal T, Gupta N, Haddad R. Bilateral and unilateral odor processing and odor perception. *Commun Biol*. 2020;3(1):1–2.
- Doty RL, Bromley SM, Moberg PJ, Hummel T. Laterality in human nasal chemoreception. In: S. Christman, editor. *Advances in psychology*. Vol. 123, pp. 497–542. Amsterdam: North Holland; 1997.
- Dunglison, R. *Human physiology: Vol. II*. Blanchard and Lea; 1856.
- Faul F, Erdfelder E, Lang A-G, Buchner A. G\*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175–191. doi:10.3758/BF03193146.
- Feng G, Zhuang Y, Yao F, Ye Y, Wan Q, Zhou W. Development of the Chinese smell identification test. *Chem Senses*. 2019;44(3):189–195.
- Frasnelli J, Ariza VLB, Collignon O, Lepore F. Localisation of unilateral nasal stimuli across sensory systems. *Neurosci Lett*. 2010;478(2):102–106.
- Gardiner JM, Atema J. The function of bilateral odor arrival time differences in olfactory orientation of sharks. *Curr Biol*. 2010;20(13):1187–1191.
- Gardiner JM, Whitney NM, Hueter RE. Smells like home: the role of olfactory cues in the homing behavior of blacktip sharks, *Carcharhinus limbatus*. *Integr Comp Biol*. 2015;55(3):495–506.
- Gardner B, Martin K. (1994). *HRTF measurements of a KEMAR dummy-head microphone*. <http://alumni.media.mit.edu/~kdm/hrtfdoc/hrtfdoc.html>
- Grobman M, Dalal T, Lavian H, Shmuel R, Belevsky K, Xu F, Korngreen A, Haddad R. A mirror-symmetric excitatory link coordinates odor maps across olfactory bulbs and enables odor perceptual unity. *Neuron*. 2018;99(4):800–813.e6.
- Hamner P, Hamner WM. Chemosensory tracking of scent trails by planktonic shrimp *Acetes sibogae australis*. *Science*. 1977;195(4281):886–888.
- Iannilli E, del Gratta C, Gerber JC, Romani GL, Hummel T. Trigeminal activation using chemical, electrical, and mechanical stimuli. *Pain*. 2008;139(2):376–388.
- Jiang Y, Chen L. Mutual influences of intermodal visual/tactile apparent motion and auditory motion with uncrossed and crossed arms. *Multisensory Res*. 2013;26(1–2):19–51.
- Karunanayaka PR, Lu J, Elyan R, Yang QX, Sathian K. Olfactory-trigeminal integration in the primary olfactory cortex. *BioRxiv*, doi:10.1101/2020.06.24.168989, 23 January 2021.
- Kermen F, Lal P, Faturus NG, Yaksi E. Interhemispheric connections between olfactory bulbs improve odor detection. *PLoS Biol*. 2020;18(4):e3000701.
- Kikuta S, Sato K, Kashiwadani H, Tsunoda K, Yamasoba T, Mori K. Neurons in the anterior olfactory nucleus pars externa detect right or left localization of odor sources. *Proc Natl Acad Sci USA*. 2010;107(27):12363–12368.
- Kleemann AM, Albrecht J, Schoepf V, Haegler K, Kopietz R, Hempel JM, Linn J, Flanagan VL, Fesl G, Wiesmann M. Trigeminal perception is necessary to localize odors. *Physiol. Behav*. 2009;97(3–4):401–405.
- Kobal G. Pleasure responses of the brain: olfactory evoked potential activity and hedonics. In: D. M. Warburton, editor. *Pleasure: the politics and the reality*. New York: Wiley; 1994. p. 22–28.
- Kobal G, van Toller S, Hummel T. Is there directional smelling? *Experientia*. 1989;45(2):130–132.
- Kuang S, Zhang T. Smelling directions: olfaction modulates ambiguous visual motion perception. *Sci Rep*. 2014;4(1):1–5.
- Love J, Selker R, Marsman M, et al. JASP: graphical statistical software for common statistical designs. *J Statis Softw*. 2019;88(2):1–7.

- Mateeff S, Hohnsbein J, Noack T. Dynamic visual capture: apparent auditory motion induced by a moving visual target. *Perception*. 1985;14(6):721–727.
- Merz S, Meyerhoff HS, Frings C, Spence C. Representational momentum in vision and touch: visual motion information biases tactile spatial localization. *Attention Percept Psychophys*. 2020;82(5):2618–2629.
- Millot J-L, Laurent L, Casini L. The influence of odors on time perception. *Front Psychol*. 2016;7:181.
- Mills AW. On the minimum audible angle. *J Acoust Soc Am*. 1958;30(4):237–246.
- Otto TU, Dassy B, Mamassian P. Principles of multisensory behavior. *J Neurosci*. 2013;33(17):7463–7474.
- Papi F, Fiore L, Fiaschi V, Benvenuti S. The influence of olfactory nerve section on the homing capacity of carrier pigeons. *Monit Zool Ital*. 1971;5(4):265–267.
- Pelli DG. The videotoolbox software for visual psychophysics transforming numbers into movies. *Spatial Vis*. 1997;10(4):437–442.
- Porter J, Anand T, Johnson B, Khan RM, Sobel N. Brain mechanisms for extracting spatial information from smell. *Neuron*. 2005;47(4):581–592.
- Porter J, Craven B, Khan RM, Chang S-J, Kang I, Judkewitz B, Volpe J, Settles G, Sobel N. Mechanisms of scent-tracking in humans. *Nat Neurosci*. 2007;10(1):27–29.
- Raithel CU, Gottfried JA. Using your nose to find your way: ethological comparisons between human and non-human species. *Neurosci Biobehav Rev*. 2021;128:766–779.
- Regenbogen C, Seubert J, Johansson E, Finkelmeyer A, Andersson P, Lundström JN. The intraparietal sulcus governs multisensory integration of audiovisual information based on task difficulty. *Hum Brain Mapp*. 2018;39(3):1313–1326.
- Sanabria D, Soto-Faraco S, Spence C. Spatial attention and audiovisual interactions in apparent motion. *J Exp Psychol Hum Percept Perform*. 2007;33(4):927–937.
- Schiffman HN, Smeets MAM, Postma A. Comparing location memory for 4 sensory modalities. *Chem Senses*. 2010;35(2):135–145. doi:10.1093/chemse/bjp090.
- Soto-Faraco S, Spence C, Kingstone A. Cross-modal dynamic capture: congruency effects in the perception of motion across sensory modalities. *J Exp Psychol Hum Percept Perform*. 2004;30(2):330–345.
- Spence C, Kettenmann B, Kobal G, McGlone FP. Selective attention to the chemosensory modality. *Percept Psychophys*. 2000;62(6):1265–1271.
- Spence C, Kettenmann B, Kobal G, McGlone FP. Shared attentional resources for processing visual and chemosensory information. *Q J Exp Psychol Sect A Hum Exp Psychol*. 2001;54(3):775–783.
- Spence C, McGlone F, Kettenmann B, Kobal G. Attention to olfaction: a psychophysical investigation. *Exp Brain Res*. 2001;138(4):432–437.
- Stein BE, Meredith MA. (1993). *The merging of the senses*. Cambridge (MA): The MIT Press.
- Welch RB, Warren DH. Immediate perceptual response to intersensory discrepancy. *Psychol Bull*. 1980;88(3):638–667.
- Welge-Lüssen A, Looser G-L, Westermann B, Hummel T. Olfactory source localization in the open field using one or both nostrils. *Rhinology*. 2014;52(1):41–47.
- Wu Y, Chen K, Ye Y, Zhang T, Zhou W. Humans navigate with stereo olfaction. *Proc Natl Acad Sci USA*. 2020;117(27):16065–16071.
- Zimmerman E, Lahav A. The multisensory brain and its ability to learn music. *Ann N Y Acad Sci*. 2012;1252(1):179–184.