Landry, C., Nazar, R., Simon, M., Genest, F., Giguère, F. L., Lepore, F., & Frasnelli, J. (2024). Behavioural evidence for enhanced olfactory and trigeminal perception in congenital hearing loss. European Journal of Neuroscience, 59(3), 434–445. https://doi.org/10.1111/ejn.16216 CC BY-NC 4.0

Received: 1 June 2022 | Revised: 5 November 2023 | Accepted: 20 November 2023

DOI: 10.1111/ejn.16216

RESEARCH REPORT

EJN European Journal of Neuroscience FENS WILEY

# Behavioural evidence for enhanced olfactory and trigeminal perception in congenital hearing loss

**Catherine Landry**[1] | **Rim Nazar**[1,2] | **Marie Simon**[1] | **François Genest**[3] | **Fanny Lécuyer Giguère**[1,4] | **Franco Lepore**[1] | **Johannes Frasnelli**[1,4,5]

[1]Département de Psychologie, Université de Montréal, Montréal, QC, Canada

[2]Research Institute of the MUHC, Montréal, QC, Canada

[3]Département de Psychologie, Université de Sherbrooke, Sherbrooke, QC, Canada

[4]Centre de recherche de l'hôpital Sacré-Coeur de Montréal, Montréal, QC, Canada

[5]Département d'anatomie, Université du Québec à Trois-Rivières, Trois-Rivières, QC, Canada

**Correspondence**
Catherine Landry, Département de Psychologie, Université de Montréal, Montréal, QC, Canada.
Email: catherine.landry.14@umontreal.ca

**Funding information**
Canada Research Chair Program, Grant/Award Number: RGPIN-8245-2014 (FL); Natural Sciences and Engineering Research Council of Canada, Grant/Award Numbers: RGPIN-2022-04813 (JF), RGPIN/05053-2014 (FL); Canadian Institutes of Health Research, Grant/Award Numbers: 166197 (FL), 173514 (JF)

Edited by: John Foxe

## Abstract

Sensory deprivation, especially hearing loss (HL), offers a valuable model for studying neuroplasticity in the human brain and adaptive behaviours that support the daily lives of those with limited or absent sensory input. The study of olfactory function is particularly important as it is an understudied aspect of sensory deprivation. This study aimed to compare the effects of congenital HL on olfactory capacity by using psychophysical tasks. Methodological concerns from previous studies regarding the onset of HL and cognitive assessments were addressed. We recruited 11 individuals with severe-to-profound sensorineural HL (SNHL) since birth and 11 age- and sex-matched typical hearing non-signers. We used standardized neuropsychological tests to assess typical cognition among participants with SNHL. We evaluated olfactory functions by assessing olfactory detection threshold, odour discrimination and odour identification. Hearing-impaired participants outperformed their typical hearing counterparts in olfactory tasks. We further evaluated the accuracy and response time in identifying and localizing odours to disentangle olfactory sensitivity from trigeminal system sensitivity. Participants with SNHL demonstrated higher sensitivity to both the identification and localization tasks. These findings suggest that congenital SNHL is associated with enhanced higher-level olfactory processing and increased trigeminal sensitivity.

**KEYWORDS**
adaptation, hearing loss, olfaction, perception, trigeminal

**Abbreviations:** 2AFC, Two-Alternative Forced Choice; AOLI, Automated Odorant Localization and Identification; CI, Cochlear Implant; HL, Hearing Loss; SST, Sniffin' Sticks test; TDI, Threshold-discrimination-identification overall score.

Catherine Landry and Rim Nazar Contributed equally to the manuscript

## 1 | INTRODUCTION

Sensory deprivation is of particular interest in the study of brain neuroplasticity and adaptive behaviour. The absence of a sensory modality such as hearing prompts individuals to rely on adaptive behaviours to effectively navigate their environment. Sensory deprivation plays a significant role in the reorganization of functional processing in intact sensory modalities, known as neuroplasticity (Alencar et al., 2019; Bavelier & Neville, 2002; Bell et al., 2019; Pavani & Bottari, 2012). Previous studies have used psychophysical tasks (e.g., Codina et al., 2017; Megreya & Bindemann, 2017; Shiell et al., 2014; Smittenaar et al., 2016) and brain imaging (e.g, Simon et al., 2020) to demonstrate enhanced visual performance in individuals with congenital HL. Despite being limited, studies examining tactile modality have shown greater sensitivity in individuals with HL, particularly in tasks that require complex cognitive processes (Sharp et al., 2020; van Dijk et al., 2013). Given the compensatory neuroplasticity observed in response to HL in both auditory and tactile modalities, it can be hypothesized that similar compensatory adaptations may occur in the olfactory system. Accordingly, this study aimed to investigate potential behavioural differences in olfactory and trigeminal abilities between individuals with congenital SNHL and those with typical hearing.

To date, few studies have quantified chemosensory abilities in relation to sensory deprivation and the findings have been contradictory (Diekmann et al., 1994; Guducu et al., 2016; for a review of participants with blindness, see Sorokowska et al., 2019). The influence of confounding factors such as delayed language acquisition in individuals with HL and cognitive abilities has not been adequately controlled. The latter is crucial given the distinctive cognitive abilities exhibited by individuals with congenital HL to direct visual attention (Colmenero et al., 2004; Parasnis & Samar, 1985) and spatial memorization (Cattani & Clibbens, 2005). Moreover, odour identification and discrimination are closely linked to executive functioning proficiency and semantic memory throughout the adult lifespan (Hedner et al., 2010; Larsson et al., 2000).

Another shortcoming of the existing literature is the high prevalence of olfactory dysfunction in HL, which complicates the interpretation of previous findings. For example, three out of thirteen hearing-impaired participants in a study (Guducu et al., 2016) exhibited normosmia (normal olfaction), seven met the clinical criteria for hyposmia (reduced odour detection) and two had anosmia (loss of smell). Despite thorough otorhinolaryngological examinations to exclude sinonasal pathologies and nasal septal deviation, the observed rate of olfactory impairment is higher than the expected prevalence in the general population (Yang & Pinto, 2016), that is, 15% for hyposmia and 5% for anosmia (Landis et al., 2009). It is unclear whether this poor olfactory performance is solely attributable to HL or whether it is influenced by cognitive factors, task comprehension or inadequate sample representation.

Therefore, our current understanding of olfactory acuity in relation to HL is constrained by notable methodological factors, including heterogeneous clinical scoring, variable onset of HL and lack of cognitive function measures. Furthermore, the duration of deafness and the potential impact of auditory rehabilitation through cochlear implants (CI) are factors known to influence the extent of neuroplasticity among individuals with hearing impairment (Kral et al., 2016). To mitigate the potential confounding effects, some of these factors were considered in the present study.

The evaluation of olfactory function poses several challenges. Odorants are complex in nature and often contain mixed olfactory and trigeminal components that can be detected even in individuals with anosmia (Doty et al., 1978). For ecological validity, it is more relevant to use odorants that are likely to be encountered in the environment rather than relying on pure odorants that exclusively stimulate the olfactory system since they are rare. Trigeminal nerve activation can be used to identify which nostrils are stimulated during monorhinal stimulation (Frasnelli et al., 2007, 2009; Kleemann et al., 2009). The trigeminal system processes sensations such as burning, cooling, itching or stinging-evoked volatile substances (Laska et al., 1997) and is associated with different polymodal ion channels from the transient receptor potential (TRP) subfamily. Activation of these channels by chemical or thermal stimulation of the trigeminal nerve can be used to identify the specific receptors involved (Frasnelli & Manescu, 2017; Viana, 2011). For example, TRPM8 receptors are activated by cool temperatures or chemical agents such as eucalyptol (eucalyptus) (Behrendt et al., 2004; Boonen et al., 2016), whereas the TRPA1 receptor is stimulated by a range of molecules, including benzaldehyde (which has an almond-like odour) (Richards et al., 2010) and other irritants (Viana, 2011). The trigeminal system plays a prominent role in shaping the overall chemosensory experience and may therefore increase sensitivity in the context of HL. However, trigeminal sensitivity has not been investigated in this population.

This study aimed to investigate olfactory and trigeminal processing in individuals with congenital SNHL using psychophysical tasks. Specifically, we measured the odour detection threshold, discrimination and identification using the Sniffin' Sticks test, and timed odour

localization and identification using the automated odorant localization and identification test. Building on previous research and controlling for cognitive function, we hypothesized that individuals with congenital SNHL would exhibit enhanced olfactory performance, consistent with the adaptive neuroplasticity observed in the visual and tactile modalities during sensory deprivation. Additionally, it was expected that this enhancement would extend to the trigeminal system, suggesting a superior ability to localize odours in individuals with SNHL.

## 2 | MATERIALS & METHODS

### 2.1 | Participant characteristics

Twenty-two participants were recruited in this study: 11 individuals with severe-to-profound bilateral congenital HL (7 females; age range = 20–51 years ($M = 35.64$; $SD = 9.63$) assessed by audiologists and 11 hearing non-signers (7 females; age range = 20–52 years ($M = 35.64$; $SD = 10.42$). The HL condition was caused by sensorineural hearing impairment, and five individuals were using a CI at the time of testing. The experimental and control groups were matched for sex and age. Only individuals with a normal sense of smell, as indicated by a combined threshold-discrimination-identification (TDI) score of ≥ 31 out of 48, were included in the study. The exclusion criteria were psychiatric or neurological disorders (Moberg et al., 1999; Moscavitch et al., 2009), otolaryngological diseases associated with olfactory dysfunction (Landis et al., 2009) and smoking (Vennemann et al., 2008). The participants were instructed to avoid eating an hour prior to the experiment and to refrain from using scented products on the day of testing. The study was approved by the Research Ethics Board of the Centre de Recherche Interdisciplinaire en Réadaptation du Montréal métropolitain and the Centre de Recherche de l'Hôpital Sacré-Coeur de Montréal. All the participants provided written informed consent and were rewarded with monetary compensation for their

**TABLE 1** Descriptive characteristics of the participants.

| Id | Condition | Age (yrs) | Gender | Education (yrs) | Language preference | CI duration (yrs) |
|---|---|---|---|---|---|---|
| 1 | HL | 45 | F | 16 | SL + oral | 42 |
| 2 | HL | 28 | F | 14 | SL + oral | 24 |
| 3 | HL | 20 | M | 14 | SL + oral | 18 |
| 4 | HL | 28 | M | 16 | Oral | 27 |
| 5 | HL | 47 | M | 9 | Oral | 42 |
| 6 | HL | 51 | F | 7 | SL | - |
| 7 | HL | 36 | F | 16 | SL | - |
| 8 | HL | 32 | F | 14 | SL | - |
| 9 | HL | 35 | M | 16 | SL | - |
| 10 | HL | 28 | F | 16 | SL | - |
| 11 | HL | 42 | F | 11 | SL | - |
| 12 | CTL | 46 | F | 11 | Oral | - |
| 13 | CTL | 47 | M | 16 | Oral | - |
| 14 | CTL | 52 | F | 13 | Oral | - |
| 15 | CTL | 36 | F | 16 | Oral | - |
| 16 | CTL | 31 | F | 16 | Oral | - |
| 17 | CTL | 20 | M | 14 | Oral | - |
| 18 | CTL | 34 | M | 14 | Oral | - |
| 19 | CTL | 28 | M | 16 | Oral | - |
| 20 | CTL | 27 | F | 21 | Oral | - |
| 21 | CTL | 26 | F | 18 | Oral | - |
| 22 | CTL | 45 | F | 12 | Oral | - |

*Note*: HL = Hearing loss; CTL = Typical hearing control; F = Female; M = Male; SL = Sign language (all signer participants used the Quebec Sign Language); CI = Cochlear implant.

involvement in the study. The sociodemographic characteristics of the participants are presented in Table 1.

### 2.1.1 | Cognitive assessments

Given previous studies suggesting cognitive differences in individuals with HL, a series of validated nonverbal neuropsychological tests were administered to ascertain cognitive function in these participants. The percentile rank scores were comparable to those of normative samples for each test. The tests used were:

1. Rey-Osterrieth Complex Figure Test: This test evaluates spatial memorization capacities, visuoconstructive skills, planning abilities, organizational skills and perceptual and motor functions (Deborah & Jane, 1985). Average Z-scores were obtained for individuals with SNHL in immediate recall ($Z = -0.67$), delayed recall ($Z = -0.6$) and recognition task ($Z = 0.2$).
2. Wechsler Abbreviated Scale of Intelligence II: The block subtest was used to measure visuospatial and visuomotor coordination skills, while the matrix subtest was used to evaluate visuoperceptual and logical reasoning skills (Wechsler, 2013). Participants with SNHL performances on the block ($Z = 1.09$) and matrix ($Z = 0.87$) subtests were calculated.
3. Ruff 2 & 7 Test: This test assesses the ability to orient and maintain an adequate and stable level of efficiency throughout visual activity (Ruff et al., 1992). Accuracy ($Z = -0.6$) and response time ($Z = 0.24$) were calculated.

## 2.2 | Procedure

Participants with SNHL were recruited through various channels, including program managers, audiologists and billboard advertisements at the Institut Raymond-Dewar de Montréal. Control participants were recruited online or through advertisements posted at the Université de Montréal and were selected to match the age and sex distributions of the experimental group. Demographic information was collected through email to ensure compliance with the inclusion criteria of the study. Participants with SNHL were asked to complete two questionnaires. The first questionnaire focused on the history of hearing impairment, covering aspects such as the cause of HL, age of onset, duration of HL and use of hearing aids and CI. The second questionnaire assessed their means of communication, including age at exposure to language, level of oral fluency and proficiency in sign language.

A Sign Language interpreter was enlisted to facilitate the communication and optimal participation of hearing-impaired signers. The interpreter translated the task instructions and research protocol into sign language, and videos of the interpreter were presented to participants via a touchpad before each task. The experimenter also communicated by writing on paper until complete understanding was reached. Verbal instructions were provided to control participants.

### 2.2.1 | Olfactory function assessment

Olfactory capacity was evaluated using the Sniffin' Sticks test (SST; Burghardt, Wedel, Germany) (Hummel et al., 1997), a validated task that typically takes 40-to-60-minute to complete (Hummel et al., 2007; Kobal et al., 2000). This test employs a set of felt-tip pen-like odour-dispensing devices – the Sniffin' Sticks – designed to release odours at increasing intensity/different quality levels and evaluates the threshold detection (T), discrimination (D) and identification (I) of odours. The scores for each subtask range from 1 to 16. The overall olfactory performance was assessed using the TDI score (Wolfensberger, 2000), which ranged from 1 to 48. Based on this scale, participants were categorized as having normosmia ($TDI \geq 31$), hyposmia ($15 < TDI < 31$), or anosmia ($TDI \leq 15$) (Hummel et al., 2007; updated version Oleszkieicz et al., 2019). To minimize the influence of visual cues on odour recognition, participants were blindfolded during the test and asked to write down their answers on paper after each trial. The following section provides a brief overview of the assessment procedure for each subtask (for more detailed information, refer to Rumeau & Jankowski, 2016).

1. The *detection* threshold (T) was evaluated using multiple forced choices following an ascending/descending staircase procedure with 16 sticks. Each trial involved the presentation of three sticks, two of which contained a solvent and one contained a diluted concentration of phenylethanol alcohol (PEA, rose-like odour), according to predefined degrees. The sticks were presented in random order for 20 s each, and participants were asked to identify the PEA stick within the triplets. Two consecutive correct identifications of the PEA stick reversed the staircase to a lower concentration staircase. An error reversed the scale to a higher concentration staircase. The test concluded following a seven-point scale reversal. The detection threshold score was determined as the average of the last four staircase turns (Hummel et al., 2007).

2. The *discrimination* task (D) involved 16 triplets of sticks randomly presented. Each set of triplets consisted of two sticks emitting the same odorant, and a third stick containing a different target odorant (Hummel et al., 2007). Participants were instructed to identify which sticks differed in odour. Each triplet was separated by at least 30 s, and each stick presentation was accompanied by a 3-second interval. The discrimination score was calculated as the sum of correctly identified odd sticks.
3. The odour *identification* (I) procedure employed a 4 multiple-forced choice format. Participants were presented with 16 sticks, each containing a different common odour (Hummel et al., 2007). They were allowed to smell sticks as much as needed before responding. A 30-second interval was allotted between each stick presentation. The identification score was calculated based on the sum of the correctly identified odours.

#### 2.2.2 | Automated odorant localization and identification (AOLI)

Olfactory and trigeminal processing were evaluated using a computer-controlled device that delivered fast and stable stimuli (Lundström et al., 2010). A total of 36 stimulations were presented: 12 air (control), 12 benzaldehyde (almond; Sigma–Aldrich, St. Louis, MO, USA), and 12 eucalyptol (eucalyptus; Galenova, St.-Hyacinth, QC, Canada) stimuli. The selection of benzaldehyde and eucalyptol was based on their ability to stimulate both olfactory and trigeminal systems. They were diluted to 50% in propylene glycol (Sigma–Aldrich, St. Louis, MO, USA). The stimulations were delivered in a randomized order to either the left or the right nostrils every 30 s.

During the experiment, participants were given two different instructions: "Where?" and "What?". In half of the trials, participants were asked to localize the stimulated nostril through a forced-choice response (R for right or L for left). In the remaining trials, participants were required to identify the delivered stimuli through a forced-choice response (A for almond or E for eucalyptus). The instructions were displayed on a computer screen before odorant delivery (Kéïta et al., 2013). By doing so, we evaluated the sensitivity of the trigeminal (odour localization) and olfactory (odour identification) systems. Participants were also instructed to press the corresponding keyboard button as quickly as possible. The number of hits (correct detection when the stimulus was present), false alarms (inaccurate detection of the stimulus when absent) and response time (s) were recorded. To prevent habituation, a 30-second fixed interval separated the stimuli, and the conditions were counterbalanced. Continuous white noise was played to mask any sounds emitted by the device and to prevent cueing during the localization or identification tasks. This preventive procedure was maintained in the group with HL to standardize the protocol.

Following Signal Detection Theory (Stanislaw & Todorov, 1999), the number of hits and false alarms were used to compute the sensitivity index ($d'$) and response bias ($C$). The sensitivity index $d'$ quantifies the accuracy of detecting the stimulus by comparing the number of hits (correct detections) to the number of false alarms (incorrect detections). Higher values of $d'$ indicate better task performance and greater sensitivity to stimuli. Response bias $C$ provides insight into participants' decision-making strategies and response tendencies. A positive bias indicates a tendency towards a specific side (in the case of the localization task) or stimulus (in the identification task).

### 2.3 | Statistical analyses

Assumptions of sphericity (Mauchly's test of sphericity, $p > 0.05$), normality (Kolmogorov–Smirnov test for normality, $p > 0.05$) and variance homogeneity (Levene's test, $p > 0.05$) were met for the SST data. An independent sample $t$-test was performed to compare the computed TDI scores between the deaf and hearing individuals. A mixed-design ANOVA was conducted to compare the effect of *group* (between-subject factor; two levels: HL and typical hearing) on scores, with *task* (three levels: detection, discrimination and identification) as a within-subject factor.

To account for the non-normality of the AOLI data, we conducted a robust mixed-design ANOVA using the sensitivity index and response bias as dependent variables, with *task* (two levels: identification and localization) as the within-subjects factor and *group* (two levels: HL and typical hearing) as the between-subjects factor.

An exploratory analysis using the Mann–Whitney U test was performed to compare the mean scores (SST and AOLI) between the five individuals with HL who were wearing a CI at the time of testing and those who had no CI experience. All post-hoc comparisons were adjusted using Bonferroni's procedure. The alpha level of significance was set at 0.05 for all analyses.

## 3 | RESULTS

### 3.1 | Olfactory function assessment

On average, participants with HL ($M = 40.159$, $SD = 3.204$) obtained a higher overall TDI score than

control participants ($M = 36.204$, $SD = 3.409$). This difference (95% CI, 0.270–2.096) was found to be statistically significant ($t[20] = -2.803$, $p = 0.011$), with a large effect size ($d = 1.195$).

The mixed-design ANOVA revealed no statistically significant interaction between *task* × *group* for the individual SST tests ($F[2,40] = 0.463$, $p = 0.633$, $\eta^2 = 0.23$). However, a significant main effect of *group* was observed ($F[1,20] = 7859$, $p = 0.011$, $\eta^2 = 0.282$), indicating that individuals with HL performed better than controls, which is consistent with the overall TDI score. There was a significant main effect of *task* ($F[2,40] = 9.795$, $p < 0.001$, $\eta^2 = 0.329$), with the highest scores observed in the identification task, followed by the discrimination and olfactory threshold tasks (Figure 1, Table 2).

## 3.2 | Automated odorant identification and localization (AOLI)

For the sensitivity index *d'*, the robust mixed-design ANOVA revealed no significant interaction between *task* * *group* ($F[1,40] = 0.008$, $p = 0.929$, $\eta^2 = 0.00$). However, there was a substantial main effect of *task* ($F[1,40] = 10.04$, $p = 0.003$, $\eta^2 = 0.20$). On average, participants were more sensitive during the identification task ($M = 1.057$, $SD = 0.666$) than during the localization task ($M = 0.361$, $SD = 0.856$). A significant main effect of *group* was also observed ($F[1,40] = 6.16$, $p = 0.017$, $\eta^2 = 0.113$), indicating that individuals with HL demonstrated a small advantage over hearing controls in both identification and localization tasks (see Table 3 for details). The results are shown in Figure 2.

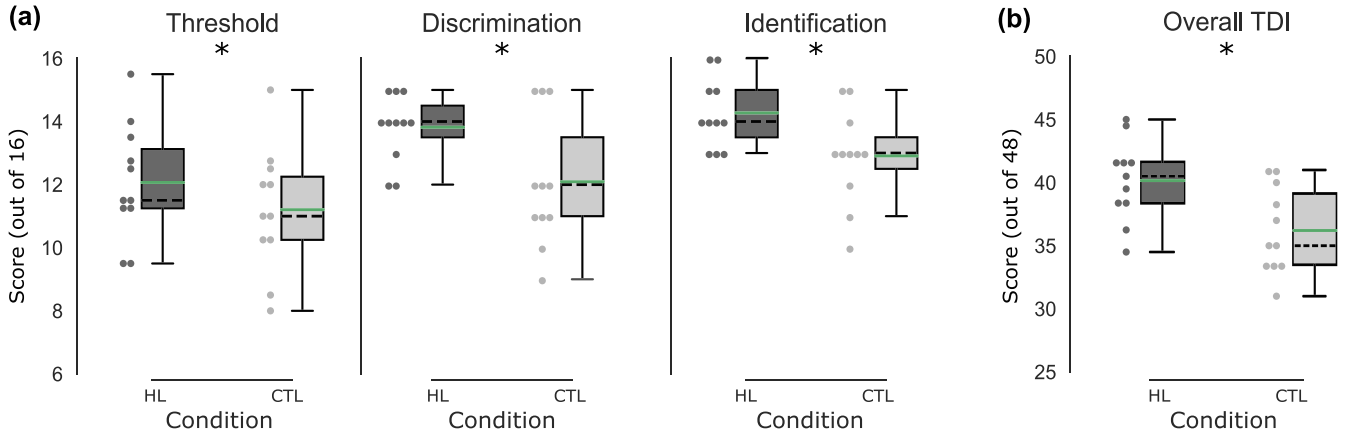


**FIGURE 1** **A)** The score distribution for olfactory detection threshold (T), discrimination (D), and identification (I) tasks; **B)** the overall TDI score on the Sniffin' Sticks test. Asterisk indicates a significant group effect at $p < 0.05$. The median is represented by the dashed line within each boxplot, whereas the group mean is represented by the solid green line. The first and third quartiles are delimited by the lower and upper horizontal lines of the boxplots. The minimum and maximum values are indicated by lower and upper fences, respectively. Each data point represents the performance of an individual participant. HL: hearing loss; CTL: typical hearing control.

**TABLE 2** Sniffin' Sticks test (SST) descriptive statistics separated by task and condition.

| | Threshold | | Discrimination | | Identification | |
|---|---|---|---|---|---|---|
| | HL | CTL | HL | CTL | HL | Control |
| *N* | 11 | 11 | 11 | 11 | 11 | 11 |
| *Mean* | 12.068 | 11.205 | 13.818 | 12.091 | 14.273 | 12.909 |
| *SD* | 1.827 | 1.981 | 1.079 | 2.071 | 1.104 | 1.514 |
| *SE* | 0.575 | 0.575 | 0.498 | 0.498 | 0.399 | 0.399 |
| *Min* | 9.5 | 8 | 12 | 9 | 13 | 10 |
| *Max* | 15.5 | 15 | 15 | 15 | 16 | 15 |

*Note*: HL = Hearing loss; CTL = Typical hearing control.

The results regarding response bias *C* did not reveal a significant effect of interaction between *task* * *group* ($F$[1,40] = 0.104, $p = 0.749$) or the main effect of *group* ($F$[1,40] = 0.074, $p = 0.787$). However, a small main effect was observed for *task* ($F$[1,40] = 9.057, $p = 0.004$, $\eta^2 = 0.184$), suggesting that different response strategies were employed depending on the task. On average, the identification task displayed a slightly positive bias ($M = 0.253$, $SD = 0.301$), whereas the localization task exhibited a negative bias ($M = -0.20$, $SD = 0.583$).

The average response times for localization ($M = 2.124$, $SD = 0.627$) and identification ($M = 2.056$, $SD = 0.686$) were similar. No significant effect of *task* was found ($F$[1,20] = 3.14, $p = 0.083$, $\eta^2 = 0.015$), and there was no interaction between *task* * *group* ($F$[1,20] = 0.32, $p = 0.860$, $\eta^2 = 0.002$). However, there was a main effect of *group* ($F$[1,20] = 6001, $p = 0.024$, $\eta^2 = 0.231$). Participants with HL ($M = 1.765$, $SD = 0.328$) were faster at identifying odorants than hearing controls ($M = 2.346$, $SD = 0.833$). This tendency also extended to the localization task, where individuals with HL ($M = 1.856$, $SD = 0.436$) had significantly faster response times than the control participants ($M = 2.392$, $SD = 0.691$). 1

### 3.2.1 | Additional sensitivity analysis

Some of the sensitivity index scores were below 0 (see Figure 2), indicating potential issues with task comprehension or other factors, such as randomness, confusion and inattention. To address this, we excluded participants who performed the task significantly below chance (with $d' \leq 0.5$, according to a binomial distribution) from further sensitivity analysis. Specifically, a robust two-way mixed-design ANOVA was conducted to accommodate violations of the normality assumption and unequal group sizes. Even after excluding these participants, the significant main effect of the *group* remained ($F$[1, 14] = 10.89, $p = 0.005$, $\eta^2 = 0.437$), suggesting that individuals with HL were more sensitive to the identification task ($M = 1.388$, $SD = 0.273$) than the hearing controls ($M = 0.97$, $SD = 0.574$). The difference was less pronounced for the localization task, with individuals with HL ($M = 0.919$, $SD = 0.543$) being slightly more sensitive than the hearing controls ($M = 0.868$, $SD = 0.561$). No interaction between *task* * *group* was found ($F$[1, 14] = 0.046, p = 0.833, $\eta^2 = 0.003$). However, the main effect of *task* was no longer significant ($F$[1, 14] = 3.75, $p = 0.073$). Nevertheless, it appears that participants tend to exhibit a greater sensitivity towards the identification

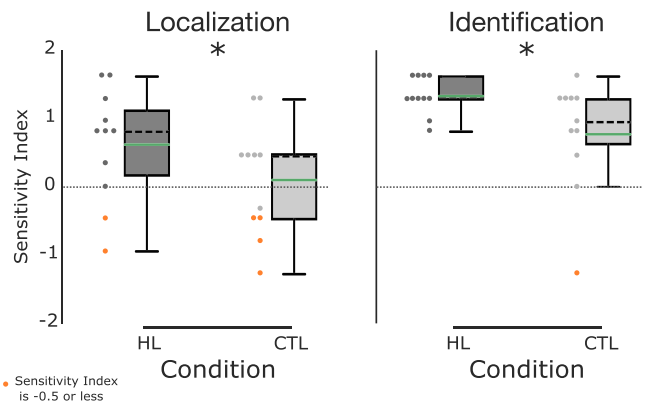


**FIGURE 2** Sensitivity index score for the automated odorant localization (left) and identification (right) tasks. Asterisk indicates a significant group effect at $p < 0.05$. The dashed line in the box represents the median value, and the solid green line represents the group mean. The first and third quartiles are delimited by lower and upper horizontal lines of the boxplots. The minimum and maximum values are indicated by the lower and upper fences, respectively. Each point indicates the performance of a single participant. Performances with *d'* values below 0.5, denoted by the orange dots, were excluded in an additional sensitivity analysis. HL: hearing loss; CTL: typical hearing control.

**TABLE 3** Automated identification and localization (AOLI) test descriptive statistics separated by task, measure, and condition.

| | **Identification** | | | | **Localization** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Sensitivity index** | | **Response bias** | | **Sensitivity index** | | **Response bias** | |
| | HL | CTL | HL | CTL | HL | CTL | HL | CTL |
| *N* | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| *Mean* | 1.339 | 0.775 | 0.227 | 0.280 | 0.622 | 0.100 | 0.178 | 0.309 |
| *SD* | 0.277 | 0.824 | 0.257 | 0.350 | 0.827 | 0.838 | 0.603 | 0.546 |
| *SE* | 0.185 | 0.185 | 0.093 | 0.093 | 0.251 | 0.2\51 | 0.173 | 0.173 |
| *Min* | 0.813 | −1.29 | 0 | −0.336 | −0.954 | −1.29 | −1.29 | −0.813 |
| *Max* | 1.627 | 1.627 | 0.813 | 0.813 | 1.627 | 1.29 | 0.813 | 1.29 |

*Note*: HL = Hearing loss; CTL = Typical hearing control.

task ($M = 1.202$, $SD = 0.467$) compared to the localization task ($M = 0.777$, $SD = 0.558$).

### 3.2.2 | Exploratory analysis: effect of cochlear implant

No significant difference was observed between CI users and those without CI in the SST global score ($U = 13.5$, $p = 0.792$). Similarly, no differences were found for AOLI identification regarding the sensitivity index ($U = 9.5$, $p = 0.329$), response bias ($U = 25$, $p = 0.082$), AOLI localization in terms of the sensitivity index ($U = 20.5$, $p = 0.329$) or response bias (U = 18, $p = 0.662$). The response times were also not significant for the identification ($U = 7$, $p = 0.117$) or localization tasks ($U = 14$, $p = 0.931$).

## 4 | DISCUSSION

This study examined the effect of congenital SNHL on several chemosensory tasks. As predicted, our findings demonstrated that individuals with SNHL outperformed typical hearing non-signers, indicating enhanced olfactory ability and trigeminal perception.

However, these results contradict the existing literature on olfaction, which has shown either reduced olfactory performance or no significant difference related to HL. One possible explanation for this discrepancy could be the selection criteria used in our study. Unlike previous studies that employed similar techniques (Diekmann et al., 1994; Guducu et al., 2016), we ensured that participants with HL exhibited typical cognitive functions, as indicated by scores within the normative range for attention, visual memory and fluid reasoning. This is particularly important for olfactory tasks that are closely linked to executive functioning proficiency and semantic memory, such as odour identification and discrimination (e.g., Hedner et al.,2010; Larsson et al., 2000). However, there is no clear consensus on how HL affects executive functions (for a review on executive functions in children with HL, refer to Simon et al., 2020). Further research is needed to explore how hearing abilities and cognitive processes intersect, especially semantic memory and executive function, which were both not assessed in our series of tests. The variability observed in previous studies, particularly regarding the prevalence of hyposmia and anosmia in individuals with HL (Guducu et al., 2016), could potentially be attributed to differences in cognitive functions. Given the limited number of studies, determining the underlying phenomena poses significant challenges.

Vocabulary knowledge is important for the SST identification task, in which participants label odorants through forced-choice responses (Hummel et al., 1997). A recent study found that receptive vocabulary level explains the lower performance in the ability to suppress the interference of distractors observed in children with HL rather than sensory deprivation (Merchán et al., 2022). To ensure accurate responses and complete comprehension of the task, future studies should use appropriate tests and present instructions and response choices in the native language of participants when working with individuals with limited verbal language and reading abilities. We believe that this factor had a minimal impact on our findings since we tailored the instructions to the preferred means of communication of the participants with HL.

The differences in the existing literature may be partly attributed to the age at HL onset, a factor known to influence compensatory plasticity (Lazzouni & Lepore, 2014). The brain has a critical period in early postnatal life when it is most receptive to change (Oberman & Pascual-Leone, 2013). However, one common limitation in studies on HL is the heterogeneity of backgrounds within their samples (Bavelier et al., 2006). For example, a sample may include individuals with congenital HL along with undetermined or late-onset HL. When these subgroups constitute only a minority within a larger sample (e.g., Diekmann et al., 1994; Sorokowska et al., 2019), the effects cannot be solely attributed to sensory deprivation. To gain a deeper understanding of the impact of sensory deprivation on the brain, our study targeted individuals with congenital HL, i.e., who had no auditory experience during their early years. By narrowing to this specific type of HL, we aimed to eliminate variability due to the onset of HL.

Multiple evidence has suggested that compensatory behaviours resulting from sensory deprivation do not systematically translate into significant differences in low-level olfactory processing (Diekmann et al., 1994; Guducu et al., 2016; Sorokowska et al., 2019). This is consistent with similar psychophysical studies conducted in other perceptual modalities, which have shown limited compensatory enhancements and often specific aspects of perception associated with higher-level or life-relevant abilities (for reviews in the vision modality, see Alencar et al., 2019; Bavelier et al., 2006). Although our study identified minor variations in olfactory thresholds between individuals with HL and controls, future research should focus on investigating higher-level olfactory processes to identify potential compensatory mechanisms.

Our findings support the allocation of additional resources to the chemosensory domain as a

compensatory mechanism for auditory deprivation. This is in line with previous studies demonstrating similar compensatory effects in the visual and tactile modalities (Megreya & Bindemann, 2017; Sharp et al., 2020; Shiell et al., 2014; Simon et al., 2020; Smittenaar et al., 2016; van Dijk et al., 2013). It is widely believed that cross-modal reorganization drives adaptive and compensatory behaviours (Merabet & Pascual-Leone, 2010), although the exact mechanisms underlying these compensatory effects remain complex (Kupers & Ptito, 2014). Future neuroimaging studies will provide valuable insights into the neurobiological basis of these sensory enhancements.

In our study, the behavioural advantage of individuals with HL extended to the trigeminal system, as they demonstrated greater sensitivity to localizing odours. This finding is consistent with previous research on early blindness (Manescu et al., 2021). To measure trigeminal sensitivity, our study used an odour-localization task that has been validated in previous research (Frasnelli et al., 2007). The trigeminal system, which is considered the third chemosensory system alongside smell and taste, serves a protective function by eliciting physiological reflexes, such as salivation, tearing, coughing, respiratory depression and sneezing (Viana, 2011). The enhanced ability to localize odours observed in individuals with HL may serve to maximize sensory perception and facilitate environmental awareness.

It is worth noting that several participants obtained sensitivity index scores below zero, posing challenges for interpretation. According to some authors (Stanislaw & Todorov, 1999), below-chance performance can be caused by response confusion, pressing the response button too quickly or unknown factors. However, our study found no evidence of unreasonably fast reaction times contributing to these scores. As explained in the Supplementary Material, below-chance performance can be expected in a 2AFC experiment using our number of trials. We believe that the limited number of trials in the AOLI test is more likely to influence these findings. Sensitivity indices such as *d'* rely on the observed frequencies of hits and false alarms. With a small number of trials, these frequencies can become more variable, making it difficult to distinguish the true performance from chance fluctuations. More trials are essential to obtain reliable estimates of an individual's true sensitivity. Our results demonstrated group differences when excluding participants with *d'* values below −0.5. However, future studies with larger sample sizes and trial numbers are needed to generalize our findings and minimize potential biases, including random variance and sensitivity index distortion.

In addition to increased response sensitivity, the findings revealed faster reaction times in both the localization and identification tasks. Previous studies have found a positive correlation between faster reaction times and higher response accuracy (Kéïta et al., 2013). Sensory deprivation has been shown to affect visual function, particularly the processing of spatial information in the peripheral visual field. This often manifests as faster reaction times to visual stimuli (Bottari et al., 2011; Chen et al., 2006; Codina et al., 2017; Nava et al., 2008; Prasad et al., 2017), which is an advantage that emerges during adolescence and persists into adulthood (Codina et al., 2011). The faster response times observed among individuals with HL may indicate behavioural compensation resulting from sensory deprivation-induced neuroplasticity.

One limitation of our study was including five individuals with HL implanted with a CI. Among them, three were implanted before the age of 3.5, meaning they had access to residual hearing during the sensitive period when the central auditory system is most receptive to change (Sharma et al., 2002). We conducted an exploratory analysis to compare the CI users to the other participants with HL. Although no statistically significant differences were found, the uneven sex distribution and small number of participants per subgroup limit the reliability of this comparison. Larger sample sizes are necessary to draw stronger conclusions regarding the influence of CI use and age at implantation on olfactory and trigeminal functions. In future studies, it is suggested to treat CI users as a distinct group, considering its implications on communication mode (oral or signed) and the degree of neuroplasticity. The small sample size in our study restricts the generalizability of our findings; therefore, caution should be exercised when interpreting the results. It should also be noted that information on handedness was only obtained for the control group, all of whom were right-handed.

## 5 | CONCLUSION

In this study, psychophysical methods were used to assess the influence of congenital SNHL on chemosensory systems. These findings indicate that individuals with severe-to-profound congenital SNHL and typical cognitive abilities exhibit higher olfactory scores than those with typical hearing. Furthermore, they demonstrated an increased sensitivity to trigeminal odour localization. Overall, these results highlight potential compensatory mechanisms in olfactory and trigeminal sensory processing in individuals with congenital SNHL.

## ACKNOWLEDGEMENTS

This research was supported by grants from the Canada Research Chair Program #RGPIN-8245–2014 [FL]; and

the Natural Sciences and Engineering Research Council of Canada #RGPIN/05053–2014 [FL] and #RGPIN-2022-04813 [JF]; and the Canadian Institutes of Health Research #166197 [FL] and #173514 [JF]. CL was supported by a salary award from Fonds de Recherche du Québec en Santé (FRQS).

## CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to disclosure.

## DATA AVAILABILITY STATEMENT

With respect to patient confidentiality, data can be made available upon request from the corresponding authors.

## PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/ejn.16216.

## AUTHOR CONTRIBUTION STATEMENT

*CL: Formal Analysis, Visualization, Writing-Reviewing and Editing. *RN: Investigation, Writing – Original Draft. MS: Conceptualization, Methodology, FG: Conceptualization, Methodology. FLG: Investigation, Methodology. FL: Supervision, Funding Acquisition. JF: Conceptualization, Reviewing, Supervision and Funding Acquisition. *CL and RN contributed equally to this study.

## ORCID

*Catherine Landry* https://orcid.org/0000-0001-6748-1417
*Johannes Frasnelli* https://orcid.org/0000-0002-8863-3982

## REFERENCES

Alencar, D. C. C., Blake, E. B., & Lomber, S. G. (2019). What and how the deaf brain sees. *Journal of Cognitive Neuroscience*, *31*(8), 1089–1109. https://doi.org/10.1162/jocn_a_01425

Bavelier, D., Dye, M. W., & Hauser, P. C. (2006). Do deaf individuals see better? *Trends in Cognitive Sciences*, *10*(11), 512–518. https://doi.org/10.1016/j.tics.2006.09.006

Bavelier, D., & Neville, H. J. (2002). Cross-modal plasticity: Where and how. *Nature Reviews Neuroscience*, *3*(6), 443–452. https://doi.org/10.1038/nrn848

Behrendt, H. J., Germann, T., Gillen, C., Hatt, H., & Jostock, R. (2004). Characterization of the mouse cold-menthol receptor TRPM8 and vanilloid receptor type-1 VR1 using a fluorometric imaging plate reader (FLIPR) assay. *British Journal of Pharmacology*, *141*(4), 737–745. https://doi.org/10.1038/sj.bjp.0705652

Bell, L., Wagels, L., Neuschaefer-Rube, C., Fels, J., Gur, R. E., & Konrad, K. (2019). The cross-modal effects of sensory deprivation on spatial and temporal processes in vision and audition: A systematic review on behavioral and neuroimaging research since 2000. *Neural Plasticity*, *2019*, 9603469. https://doi.org/10.1155/2019/9603469

Boonen, B., Startek, J. B., & Talavera, K. (2016). Chemical Activation of Sensory TRP Channels. In D. Krautwurst (Ed.), *Taste and smell* (Vol. 23, pp. 73–113). Springer International Publishing. https://doi.org/10.1007/7355_2015_98

Bottari, D., Caclin, A., Giard, M. H., & Pavani, F. (2011). Changes in early cortical visual processing predict enhanced reactivity in deaf individuals. *PLoS ONE*, *6*(9), e25607. https://doi.org/10.1371/journal.pone.0025607

Cattani, A., & Clibbens, J. (2005). Atypical lateralization of memory for location: Effects of deafness and sign language use. *Brain and Cognition*, *58*(2), 226–239. https://doi.org/10.1016/j.bandc.2004.12.001

Chen, Q., Zhang, M., & Zhou, X. (2006). Effects of spatial distribution of attention during inhibition of return (IOR) on flanker interference in hearing and congenitally deaf people. *Brain Research*, *1109*(1), 117–127. https://doi.org/10.1016/j.brainres.2006.06.043

Codina, C., Buckley, D., Port, M., & Pascalis, O. (2011). Deaf and hearing children: A comparison of peripheral vision development. *Developmental Science*, *14*(4), 725–737. https://doi.org/10.1111/j.1467-7687.2010.01017.x

Codina, C. J., Pascalis, O., Baseler, H. A., Levine, A. T., & Buckley, D. (2017). Peripheral visual reaction time is faster in deaf adults and British sign language interpreters than in hearing adults. *Frontiers in Psychology*, *8*, 50. https://doi.org/10.3389/fpsyg.2017.00050

Colmenero, J. M., Catena, A., Fuentes, L. J., & Ramos, M. M. (2004). Mechanisms of visuospatial orienting in deafness. *European Journal of Cognitive Psychology*, *16*(6), 791–805. https://doi.org/10.1080/09541440340000312

Deborah, P. W., & Jane, M. H. (1985). Assessing children's copy productions of the Rey-Osterrieth complex figure. *Journal of Clinical and Experimental Neuropsychology*, *7*(3), 264–280. https://doi.org/10.1080/01688638508401259

Diekmann, H., Walger, M., & von Wedel, H. (1994). Sense of smell in deaf and blind patients. *HNO*, *42*(5), 264–269.

van Dijk, R., Kappers, A. M., & Postma, A. (2013). Superior spatial touch: Improved haptic orientation processing in deaf individuals. *Experimental Brain Research*, *230*(3), 283–289. https://doi.org/10.1007/s00221-013-3653-7

Doty, R. L., Brugger, W. E., Jurs, P. C., Orndorff, M. A., Snyder, P. J., & Lowry, L. D. (1978). Intranasal trigeminal stimulation from odorous volatiles: Psychometric responses from anosmic and normal humans. *Physiology & Behavior*, *20*(2), 175–185. https://doi.org/10.1016/0031-9384(78)90070-7

Frasnelli, J., Charbonneau, G., Collignon, O., & Lepore, F. (2009). Odor localization and sniffing. *Chemical Senses*, *34*(2), 139–144. https://doi.org/10.1093/chemse/bjn068

Frasnelli, J., & Manescu, S. (2017). The Intranasal Trigeminal System. In A. Buettner (Ed.), *Springer Handbook of Odor* (pp. 113–114). Springer International Publishing. https://doi.org/10.1007/978-3-319-26932-0_46

Frasnelli, J., Schuster, B., & Hummel, T. (2007). Interactions between olfaction and the trigeminal system: What can be learned from olfactory loss. *Cerebral Cortex*, *17*(10), 2268–2275. https://doi.org/10.1093/cercor/bhl135

Guducu, C., Oniz, A., Ikiz, A. O., & Ozgoren, M. (2016). Chemosensory function in congenitally blind or deaf teenagers. *Chemosensory Perception*, *9*(1), 8–13. https://doi.org/10.1007/s12078-015-9199-2

Hedner, M., Larsson, M., Arnold, N., Zucco, G. M., & Hummel, T. (2010). Cognitive factors in odor detection, odor discrimination, and odor identification tasks. *Journal of clinical and experimental neuropsychology*, *32*(10), 1062-1067. https://doi.org/10.1080/13803391003683070

Hummel, T., Kobal, G., Gudziol, H., & Mackay-Sim, A. (2007). Normative data for the "Sniffin' sticks" including tests of odor identification, odor discrimination, and olfactory thresholds : An upgrade based on a group of more than 3,000 subjects. *European Archives of Oto-Rhino-Laryngology*, *264*(3), 237–243. https://doi.org/10.1007/s00405-006-0173-0

Hummel, T., Sekinger, B., Wolf, S. R., Pauli, E., & Kobal, G. (1997). 'Sniffin' Sticks': Olfactory performance assessed by the combined testing of odor identification, odor discrimination and olfactory threshold. *Chemical Senses*, *22*(1), 39–52. https://doi.org/10.1093/chemse/22.1.39

Kéïta, L., Frasnelli, J., La Buissonnière-Ariza, V., & Lepore, F. (2013). Response times and response accuracy for odor localization and identification. *Neuroscience*, *238*, 82–86. https://doi.org/10.1016/j.neuroscience.2013.02.018

Kleemann, A. M., Albrecht, J., Schöpf, V., Haegler, K., Kopietz, R., Hempel, J. M., ... Wiesmann, M. (2009). Trigeminal perception is necessary to localize odors. *Physiology & Behavior*, *97*(3–4), 401–405. https://doi.org/10.1016/j.physbeh.2009.03.013v

Kobal, G., Klimek, L., Wolfensberger, M., Gudziol, H., Temmel, A., Owen, C. M., Seeber, H., Pauli, E., & Hummel, T. (2000). Multicenter investigation of 1,036 subjects using a standardized method for the assessment of olfactory function combining tests of odor identification, odor discrimination, and olfactory thresholds. *European Archives of Oto-Rhino-Laryngology*, *257*(4), 205–211. https://doi.org/10.1007/s004050050223

Kral, A., Kronenberger, G. W., Pisoni, B. D., & O'Donoghue, M. G. (2016). Neurocognitive factors in sensory restoration of early deafness: A connectome model. *The Lancet Neurology*, *15*(6), 610–621. https://doi.org/10.1016/S1474-4422(16)00034-X

Kupers, R., & Ptito, M. (2014). Compensatory plasticity and cross-modal reorganization following early visual deprivation. *Neuroscience & Biobehavioral Reviews*, *41*, 36–52. https://doi.org/10.1016/j.neubiorev.2013.08.001

Landis, B. N., Konnerth, C. G., & Hummel, T. (2009). A study on the frequency of olfactory dysfunction. *The Laryngoscope*, *114*(10), 1764–1769. https://doi.org/10.1097/00005537-200410000-00017

Larsson, M., Finkel, D., & Pedersen, N. L. (2000). Odor identification: Influences of age, gender, cognition, and personality. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *55*(5), 304–310. https://doi.org/10.1093/geronb/55.5.P304

Laska, M., Distel, H., & Hudson, R. (1997). Trigeminal perception of odorant quality in congenitally anosmic subjects. *Chemical Senses*, *22*(4), 447–456. https://doi.org/10.1093/chemse/22.4.447

Lazzouni, L., & Lepore, F. (2014). Compensatory plasticity: Time matters. *Frontiers in Human Neuroscience*, *8*, 340. https://doi.org/10.3389/fnhum.2014.00340

Lundström, J. N., Gordon, A. R., Alden, E. C., Boesveldt, S., & Albrecht, J. (2010). Methods for building an inexpensive computer-controlled olfactometer for temporally-precise experiments. *International Journal of Psychophysiology*, *78*(2), 179–189. https://doi.org/10.1016/j.ijpsycho.2010.07.007

Manescu, S., Chouinard-Leclaire, C., Collignon, O., Lepore, F., & Frasnelli, J. (2021). Enhanced odorant localization abilities in congenitally blind but not in late-blind individuals. *Chemical Senses*, *46*. https://doi.org/10.1093/chemse/bjaa073

Megreya, A. M., & Bindemann, M. (2017). A visual processing advantage for young-adolescent deaf observers: Evidence from face and object matching tasks. *Scientific Reports*, *7*(1), 41133. https://doi.org/10.1038/srep41133

Merabet, L. B., & Pascual-Leone, A. (2010). Neural reorganization following sensory loss: The opportunity of change. *Nature Reviews Neuroscience*, *11*, 44–52. https://doi.org/10.1038/nrn2758

Merchán, A., García, L. F., Maurno, N. G., Castañeda, P. R., & González, M. T. D. (2022). Executive functions in deaf and hearing children: The mediating role of language skills in inhibitory control. *Journal of Experimental Child Psychology*, *218*, 105374. https://doi.org/10.1016/j.jecp.2022.105374

Moberg, P. J., Agrin, R., Gur, R. E., Gur, R. C., Turetsky, B. I., & Doty, R. L. (1999). Olfactory dysfunction in schizophrenia: A qualitative and quantitative review. *Neuropsychopharmacology*, *21*(3), 325–340. https://doi.org/10.1016/S0893-133X(99)00019-6

Moscavitch, S.-D., Szyper-Kravitz, M., & Schoenfeld, Y. (2009). Autoimmune pathology accounts for common manifestations in a wide range of neuro-psychiatric disorders: The olfactory and immune system interrelationship. *Clinical Immunology*, *130*(3), 235–243. https://doi.org/10.1016/j.clim.2008.10.010

Nava, E., Bottari, D., Zampini, M., & Pavani, F. (2008). Visual temporal order judgment in profoundly deaf individuals. *Experimental Brain Research*, *190*(2), 179–188. https://doi.org/10.1007/s00221-008-1459-9

Oberman, L., & Pascual-Leone, A. (2013). Chapter 4 - Changes in Plasticity Across the Lifespan: Cause of Disease and Target for Intervention. In M. M. Merzenich, M. Nahum, & T. M. Van Vleet (Eds.), *Progress in brain research* (Vol. 207, pp. 91–120). Elsevier. https://doi.org/10.1016/B978-0-444-63327-9.00016-3

Oleszkiewicz, A., Schriever, V. A., Croy, I., Hähner, A., & Hummel, T. (2019). Updated Sniffin' Sticks normative data based on an extended sample of 9139 subjects. *European Archives of Oto-rhino-laryngology*, *276*, 719-728. https://doi.org/10.1007/s00405-018-5248-1

Parasnis, I., & Samar, V. J. (1985). Parafoveal attention in congenitally deaf and hearing young adults. *Brain and Cognition*, *4*(3), 313–327. https://doi.org/10.1016/0278-2626(85)90024-7

Pavani, F., & Bottari, D. (2012). Visual Abilities in Individuals with Profound Deafness: A Critical Review. In M. M. Murray & M. T. Wallace (Eds.), *The neural bases of multisensory processes*. CRC Press/Taylor & Francis. http://www.ncbi.nlm.nih.gov/books/NBK92865/

Prasad, S., Patil, G. S., & Mishra, R. K. (2017). Cross-modal plasticity in the deaf enhances processing of masked stimuli in the visual modality. *Scientific Reports*, *7*(1), 8158. https://doi.org/10.1038/s41598-017-08616-4

Richards, P. M., Johnson, E. C., & Silver, W. L. (2010). Four irritating odorants target the trigeminal chemoreceptor TRPA1. *Chemosensory Perception*, *3*(3), 190–199. https://doi.org/10.1007/s12078-010-9081-1

Ruff, M. R., Niemann, H., Allen, C. C., Farrow, E. C., & Wylie, T. (1992). The Ruff 2 and 7 selective attention test: A neuropsychological application. *Perceptual and Motor Skills*, *75*(3), 1311–1319. https://doi.org/10.2466/pms.1992.75.3f.1311

Rumeau, C., Nguyen, D. T., & Jankowski, R. (2016). How to assess olfactory performance with the Sniffin'Sticks test®. *European Annals of Otorhinolaryngology, Head and Neck Diseases*, *133*(3), 203–206. https://www.sciencedirect.com/science/article/pii/S1879729615001039 https://doi.org/10.1016/j.anorl.2015.08.004

Sharma, A., Dorman, M. F., & Spahr, A. J. (2002). A sensitive period for the development of the central auditory system in children with cochlear implants: Implications for age of implantation. *Ear and Hearing*, *23*(6), 532–539. https://doi.org/10.1097/00003446-200212000-00004

Sharp, A., Bacon, B. A., & Champoux, F. (2020). Enhanced tactile identification of musical emotion in the deaf. *Experimental Brain Research*, *238*(5), 1229–1236. https://doi.org/10.1007/s00221-020-05789-9

Shiell, M. M., Champoux, F., & Zatorre, R. J. (2014). Enhancement of visual motion detection thresholds in early deaf people. *PLoS ONE*, *9*(2), e90498. https://doi.org/10.1371/journal.pone.0090498

Simon, M., Campbell, E., & Lepore, F. (2020). Cross-modal plasticity and central deficiencies: The case of deafness and the use of cochlear implants. In *Handbook of Clinical Neurology* (Vol. *174*, pp. 343–355). Elsevier. https://doi.org/10.1016/B978-0-444-64148-9.00025-9

Simon, M., Lazzouni, L., Campbell, E., Delcenserie, A., Muise-Hennessey, A., Newman, A. J., Champoux, F., & Lepore, F. (2020). Enhancement of visual biological motion recognition in early-deaf adults: Functional and behavioral correlates. *PLoS ONE*, *15*(8), e0236800. https://doi.org/10.1371/journal.pone.0236800

Smittenaar, C. R., MacSweeney, M., Sereno, M. I., & Schwarzkopf, D. S. (2016). Does congenital deafness affect the structural and functional architecture of primary visual cortex. *The Open Neuroimaging Journal*, *10*, 1–19. https://doi.org/10.2174/1874440001610010001

Sorokowska, A., Sorokowski, P., Karwowski, M., Larsson, M., & Hummel, T. (2019). Olfactory perception and blindness: a systematic review and meta-analysis. *Psychological research*, *83*, 1595-1611. https://doi.org/10.1007/s00426-018-1035-2

Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods, Instruments, & Computers*, *31*(1), 137–149. https://doi.org/10.3758/BF03207704

Vennemann, M. M., Hummel, T., & Berger, K. (2008). The association between smoking and smell and taste impairment in the general population. *Journal of neurology*, *255*, 1121-1126. https://doi.org/10.1007/s00415-008-0807-9

Viana, F. (2011). Chemosensory properties of the trigeminal system. *ACS Chemical Neuroscience*, *2*(1), 38–50. https://doi.org/10.1021/cn100102c

Wechsler, D. (2013). WASI -II: Wechsler abbreviated scale of intelligence—Second edition. *Journal of Psychoeducational Assessment*, *31*(3), 337–341. https://doi.org/10.1177/0734282912467756

Wolfensberger, M. (2000). Sniffin'Sticks: A new olfactory test battery. *Acta Oto-Laryngologica*, *120*(2), 303–306. https://doi.org/10.1080/000164800750001134

Yang, J., & Pinto, J. M. (2016). The epidemiology of olfactory disorders. *Current Otorhinolaryngology Reports*, *4*(2), 130–141. https://doi.org/10.1007/s40136-016-0120-6

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Landry, C., Nazar, R., Simon, M., Genest, F., Giguère, F. L., Lepore, F., & Frasnelli, J. (2024). Behavioural evidence for enhanced olfactory and trigeminal perception in congenital hearing loss. *European Journal of Neuroscience*, *59*(3), 434–445. https://doi.org/10.1111/ejn.16216