Effects of blindness and anosmia on auditory discrimination of temperature and carbonation of liquids

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Abstract

Our experience of the world around us is multisensory. Although vision is considered the dominant (spatial) sense, attention is increasingly being paid to the importance of auditory cues in navigating everyday life behaviors. The sounds associated with preparing and consuming foods and drinks have been shown to play an important role in hedonic perception. Yet, little is known about the extent to which auditory cues influence the behavior of blind or anosmic individuals. In the absence of vision, it is likely that more attention is paid to the sounds associated with a certain food or drink items, in order to assess their sensory qualities (e.g., freshness) and help guide their preparation. Product sounds may compensate for the lack of aroma perception in anosmia. We addressed these assumptions by studying a sample of 401 participants of whom 101 were anosmic and 101 were blind. We included two respective control groups with fully functional sensory modalities (sighted: n=99 and normosmic: n=100). All of the participants were asked to discriminate the temperature and carbonation of drinks based solely on auditory cues. The results of the study indicate that auditory cues are particularly important for the assessment of drink temperature in blind people and carbonation in anosmic individuals. These supranormal abilities likely develop for adaptive purposes. The results of the present study supplement the discussion concerning sensory compensation in blindness, but as one of a few demonstrates this ability in a practical, everyday context of a highly ecological task.

Keywords: audition; sensory compensation; blindness; anosmia; temperature; carbonation

1. Introduction

Our experience of the environment that surrounds us is multisensory. Yet the prevailing view is that sight is the dominant (spatial) sense, often calibrating the input from other modalities (Hutmacher, 2019; Lewald, 2002; Zwiers et al., 2001). However, emerging evidence also points to the importance of audition in variety of everyday situations, including the assessments of food and drink. Auditory information plays the key role of both the background noise (Mathiesen et al., 2022; Motoki et al., 2022; Peng-Li et al., 2022; Spence, 2014) and the sonic properties of food and beverage products that can help to shape consumers' hedonic expectations and assessments (Spence, 2012, 2015). Untrained consumers are able to discriminate between the sounds of hot and cold drinks being poured at a level that is significantly better than chance, even though they are not necessarily aware that they are able to do so (Velasco et al., 2013). The ability to "hear the temperature" seems to be subject to developmental experience. Children may perceptually learn the cross-modal correspondences (Chow et al., 2016; Nava et al., 2016). Starting from 7 years of age, children can accurately discriminate cold from hot water based on nothing more than sonic cues, while younger children do not show this ability (Agrawal & Schachner, 2022). Furthermore, auditory cues also allow for the differentiation of drinks having differing levels of carbonation. Mineral water, prosecco, and Champagne can be distinguished from one another at a level that is significantly better than chance by trained and untrained consumers solely on the basis of the sound they make while poured into a flute glass (Spence & Wang, 2015; see also Zampini & Spence, 2005). The key role of auditory perception in chemosensory experience has been demonstrated in those studies in which deaf individuals have been shown to exhibit significantly higher gustatory thresholds and lower taste liking in comparison to their hearing controls and blind individuals (Oleszkiewicz et al., 2023).

Our understanding of the role of audition in influencing chemosensory experience is limited and overlooks the role that sensory compensation might play in attributing greater meaning to auditory cues relating specifically to chemosensory experience. Typically, we use the five classical sensory modalities (and more) to interact with the world around us, yet some people who experience sensory loss may develop supra-normal sensory abilities in the intact domains to compensate for the missing modality (Glick & Sharma, 2017; Voss et al., 2010). Sensory compensation may be caused by either the redistribution of attentional resources, the beneficial effects of the increased practice of a particular sense (Münte et al., 2001; Saito et al., 2006), and/or neural reorganization followed by the general improvement of the intact senses (Gougoux et al., 2005; Striem-Amit et al., 2011). All may lead to enhanced exposure-related sensitivity (Gagnon et al., 2014). Therefore, blind individuals may be more attentive to auditory cues and may recruit visual cortices to process input for their intact senses.

Supranormal auditory performance in those individuals with vision loss has been reported for specific tasks such as spatial processing (Doucet et al., 2005; Lessard et al., 1998; Nilsson & Schenkman, 2016; Röder et al., 1999; Voss et al., 2004), pitch discrimination and categorization tasks (Kupers & Ptito, 2014), episodic auditory memory (Röder et al., 2001), verbal memory (Amedi et al., 2003), and the processing and memorization of environmental sounds (Röder & Rösler, 2003). Congenitally blind individuals are also known to react more rapidly to non-visual (i.e., auditory and tactile) spatial targets (Collignon et al., 2006; Collignon & de Voider, 2009). In contrast, late blind individuals are typically less successful in compensating for the lack of vision in auditory tasks (Wan et al., 2010). Despite the compelling evidence for the supranormal auditory skills in blind individuals, little research has been conducted to apply it to practical situations, such as the assessment of food or drink. Yet, it is plausible that individuals with blindness may use their specific auditory skills when assessing foods or drinks and pay more attention to sounds when making choices about them. The auditory discrimination of hot and cold drinks may be important for navigating the environment and preventing themselves from being burnt by a hot beverage, say. The physical properties of liquids, such as viscosity and specific heat, drive sound absorption (Parthasarathy & Chhapgar, 1955), making the drinks sound differently in varying temperatures. Blind people outperform the sighted in pitch discrimination and categorization tasks, therefore it is plausible that they might be able to "hear the temperature" better. If true, this would help to open up further considerations regarding the design of those products and experiences that may be tailored to blind individuals.

While blindness results in enhanced auditory processing and the recruitment of occipital cortex in sound processing, anosmia, the loss of smell functionality, has not been found to directly impact any of the spatial senses (vision, audition, or touch). Additionally, given no apparent advantage of blind people over the sighted in olfactory tasks (for a review and meta-analysis, see Sorokowska et al., 2019) there is little-to-no evidence for crossmodal plasticity between the spatial and chemosensory modalities (Gagnon et al., 2014), except for the taste impairment and hedonic perception of taste in deaf individuals (Oleszkiewicz et al., 2023). Nevertheless, anosmic individuals may be more attentive to auditory signals that convey information about the properties of drinks, to compensate for the lack of aroma perception and enrich their chemosensory experience through visual, auditory, and/or tactile input (Pascua et al., 2013; van Eck & Stieger, 2020). Indeed, anosmic individuals pay more attention to the texture of food, which involves trigeminal, tactile, and auditory stimulation (de Graaf, 2020; Frasnelli & Hummel, 2007; Høier et al., 2021; Joyner (Melito), 2018; Laguna et al., 2021), but it remains unknown to what extent they can use auditory cues to assess the qualities of food and drink. Importantly, the role of auditory cues generated during the preparation phase (e.g., packaging and pouring sounds) in those individuals who are sensorially-deprived, who may rely on these cues to a greater extent in comparison to individuals with no sensory impairments, has received little attention from researchers to date.

The above assumptions about enhanced processing and elevated meaning attached to auditory cues in the food assessment of individuals with blindness or anosmia have not been addressed empirically. Therefore, we examined the accuracy of auditory temperature and carbonation discrimination in blind and anosmic participants and compared their responses with the respective control groups. Carbonation was operationalized in terms of the size of the bubbles (further referred to as bubbliness) and mousse that builds on the surface of carbonated drinks during pouring (further referred to as foaminess). Both these dimensions of carbonations have been demonstrated to be discriminable by consumers (Spence & Wang, 2015). To overcome the caveats of many previous reports, this study involves a large sample of people with blindness and those with anosmia.

2. Materials and methods

2.1 Participants

A total of 401 participants took part in this study. Normosmia in the control sample was ascertained by obtaining 30.75 or more TDI points in the Sniffin' Sticks test, out of possible 48 points. Anosmia was diagnosed in 99 individuals whose Sniffin' Sticks test TDI score was ≤16 points according to the normative data (Oleszkiewicz et al., 2019) and the remaining two patients presented profound hyposmia (18 and 16.25 TDI points in the Sniffin' Sticks test). Etiologies of olfactory dysfunction were as follows: idiopathic (n=37), post-infectious (n=26), post-traumatic (n=19), unknown (n=7), sinonasal (n=7), exposure to toxins (n=3) or congenital (n=2). There were similar gender proportions in the anosmia and normosmia groups $\chi^2(1)=0.23$, $p=.63$, and groups were of similar age, $t(200)=0.57$, $p=.57$, $d=14$.

One hundred and one participants with blindness were categorized as early blind if they had lost their sight before reaching two years of age and if they lost their sight later in life, they were categorized as late blind (Rombaux et al., 2010). They had marginal (n=49) to no light sensitivity (n=52), and none of the blind participants or sighted controls reported suffering from diabetic, neurological, or psychiatric diseases. The control group constituted individuals without any vision problems. There were slightly more sighted women than women with blindness, $\chi^2(1)=14.3$, $p<.001$, and the participants with blindness were slightly older (M=35.8±1 year) than their sighted controls (M=31.8±1 year), $t(199)=8$, $p<.001$.

Table 1: Basic demographic characteristics of the participants

	n	M_{age} (SD) [years]	% Females
Anosmic	101	56.6 (14.2)	51
Normosmic	100	56.2 (14.1)	52.2
Early blind	50	31.5 (8.2)	45.1
Late blind	51	40 (9.9)	47.2
Sighted	99	31.8 (10.1)	55

2.2 Recording samples

The auditory stimuli consisted of seven sounds in total, four sounds for the temperature discrimination task and three sounds for the carbonation discrimination task. Two of the temperature sounds consisted of cold and hot water being poured into a glass. The cold water fresh from the fridge was poured at a temperature of 6-8ºC whereas the hot water had a temperature of 82-84ºC. A volume of 200ml of liquid was poured into each vessel from a height of 10cm from a plastic measuring jug at a flow rate of 40 ml/s. The two sound recordings were then modified by changing the equalization (EQ) of the sounds; using opposite settings for each sound. The EQ of the hot sound was increased around 200Hz and decreased around 5-6kHz. The EQ of the cold sound was decreased at around 200Hz while being increased around 5-6kHz. The two original pouring sounds were modified in order to amplify the difference in sound by obtain a putatively 'hotter' and 'colder' sound, and to assess whether people's perception of hot or cold would change based on the modification of the original recordings' sonic qualities. Additionally, three original sounds were recorded for carbonation discrimination task. These were the sounds of San Pellegrino sparkling water (Bergamo, Italy), Pisani prosecco (Venetto, Italy), and Tattinger NV Champagne (Reims, France) each being poured into a champagne flute. All the original recordings were made using a Sennheiser 416 (Wennebostel, Germany) directional shotgun microphone located 25cm from the vessels.

2.3 Procedure

Participants were tested individually. They used Sennheiser HD-280 professional headphones to listen to the sounds. They were seated comfortably in front of a screen and designated software was launched on the computer by the experimenter. The participants played two recordings themselves in the order in which they were presented on the screen and then answered questions concerning the relative qualities of the recorded liquids (see below for details). The entire session did not exceed 10 min in duration, with the order of the tasks being randomized.

2.3.1 Task 1: Temperature discrimination

Each time, two recordings were displayed to the participant showing one of the following pairs: hotter-hot, hot-cold, cold-colder in a randomized order. The participant's task was to determine which one had a higher temperature and how big the temperature difference appeared to be by using a 6-point Likert-type scale: [1] Liquid 1 has a much higher temperature than Liquid 2; [2] Liquid 1 has a higher temperature than Liquid 2; [3] Liquid 1 has a somewhat higher temperature than Liquid 2; [4] Liquid 2 has a somewhat higher temperature than Liquid 1; [5] Liquid 2 has a higher temperature than Liquid 1; [6] Liquid 2 has a much higher temperature than Liquid 1. Each participant compared eight pairs of liquids chosen at random by the software. Answers were recoded so that increasing scores represent increasing temperature (i.e., participants are correct and certain).

2.3.2 Task 2: Carbonation discrimination

The icons that were associated with the two recordings appeared on the screen and the participant was asked to listen to them. Each recording was a sound of either mineral water, prosecco, or Champagne being poured into a glass. The software randomly drew two recordings (out of three) and presented them to the participant in a randomized order. The participant played recordings in the order displayed. Next, they answered two questions comparing the recordings to each other. The two questions compared the relative carbonation of two liquids with the 6-point Likert scale: [1] Liquid 1 is much foamier/bubblier than Liquid 2; [2] Liquid 1 is foamier/bubblier than Liquid 2; [3] Liquid 1 is somewhat foamier/bubblier than Liquid 2; [4] Liquid 2 is somewhat foamier/bubblier than Liquid 1; [5] Liquid 2 is foamier/bubblier than Liquid 1; [6] Liquid 2 is much foamier/bubblier than Liquid 1. Mineral water is characterized by bigger, “popping” bubbles and minimal foaminess to mute the “popping” sound, while Champagne is characterized by small, silent bubbles covered with foam that builds up during pouring. Prosecco falls in-between the middle of these two characteristics. Each participant compared eight pairs of liquids randomly chosen by the software. Answers were recorded in a way that increasing scores represent increasing foaminess (Champagne – prosecco – mineral water) while the reverse order is true for the size of the bubbles (bubbliness).

2.4 Statistical analyses

Data were analyzed with IBM SPSS software version 27 (IBM Corp. Released 2020, Armonk, NY: IBM Corp) with the level of significance set to α=.05. Linear mixed models with restricted likelihood estimation were built to examine the fixed effect of sensory status and the compared pair of liquids on the estimates of the relative difference in (1) temperature,

(2) foaminess, and (3) bubbliness, separately for the comparison between (a) anosmic and normosmic individuals, and (b) blind and sighted individuals, resulting in a total of six linear mixed models. The slopes were allowed to vary as a function of each participant, assuming their different sensory experience. Each model included gender as a fixed covariate. The data are available from the corresponding author upon request.

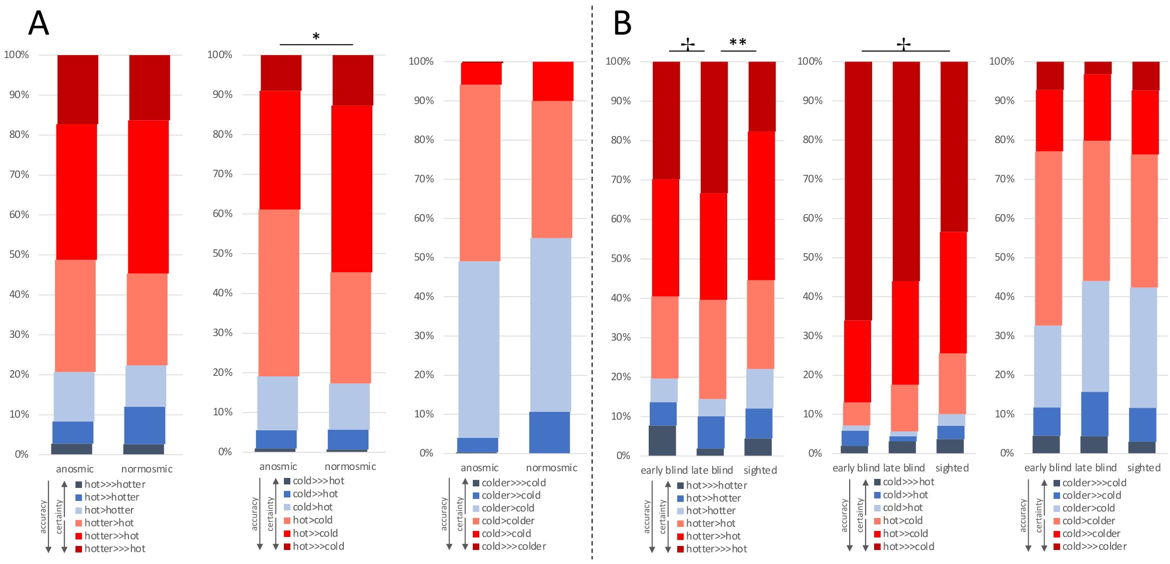
3. Results

3.1 Temperature discrimination

There was no significant differences in the accuracy of temperature discrimination between individuals with anosmia and normosmia, $F(1,193)=0.29$, $p=.59$. However, a significant interaction effect between the sensory status and compared pair of liquids compared, $F(1,1666)=3.93$, $p=.020$, revealed a small but significant advantage for individuals with normosmia over those with anosmia in discriminating a hot liquid from a cold liquid ($p=.02$, mean difference=0.2 points; Figure 1a) suggesting that deficits in chemosensory perception do not enhance the ability to "hear" temperature of liquids being poured into a glass and certainty of the judgment. In fact, participants with normosmia outperformed those with anosmia in discriminating a hot from a cold liquid. We found no difference between individuals with normosmia and anosmia in discriminating cold from colder and hot from hotter sounds (Figure 1a). Gender was not a significant covariate ($p=.96$). Both fixed and random effects accounted for approximately 19% of the variability in the accuracy of temperature discrimination (conditional $R^2=.19$).

Sighted participants were less accurate in discriminating liquids of different temperatures than the early blind ($p=.03$) and late blind ($p=.03$) participants, $F(2,193)=3.67$, $p=.03$. However, this disadvantage was moderated by the temperatures being compared, $F(4,1629)=2.70$, $p=.03$. When the hotter liquid was discriminated from hot liquid, the late blind participants were significantly more accurate than sighted people ($p=.013$) and marginally more accurate than the early blind (p=.064). When a hot liquid was discriminated from cold, the early blind participants were marginally more accurate than the sighted controls (p=.062). Finally, comparing cold and colder drinks did not yield any between-group differences. See Figure 1b for the exact distribution of assessments. The model accounted for 30% of the variability in the accuracy of temperature discrimination, as indicated by the conditional R^2=.30.

Figure 1: The distribution of scores for the temperature discrimination task comparing individuals with anosmia with the respective control group (A) and individuals with early and late blindness to the respective control group (B).

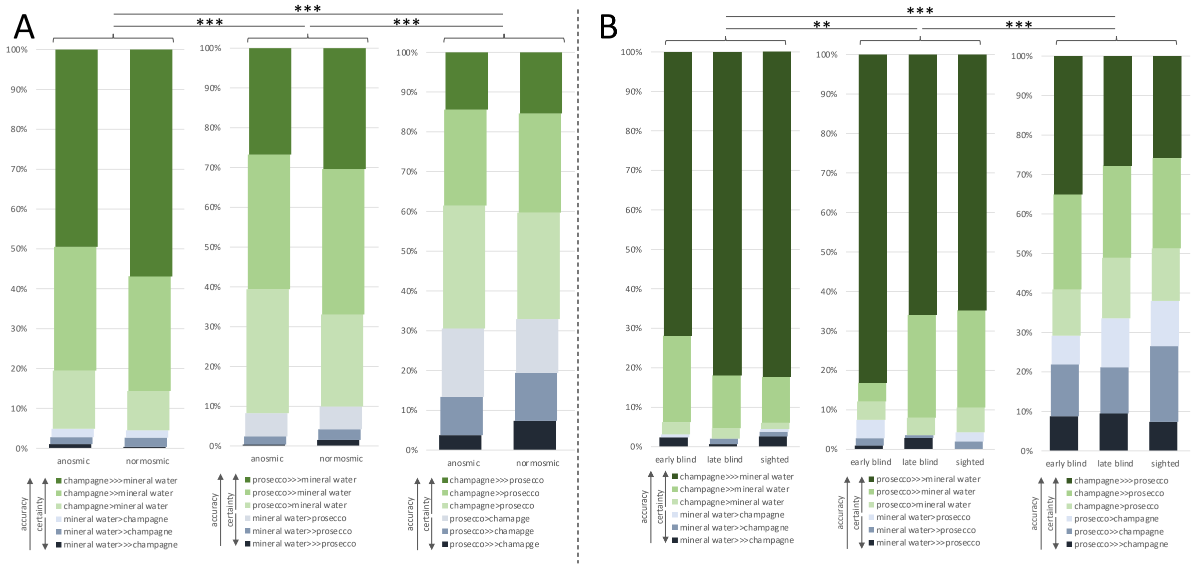


Note: >>> - has much higher temperature; >> - has higher temperature; > - has somewhat higher temperature; ** - p<.01; * - p<.05; † - p<.10. Red color denotes correct answers and gradient denotes certainty.

3.2 Foaminess discrimination

We did not observe any effects of anosmia or blindness on foaminess discrimination (all ps<.05), yet both models consistently showed that the mineral water and Champagne were significantly easier to discriminate from each other than the two other sounds pairs and that mineral water and prosecco were also easier to discriminate from each other than prosecco and Champagne (all *p*s<.035; See Figure 2). There were no other significant main or interaction effects (all *p*s>.21). Conditional R^2 indicated that the models looking into the effects of anosmia and blindness explained 25% and 29% of variance, respectively.

Figure 2: The distribution of scores for the foaminess discrimination task comparing individuals with anosmia with the respective control group (A) and individuals with early and late blindness to the respective control group (B).



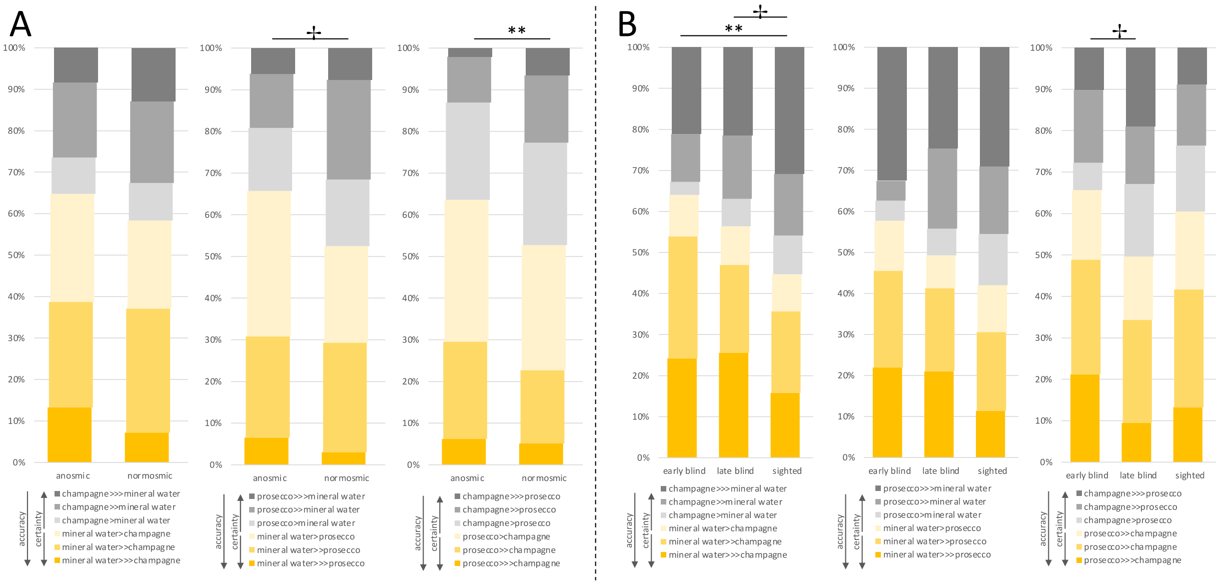
Note: >>> - is much foamier; >> - is foamier; > - is somewhat foamier; *** - *p*<.001; ** - *p*<.01; † - *p*<.10. Green color denotes correct answers and gradient denotes certainty

3.3 Bubbliness discrimination

Anosmic individuals were consistently more accurate in discriminating the more bubbly liquids from less bubbly liquids, irrespective of the quality of compared liquids (pairs), $F(1,203)=4.8$, $p=.03$. This advantage especially applied to comparisons between prosecco and Champagne ($p=.031$) and was marginal for the comparison mineral water and prosecco ($p=.06$). There were no other significant main or interaction effects (*p*s>.48). The proportion of explained total variance for this model was 36% as indicated by the conditional R^2.

Early blindness gave rise to advantage in hearing carbonation, $F(1,1614)=3.77$, $p=.005$. The sighted participants were less accurate and less certain in discriminating the carbonation of mineral water from Champagne than early blind ($p=.007$) and marginally less advanced than late blind ($p=.068$). The early blind slightly outperformed late blind individuals (but not the sighted) in discriminating bubbliness of prosecco and Champagne ($p=.086$). The proportion of explained variance was relatively high, as indicated by the conditional $R^2=.28$.

Figure 3: The distribution of scores for the bubbliness discrimination task comparing individuals with anosmia with the respective control group (A) and individuals with early and late blindness to the respective control group (B).



Note: >>> - is much bubblier; >> - is bubblier; > - is somewhat bubblier; ** - $p<.01$; † - $p<.10$. Yellow color denotes correct answers and gradient denotes certainty.

4. Discussion

The results of the study reported here investigation point to compensatory effects in blindness and anosmia when using auditory cues being used to discriminate the sound of drinks of varying temperature and types of carbonation. Blind individuals were more accurate when discriminating drinks based on their heard temperature than were the sighted controls. We did not see any compensatory effects among anosmic individuals– their accuracy was no different from that of those with normosmia (except for the hot-cold pair when individuals with normosmia were more accurate and certain when indicating which drink had higher temperature). The results of the present study did not yield any significant effects with regards to the auditory perception of foaminess, but rather demonstrated that the selected drinks recordings constituted a difficult task for some of the participants. Interestingly, compensatory effects were seen in the sensory impaired groups with regard to hearing how bubbly the drinks were. Both individuals with blindness and those with anosmia were more accurate and more certain of their judgments than the respective control groups including sighted and normosmic individuals.

The results of the present investigation are consistent with previous studies that have demonstrated enhanced auditory processing in blind individuals (Doucet et al., 2005; Frasnelli et al., 2011; Gougoux et al., 2005; Kärnekull et al., 2016; Lessard et al., 1998; Lewald, 2002; Nilsson & Schenkman, 2016; Röder et al., 1999; Röder & Rösler, 2003; Voss et al., 2004) and further supports such a conclusion by presenting the compensatory mechanism in a large sample of individuals with sensory impairment. Furthermore, the study examines sensory compensation in a more practical context, one that is relatively easy to link to the daily activities of the participants. Importantly, the present study demonstrates that the compensatory mechanism is not straightforward or obvious and does not depend on the onset of blindness. Depending on the temperature of the drinks, the early or late blind participants were both more accurate and more certain/confident in their judgments. When the hot drink was discriminated from a cold one, early blind individuals were significantly better than late blind or sighted individuals, but when hot was discriminated from hotter, it was late-blind individuals who excelled in the task.

The hypothesis regarding an attentive compensatory mechanism in individuals with anosmia gained mixed support. Although a minor effect in the opposite direction was seen in the temperature discrimination task when the hot and cold drinks were presented, anosmic individuals consistently outperformed those with normosmia in the accuracy of bubbliness discrimination. These observations are partially in line with the notion that texture, stimulating physical sensations in the mouth, is important for individuals whose aroma perception is impaired (de Graaf, 2020; Frasnelli & Hummel, 2007; Høier et al., 2021; Joyner (Melito), 2018; Laguna et al., 2021). The bubbles contain CO_2, an odorless gas known as a trigeminal stimulant (Carlson et al., 2013; Chevy & Klingler, 2014; Fröhlich, 1851; Oleszkiewicz et al., 2018) supporting the notion that trigeminal activation can be an important part of food experience in anosmia. We did not observe analogous effects for foaminess of the drinks, suggesting that texture qualities may have different impact on food perception in sensory loss.

Although previous research suggests that people are unaware that they are able to hear the temperature of a drink (Velasco et al., 2013), in the light of previous research (Spence & Wang, 2015; Zampini & Spence, 2005) and the current evidence, they actually can do it with considerable accuracy and confidence that may even be enhanced in blindness. We did not measure blind peoples' self-beliefs, but the observed results correspond with former reports pointing to the inflated views about their own sensory performance in the auditory domain, presented by blind individuals and sighted controls (Pieniak et al., 2021). Both people who experience sensory loss and healthy people considering the sensory performance of the sensory impaired, share beliefs that sensory impairment automatically leads to an increase in the performance of the intact senses. While sensory compensation is not an automatic or straightforward process, in the case of the current study we demonstrate that this adaptive conviction held true in some daily activities, that people are likely to train regularly.

There are several potential caveats associated with the present study that are worth discussing in order to refine further attempts focused on exploring the role of auditory cues in the assessment of food and drink. The pairs of drink that we used were not equally difficult to discriminate in terms of either temperature or foaminess. The cold versus colder pair of stimuli was apparently more confusing to all of the participants than the two pairs of hot versus cold or hot versus hotter pairs. It could either be that people had troubles referring to the auditory representation of such characteristics, or the recordings were too similar to each other. It could have been the case that the sole manipulation of EQ to transform 'cold' recording into 'colder' and 'hot' recording into 'hotter' failed to make these two laboratory-modified sounds sound natural. Although our aim was to amplify the difference in sound between hot and cold, the participants may have negligible experience with hearing the sound of a liquid at temperatures <6-8ºC or >82-84ºC. However, by reflecting this difficulty, our results advocate for the accuracy of participants' auditory representation of liquid beverages in a physically possible temperature range and not beyond that, therefore suggesting the sound-temperature association is based on real-life experience rather than associative learning. In the future, recordings could be pretested to examine how much the manipulation of sonic properties has "raised/lowered" the putative temperature/carbonation. Champagne and prosecco were the most difficult pair to discriminate in terms of foaminess, irrespective of the sensory impairment. The difference in foaminess between these two drinks is very subtle and probably requires prior experience, which we did not control in the current study. Although we decided not to directly compare individuals with anosmia with individuals with blindness due to the profound difference in the nature of their sensory impairment, from a look at Figure 1 one can clearly read that the foaminess task was much more difficult for individuals with anosmia and their control group as compared to the individuals with blindness and their sighted controls. Therefore, our study including both sensory-impaired groups lays the ground for more specific investigations focused on more homogenous samples. Finally, some of the discussed effects only marginally reached the conventional level of statistical significance (α=.05). This, together with the large sample involved in this study, imposes the conclusion of rather small effects reported. On the other hand, the auditory cues on which the study participants relied were very subtle yet revealed some sensory compensation mechanisms. It can therefore be assumed that more pronounced sound differences may more clearly guide the consumer decisions of people with visual and olfactory deficits.

5. Conclusion

The results of the present study demonstrate that auditory cues are particularly important for the assessment of the temperature of drinks in blind people and bubbliness in anosmic individuals. The increased accuracy in "hearing the temperature" is likely to develop for adaptative purposes. Blind people are more aware of the drink temperature, while individuals with anosmia are likely to search for additional trigeminal stimulation in the absence of aroma perception.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This work was supported by the National Science Centre in Poland, grant #2017/25/B/HS6/00561 awarded to AO.

References

Agrawal, T., & Schachner, A. (2022). Hearing water temperature: Characterizing the development of nuanced perception of sound sources. *Developmental Science*. https://doi.org/10.1111/desc.13321

Amedi, A., Raz, N., Pianka, P., Malach, R., & Zohary, E. (2003). Early "visual" cortex activation correlates with superior verbal memory performance in the blind. *Nature Neuroscience*, *6*(7), 758–766. https://doi.org/10.1038/nn1072

Carlson, K. S., Xia, C. Z., & Wesson, D. W. (2013). Encoding and Representation of Intranasal CO2 in the Mouse Olfactory Cortex. *Journal of Neuroscience*, *33*(34).

Chevy, Q., & Klingler, E. (2014). Odorless Trigeminal Stimulus CO2 Triggers Response in the Olfactory Cortex. *Journal of Neuroscience*, *34*(2).

Collignon, O., & de Voider, A. G. (2009). Further evidence that congenitally blind participants react faster to auditory and tactile spatial targets. *Canadian Journal of Experimental Psychology*, *63*(4). https://doi.org/10.1037/a0015415

Collignon, O., Renier, L., Bruyer, R., Tranduy, D., & Veraart, C. (2006). Improved selective and divided spatial attention in early blind subjects. *Brain Research*, *1075*(1). https://doi.org/10.1016/j.brainres.2005.12.079

de Graaf, K. (2020). Sensory Responses in Nutrition and Energy Balance: Role of Texture, Taste, and Smell in Eating Behavior. In *Handbook of Eating and Drinking*. https://doi.org/10.1007/978-3-030-14504-0_117

Doucet, M. E., Guillemot, J. P., Lassonde, M., Gagné, J. P., Leclerc, C., & Lepore, F. (2005). Blind subjects process auditory spectral cues more efficiently than sighted individuals. *Experimental Brain Research*, *160*(2). https://doi.org/10.1007/s00221-004-2000-4

Frasnelli, J., Collignon, O., Voss, P., & Lepore, F. (2011). Crossmodal plasticity in sensory loss. In *Progress in Brain Research* (Vol. 191). https://doi.org/10.1016/B978-0-444-53752-2.00002-3

Frasnelli, J., & Hummel, T. (2007). Interactions between the chemical senses: Trigeminal function in patients with olfactory loss. In *International Journal of Psychophysiology* (Vol. 65, Issue 3). https://doi.org/10.1016/j.ijpsycho.2007.03.007

Fröhlich, R. (1851). Ueber einige Modificationen des Geruchsinnes. *Akademie Der Wissenschaften Wien / Mathematisch-Naturwissenschafliche Classe*, *6*, 322–328.

Gagnon, L., Ptito, M., & Kupers, R. (2014). Making sense of the chemical senses. *Multisensory Research*, *27*(5–6). https://doi.org/10.1163/22134808-00002461

Glick, H., & Sharma, A. (2017). Cross-modal plasticity in developmental and age-related hearing loss: Clinical implications. In *Hearing Research* (Vol. 343). https://doi.org/10.1016/j.heares.2016.08.012

Gougoux, F., Zatorre, R. J., Lassonde, M., Voss, P., & Lepore, F. (2005). A functional neuroimaging study of sound localization: Visual cortex activity predicts performance in early-blind individuals. *PLoS Biology*, *3*(2). https://doi.org/10.1371/journal.pbio.0030027

Høier, A. T. Z. B., Chaaban, N., & Andersen, B. V. (2021). Possibilities for Maintaining Appetite in Recovering COVID-19 Patients. *Foods*, *10*(2). https://doi.org/10.3390/foods10020464

Hutmacher, F. (2019). Why Is There So Much More Research on Vision Than on Any Other Sensory Modality? *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.02246

Joyner (Melito), H. S. (2018). Explaining food texture through rheology. In *Current Opinion in Food Science* (Vol. 21). https://doi.org/10.1016/j.cofs.2018.04.003

Kärnekull, S. C., Arshamian, A., Nilsson, M. E., & Larsson, M. (2016). From perception to metacognition: Auditory and olfactory functions in early blind, late blind, and sighted individuals. *Frontiers in Psychology*, *7*(SEP). https://doi.org/10.3389/fpsyg.2016.01450

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

Laguna, L., Fiszman, S., & Tarrega, A. (2021). Saliva matters: Reviewing the role of saliva in the rheology and tribology of liquid and semisolid foods. Relation to in-mouth perception. *Food Hydrocolloids*, *116*. https://doi.org/10.1016/j.foodhyd.2021.106660

Lessard, N., Paré, M., Lepore, F., & Lassonde, M. (1998). Early-blind human subjects localize sound sources better than sighted subjects. *Nature*, *395*(6699). https://doi.org/10.1038/26228

Lewald, J. (2002). Vertical sound localization in blind humans. *Neuropsychologia*, *40*(12). https://doi.org/10.1016/S0028-3932(02)00071-4

Mathiesen, S. L., Hopia, A., Ojansivu, P., Byrne, D. V., & Wang, Q. J. (2022). The sound of silence: Presence and absence of sound affects meal duration and hedonic eating experience. *Appetite*, *174*. https://doi.org/10.1016/j.appet.2022.106011

Motoki, K., Takahashi, N., Velasco, C., & Spence, C. (2022). Is classical music sweeter than jazz? Crossmodal influences of background music and taste/flavour on healthy and indulgent food preferences. *Food Quality and Preference*, *96*. https://doi.org/10.1016/j.foodqual.2021.104380

Münte, T. F., Kohlmetz, C., Nager, W., & Altenmüller, E. (2001). Superior auditory spatial tuning in conductors. *Nature*, *409*(6820). https://doi.org/10.1038/35054668

Nava, E., Grassi, M., & Turati, C. (2016). Audio-Visual, Visuo-Tactile and Audio-Tactile Correspondences in Preschoolers. *Multisensory Research*, *29*(1–3), 93–111. https://doi.org/10.1163/22134808-00002493

Nilsson, M. E., & Schenkman, B. N. (2016). Blind people are more sensitive than sighted people to binaural sound-location cues, particularly inter-aural level differences. *Hearing Research*, *332*. https://doi.org/10.1016/j.heares.2015.09.012

Oleszkiewicz, A., Resler, K., Masala, C., Landis, B. N., Hummel, T., & Sorokowska, A. (2023). Alterations of gustatory sensitivity and taste liking in individuals with blindness or deafness. *Food Quality and Preference*, *103*, 104712. https://doi.org/10.1016/j.foodqual.2022.104712

Oleszkiewicz, A., Schriever, V. A. A., Croy, I., Hähner, A., & Hummel, T. (2019, December 15). Updated Sniffin' Sticks normative data based on an extended sample of 9139 subjects. *European Archives of Oto-Rhino-Laryngology*, *276*(3), 719–728. https://doi.org/10.1007/s00405-018-5248-1

Oleszkiewicz, A., Schultheiss, T., Schriever, V. A., Linke, J., Cuevas, M., Hähner, A., & Hummel, T. (2018). Effects of "trigeminal training" on trigeminal sensitivity and self-rated nasal patency. *European Archives of Oto-Rhino-Laryngology*. https://doi.org/10.1007/s00405-018-4993-5

Parthasarathy, S., & Chhapgar, A. F. (1955). Sound Absorption in Liquids in Relation to Their Physical Properties Viscosity and Specific Heats. *Annalen Der Physik*, *451*(5–8), 297–303. https://doi.org/10.1002/andp.19554510509

Pascua, Y., Koç, H., & Foegeding, E. A. (2013). Food structure: Roles of mechanical properties and oral processing in determining sensory texture of soft materials. In *Current Opinion in Colloid and Interface Science* (Vol. 18, Issue 4). https://doi.org/10.1016/j.cocis.2013.03.009

Peng-Li, D., Andersen, T., Finlayson, G., Byrne, D. V., & Wang, Q. J. (2022). The impact of environmental sounds on food reward. *Physiology and Behavior*, *245*. https://doi.org/10.1016/j.physbeh.2021.113689

Pieniak, M., Lachowicz-Tabaczek, K., Karwowski, M., & Oleszkiewicz, A. (2021). Sensory compensation beliefs among blind and sighted individuals. *Scandinavian Journal of Psychology*. https://doi.org/10.1111/sjop.12781

Röder, B., & Rösler, F. (2003). Memory for environmental sounds in sighted, congenitally blind and late blind adults: Evidence for cross-modal compensation. *International Journal of Psychophysiology*, *50*(1–2). https://doi.org/10.1016/S0167-8760(03)00122-3

Röder, B., Rösler, F., & Neville, H. J. (2001). Auditory memory in congenitally blind adults: a behavioral-electrophysiological investigation. *Cognitive Brain Research*, *11*(2), 289–303. https://doi.org/10.1016/S0926-6410(01)00002-7

Röder, B., Teder-Sälejärvi, W., Sterr, A., Rösler, F., Hillyard, S. A., & Neville, H. J. (1999). Improved auditory spatial tuning in blind humans. *Nature*, *400*(6740). https://doi.org/10.1038/22106

Rombaux, P., Huart, C., de Volder, A. G., Cuevas, I., Renier, L., Duprez, T., & Grandin, C. (2010). Increased olfactory bulb volume and olfactory function in early blind subjects. *Neuroreport*, *21*(17), 1069–1073. https://doi.org/10.1097/WNR.0b013e32833fcb8a

Saito, D. N., Okada, T., Honda, M., Yonekura, Y., & Sadato, N. (2006). Practice makes perfect: The neural substrates of tactile discrimination by Mah-Jong experts include the primary visual cortex. *BMC Neuroscience*, *7*. https://doi.org/10.1186/1471-2202-7-79

Sorokowska, A., Sorokowski, P., Karwowski, M., Larsson, M., & Hummel, T. (2019). Olfactory perception and blindness: a systematic review and meta-analysis. *Psychological Research*, *83*(8). https://doi.org/10.1007/s00426-018-1035-2

Spence, C. (2012). Auditory contributions to flavour perception and feeding behaviour. *Physiology and Behavior*, *107*(4). https://doi.org/10.1016/j.physbeh.2012.04.022

Spence, C. (2014). Noise and its impact on the perception of food and drink. *Flavour*, *3*(1). https://doi.org/10.1186/2044-7248-3-9

Spence, C. (2015). Eating with our ears: assessing the importance of the sounds of consumption on our perception and enjoyment of multisensory flavour experiences. *Flavour*, *4*(1). https://doi.org/10.1186/2044-7248-4-3

Spence, C., & Wang, Q. (2015). Sensory expectations elicited by the sounds of opening the packaging and pouring a beverage. *Flavour*, *4*(1). https://doi.org/10.1186/s13411-015-0044-y

Striem-Amit, E., Bubic, A., & Amedi, A. (2011). Neurophysiological mechanisms underlying plastic changes and rehabilitation following sensory loss in blindness and deafness. In *The Neural Bases of Multisensory Processes*. https://doi.org/10.1201/b11092-27

van Eck, A., & Stieger, M. (2020). Oral processing behavior, sensory perception and intake of composite foods. In *Trends in Food Science and Technology* (Vol. 106). https://doi.org/10.1016/j.tifs.2020.10.008

Velasco, C., Jones, R., King, S., & Spence, C. (2013). The Sound of Temperature: What Information do Pouring Sounds Convey Concerning the Temperature of a Beverage. *Journal of Sensory Studies*, *28*(5). https://doi.org/10.1111/joss.12052

Voss, P., Collignon, O., Lassonde, M., & Lepore, F. (2010). Adaptation to sensory loss. *Wiley Interdisciplinary Reviews: Cognitive Science*, *1*(3), 308–328. https://doi.org/10.1002/wcs.13

Voss, P., Lassonde, M., Gougoux, F., Fortin, M., Guillemot, J. P., & Lepore, F. (2004). Early- and late-onset blind individuals show supra-normal auditory abilities in far-space. *Current Biology*, *14*(19). https://doi.org/10.1016/j.cub.2004.09.051

Wan, C. Y., Wood, A. G., Reutens, D. C., & Wilson, S. J. (2010). Early but not late-blindness leads to enhanced auditory perception. *Neuropsychologia*, *48*, 344–348. https://doi.org/10.1016/j.neuropsychologia.2009.08.016

Zampini, M., & Spence, C. (2005). Modifying the multisensory perception of a carbonated beverage using auditory cues. *Food Quality and Preference*, *16*(7). https://doi.org/10.1016/j.foodqual.2004.11.004

Zwiers, M. P., van Opstal, A. J., & Cruysberg, J. R. (2001). A spatial hearing deficit in early-blind humans. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *21*(9). https://doi.org/10.1523/jneurosci.21-09-j0002.2001