



FIA 2020/22

XII CONGRESSO/CONGRESO IBEROAMERICANO DE ACÚSTICA

XXIX ENCONTRO DA SOCIEDADE BRASILEIRA DE ACÚSTICA - SOBRAC

Florianópolis, SC, Brasil

Auditory distance perception by blind and sighted participants for both within- and beyond-reach sources

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Resumen

Este estudio tuvo como objetivo probar la hipótesis que asocia a la ceguera con una capacidad reducida para juzgar la distancia absoluta de fuentes sonoras. Nuestras hipótesis de trabajo fueron: 1) Dentro del alcance, un sujeto ciego podrá compensar la falta de visión utilizando información propioceptiva para calibrar las señales acústicas de percepción de distancia. 2) A medida que la fuente se vuelve inalcanzable, las personas ciegas mostrarán mayores sesgos ya que, fuera del alcance, no se podría utilizar el mecanismo de calibración propuesto. Para abordar estos temas, llevamos a cabo una serie de experimentos de distancia auditiva en los que les pedimos a los participantes videntes y ciegos que informaran sus estimaciones de distancia verbalmente o alcanzando la fuente de sonido. Los resultados dentro del alcance mostraron que los participantes ciegos se desempeñaron mejor que (en la tarea de reaching) o similar a (informe verbal) los videntes. Los resultados del informe verbal mostraron sesgos similares entre ambos grupos. Sin embargo, los participantes ciegos tenían respuestas mas compresivas que los videntes. Además, los participantes ciegos mostraron respuestas más sesgadas en el campo lejano que en el espacio peripersonal, mientras que los participantes videntes mostraron sesgos similares independientemente de la distancia. Nuestros resultados sugieren fuertemente que los ciegos pueden calibrar sus estimaciones de distancia mediante el uso de información espacial propioceptiva.

Palabras-clave: distancia auditiva, calibración multimodal, ceguera, localización de sonido, percepción auditiva.

PACS: 43.66.-x

Abstract

This study aimed to test the hypothesis that associated blindness with a reduced ability to judge the absolute distance from sound sources. Our working hypotheses were: 1) Within reach, a blind subject will be able to make up for the lack of vision using proprioceptive information to calibrate the acoustic distance perception cues. 2) As the source becomes unreachable, blind people will show greater biases since, out of reach, the proposed mechanism for calibration could not be used. To approach these topics we carried out a series of auditory distance experiments in which we asked sighted and blind participants to report their distance estimates verbally or by reaching the sound source. Within reach results showed that blind participants performed better than (reaching) or similar to (verbal report) the sighted. The verbal report results showed similar biases between both groups. However, blind participants had less compressive responses than the sighted. Furthermore, blind participants showed more biased responses in the far field than in the peripersonal space, while sighted participants showed similar biases regardless of distance. Our results strongly suggest that the blind can calibrate their distance estimations through the use of proprioceptive spatial information.

Keywords: auditory distance, multimodal calibration, blindness, sound localization, auditory perception.



1. INTRODUCTION

Vision provides the most accurate spatial information and therefore is the most influential in the multisensory representation of the environment [1]. Consequently, the lack of vision can lead to a detriment of the representation of space [2-3]. This evidence, along with the importance of spatial navigation in our life, is the reason why studying the way humans build spatial representations of the environment in the absence of vision is relevant. There are two opposing hypotheses regarding spatial perception in the absence of vision. The first one, known as the perceptual deficit hypothesis, proposes that the lack of vision hinders the precise calibration of other sensory modalities (especially the auditory one), affecting the performance in localization tasks [4-5]. It has been reported that the blind perform poorly in auditory spatial tasks such as estimation of source elevation [6-8], spatial bisection [9], sound speed discrimination [10], sound motion [11-12], relative sound distance [13], and absolute distance judgments [14-17]. On the other hand, the sensory compensation hypothesis proposes that to compensate for visual loss, blind individuals develop exceptional perceptual abilities using their remaining sensory modalities [18]. The blind are better than the sighted in tasks such as echolocation [17, 19], localization in azimuth [20], sound localization in the horizontal dimension [21], motion detection [22], and relative discrimination of auditory distance [23-24].

Humans receive information from sound sources that can be located both within and beyond reach (peripersonal and extrapersonal space respectively). The concept of peripersonal space becomes relevant to understand auditory distance perception (ADP) of the blind since, for near sources, proprioceptive-tactile modalities could provide important spatial cues that could calibrate the less accurate auditory distance cues. Likewise, several studies demonstrated that a tactile-proprioceptive feedback session in the absence of vision significantly reduce the biases in the auditory perceived location of sources located within-reach space both in

sighted and blind people [25-28]. In contrast, when a source is located beyond reach, the tactile-proprioceptive ADP calibration is not possible so the only way to calibrate ADP cues with reliable spatial information is by using vision. In this vein, blind have been shown to be less accurate than the sighted at perceiving the absolute distance to a sound source located in the far field [16]. However, two previous studies have observed similar capacities between sighted and blind participants to perceive the distance to far sources [29-30]. Together, these results show that blind participants' performance in absolute auditory distance estimation tasks is worse or, at best, similar to that of sighted ones for sources in the far field.

Regarding the ability of blind subjects to perceive the distance to sources located within the personal space, previous research has been inconclusive. Macé et al. [15] showed that early-blind participants were slightly less accurate than sighted ones in a within reach ADP task. In the same way, Wanet & Veraart [14] reported that early-blind subjects were less accurate than late-blind ones and sighted participants in near-field ADP experiments. On the contrary, Ashmead et al. [30] showed that children with congenital blindness were more accurate than children with normal vision at perceiving the distance to broadband sources.

1.1 The aim of this study

Blindness is often associated with a reduced ability to judge the absolute distance of sound sources [2, 31]. This is in accordance with the perceptual deficit hypothesis. This hypothesis seems plausible for sources located beyond reach, where the blind cannot take advantage of the valuable visual information to calibrate ADP cues. However, in our opinion, the use of the perceptual deficit hypothesis for near-field sources needs to be reviewed. Firstly, unlike in the far field where ADP cues cannot be calibrated with accurate spatial information, within arm's reach the tactile and proprioceptive spatial cues could potentially be used to calibrate distance estimates. Also, there are few studies on the effect of blindness on near-field ADP and, as we have reviewed, their

results are contradictory. Our hypothesis is that, within reach, a blind subject will be able to compensate for the lack of vision by using tactile-proprioceptive information to calibrate the acoustic ADP cues, thus achieving a performance similar to that of a sighted person. We also expect that, as the source becomes unreachable, a blind subject will show greater biases since the proposed mechanism for calibration could not be used.

2. METHODS

2.1 Participants

Participants were divided into two groups: blind ($n = 19$, 7 females, mean age 46.7 ± 16.0 y.o.) and normally sighted ($n = 19$, 7 females, mean age 37.7 ± 15.3 y.o.). Blind participants were either totally blind or had some light perception only, and fell into categories 4–5 of the World Health Organization classification ICD-10, 2019 (See Table 1). Participants S009, S011, S012, S014, S023, S024, S025 and S026 were excluded from the present work since they reported residual vision (WHO categories 2 and 3).

Sighted participants reported normal or corrected vision and normal hearing. The experiments were undertaken with the understanding and written consent of each subject, following the Code of Ethics of the World Medical Association (Declaration of Helsinki), and were approved by the Ethics Committee of the Universidad Nacional de Quilmes. Participants did not have previous knowledge of the experimental room nor of the goals of the study.

2.2 Testing Environment

All experiments were performed in a semi-reverberant room of size $5.9 \times 6.2 \times 2.9$ m (length $\times$ width $\times$ height). The mid-frequency average reverberation time (T_{20} ; 500 & 1000 Hz) of the room was 0.3 s. The reverberation time was obtained by using an exponential sweep (Farina, 2000) measured at the position of the listener with the source located at the farthest position. The background noise of the room was 30.3 dBA (measured with an SVAN 959 sound-level

meter at the position of the listener). The room was composed of concrete walls and the ceiling was covered by sound-absorbing material.

2.3 Apparatus and Stimuli

The experimental set-up consisted of a wooden table (270-cm long, 50-cm wide). The table was covered with foam and lined with a soft fabric. A printed 260-cm-long ruler was fixed over the fabric. Participants were seated on a height-adjustable chair located at the head of the table. The position of the chair was adjusted such that when the participant's head was centered along the long direction of the table, his/her ears were at 1.3 m from the floor (~ 63 cm height between ears and table) and his/her belly button (considered as the zero point) was 20 cm from the table. Auditory targets could be presented at different distances ranging from 20 to 290 cm from the zero point. The sound source was a portable wireless speaker (Sony SRS-X11). The auditory stimulus was a 500-ms-long white-noise clip with the onset and offset rounded by a 50-ms raised cosine. The sound level of the source was calibrated to a comfortable level of approximately 65 dBA measured at the participant's head position with the sound source located at 1 m. Sound sources were located directly in front of the participant (azimuth 0°), in both within- and beyond-reach space at distances 40, 53, 66, 81, 97, 115, 135, 159, 185, 215, 250 and 290 cm. The experimental procedure was controlled by a Mac Mini personal computer running Matlab R2012a, using the Psychophysics Toolbox extensions. Signals were delivered to the speakers through a Focusrite Saffire LE external soundboard, with a sampling frequency of 44.1 kHz.

One experimenter was present in the room during the whole procedure. He was in charge of placing the sound source at the distance indicated by the computer screen at each trial and removing it after the stimulus was delivered, in order to avoid the subject from obtaining tactile feedback on the source's position. In front of the subject, and on each side, two loudspeakers (Edifier R1000TCN 25W) delivered a masking noise while the



target sound source was being manipulated by the experimenter. Each trial consisted of the presentation of the masker (7-s long) followed by a 2-s-long silence, after which the stimulus was delivered. Then, the subject reported the perceived distance from the source using the two methods described in the Experimental Procedure. Finally, the experimenter entered the response into the computer via a wireless keyboard.

2.4 Experimental Procedure

Participants were received in a room contiguous to the experimental room, where they were informed of the experimental task and its details before signing the consent form. Then, participants were blindfolded (including blind participants) and guided by the experimenter into the testing room and to the chair, where they remained blindfolded. Once the subject was seated and the chair was adjusted to the proper position, s/he was instructed to reach the farthest with his/her dominant hand on the experimental table. To do so, s/he was allowed to lean forward without raising from the chair, and the experimenter registered the position of the middle finger on the ruler. The measured magnitude is what we called the “maximum reachable distance” of the participant. This magnitude was referenced to the center of the hand by subtracting 10.9 cm (mean fingertip-to-center distance across subjects).

Each experimental session consisted of two ADP tasks presented in a between-subjects counterbalanced way. In the Verbal Report Task, subjects were instructed to report the distance estimates verbally using a meter scale. In the Reaching Task, the experimenter informed the subject that the sound source would be removed as soon as the sound ceased. Then, the subject was asked to extend their arm and reach the perceived position of the sound source with the open hand and rest the palm on the table. Since the sound source was removed before the reaching action, subjects did not have any tactile feedback. Then, the experimenter recorded the distance reached by the middle finger by looking at the ruler on the table. If the subject perceived the source as out of reach, s/he reported the source as

“unreachable”. To ensure that participants understood the task, we conducted a practice block. Finally, subjects performed a calibration task in which they were requested to place their hand at a set of given distances on the table (30, 40, 50, 60, 70 and 90 cm, with three repetitions per distance). The whole experimental session lasted approximately 60 minutes.

2.5 Statistical analysis

Reaching data

To avoid sampling biases we only kept the responses for distances in which the participant responded (i.e. tried to reach the target) for 100% of the presentations (97% of the total within-reach trials). This does not mean that we narrowed down the results to those within participants’ reach but to those physical distances in which we could have an unbiased estimation of the perceived reaching distance.

Verbal Report data

For the bias analysis of the Verbal Report task, we split the participants’ responses into two groups as within- or beyond-reach. The separation between these spatial regions is subject-dependent and it was defined using the maximum reachable distance (defined in Experimental Procedure). The rationale for this classification is to differentiate target distances that could and could not have been reached by the participant.

Statistical models

We fitted linear models (LMs) and linear mixed-effect models (LMEMs) to estimate the associations of the magnitudes (perceived distance and absolute and relative biases) with the group, reachability (when applicable), and target distance. An exception was made for the association between perceived and source distance in the Verbal Report task, as in this case, the estimates displayed a non-linear dependence with source distance. Therefore, for this data, we fitted non-linear mixed-effect models (nLMEMs). LMEMs and nLMEMs were fitted when we tested for within-subject effects.

Absolute and relative bias

We define the signed absolute bias as the difference between the perceived and the physical distance for a given trial. The signed relative bias is the absolute bias divided by the physical distance. Both signed biases indicate the overestimation (if positive) or underestimation (if negative) of the subjects' perception, and therefore are useful for measuring the estimates' accuracy. The signed relative bias is also useful for comparing estimates for sources that span over a wide range, as is the case in our study. The unsigned (absolute or relative) bias is obtained by applying modulus to the signed version. These measures indicate the estimation error without considering its direction.

We calculated the relative bias (signed and unsigned) for each subject, source position, presentation, and task, and averaged it across presentations and source positions, in order to obtain the individual collapsed bias for each task. This magnitude allowed us to measure the global accuracy of the subjects' estimates. It is important to note that the collapsed unsigned bias is always zero or positive by definition, while the signed one can take any value, negative, zero, or positive, even when the unsigned bias is larger than zero.

3. RESULTS

3.1 Reaching task

Distance estimation

As we can see in Figure 1a, blind participants reported average reaching distances closer to the physical distances than sighted ones. The slopes of both groups are very similar and smaller than one. To quantify these relations, we fitted an LMEM with fixed effects visual condition and target distance and both random intercept and slopes for each subject. Both the parameter estimates and the p-values indicate that the slope is not responsible for the differences found between the groups (slope=0.58, 95% CI=[0.33, 0.73] for sighted and 0.62, 95% CI=[0.51, 0.84] for blind

participants). However, the difference in the intercept (i.e. the shift of the whole response curve) is 14.8 cm (95% CI=[6.12, 23.5]) and its associated effect is statistically significant (fixed-effect test: $F(1,31.8)=11.2$, $p=0.002$).

Bias analysis

Next, we present the mean signed and signed relative bias. In Figure 1.b we show the individual data points (i.e. per subject) along with the between-subject mean for each group, and its standard error (SEM). Blind participants present a mean signed bias close to zero ($M=3.5\%$, 95% CI=[-5.6, 12.6]%) while sighted participants systematically underestimate the distance to the target ($M=-29.8\%$, 95% CI [-38.9, -20.7]%). After fitting a linear model with visual condition as a fixed effect, we confirmed that blind participants performed significantly better than sighted ones ($\beta=33.3\%$, 95% CI=[18.3, 48.3]%, fixed-effect test: $F(1,34)=27.75$, $p=7.71e-6$). The confidence intervals of the estimations also support the better performance of blind participants for the within-reach targets since the blind show an inferior limit of 5.6% of relative overestimation, while sighted participants show a superior limit of 20.7% for signed relative bias. In Figure 1.c we present the mean unsigned relative bias. Blind participants present a estimation error smaller ($M=25.1\%$, 95% CI=[20.3, 30]%) than sighted participants ($M=32.6\%$, 95% CI [27.8, 37.5]%). After fitting a linear model with visual condition as a fixed effect, we confirmed that blind participants performed significantly better than sighted ones ($\beta=7.5\%$, 95% CI=[0.01, 14.1]%, fixed-effect test: $F(1,34)=5.16$, $p=0.03$).

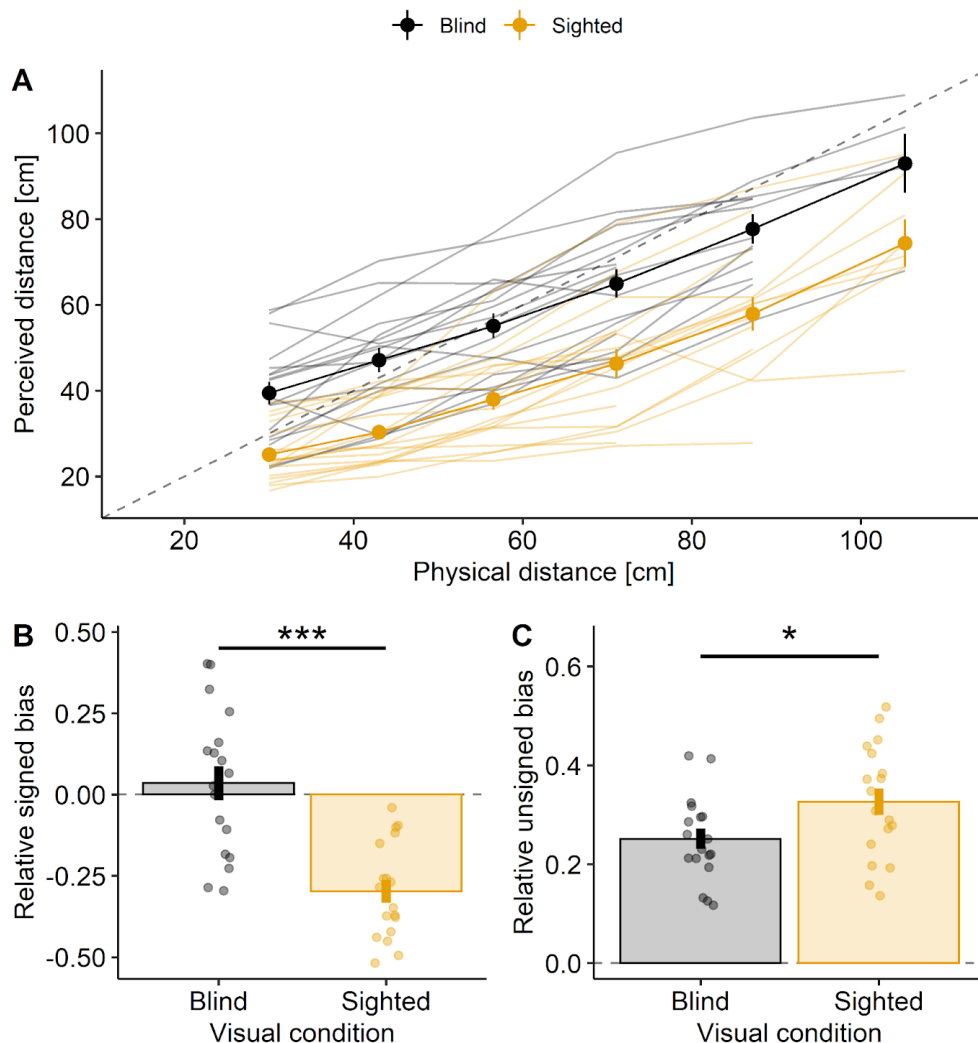


Figure 1: (a) Reported auditory distance by reaching the target as a function of the target's distances. Mean responses ($\pm$ SEM: standard error of the mean) for the sighted - yellow - (or light grey in the printed version) and blind - black- participants are plotted as dots (and error bars) and joined by a solid line. Each thin curve represents a single subject. The grey dashed line indicates perfect performance (response = true distance). (b) Relative signed bias and (c) relative unsigned bias collapsed across distances (mean $\pm$ SEM) for the reaching task. Each point represents a single subject.

3.2 Verbal report task

Distance estimation

In Figure 2.a we show the verbally-reported distance as a function of source position, for both blind and sighted participants. In both cases, we can distinguish three regions: an expansive region for closer distances (less than 60 cm), a linear region for intermediate distances (around 100 cm), and a compressive region for further distances (more than 150 cm). This kind of curve is effectively modeled by a logistic function. The distance estimates

were then fitted with a non-linear mixed-effects model (nLME)

Both in Figure 2.a and in the model point estimates, we can see that sighted participants present a less compressed response for farther sources (SupAsym=173 cm for sighted vs. 148 cm for blind) but not a great difference in their compression for short target distances (InfAsym=29.2 cm for sighted vs. InfAsym=23.7 cm for blind). Also, the inflection point occurs for farther sources in sighted participants (MidDistance=114 cm for sighted vs. MidDistance=106 cm for blind) and the slope in this region is greater for sighted

participants (Slope=1.39 for sighted vs. Slope=0.898 for blind), indicating a less compressive response in the vicinity of the inflection point (~110cm). Finally, we tested the statistical significance of the model parameters (without including the slope) and

found a significant difference for InfAsym ($F(1,395)=5.67$, $p=0.018$) and Scale ($F(1,395)=4.24$, $p=0.040$).

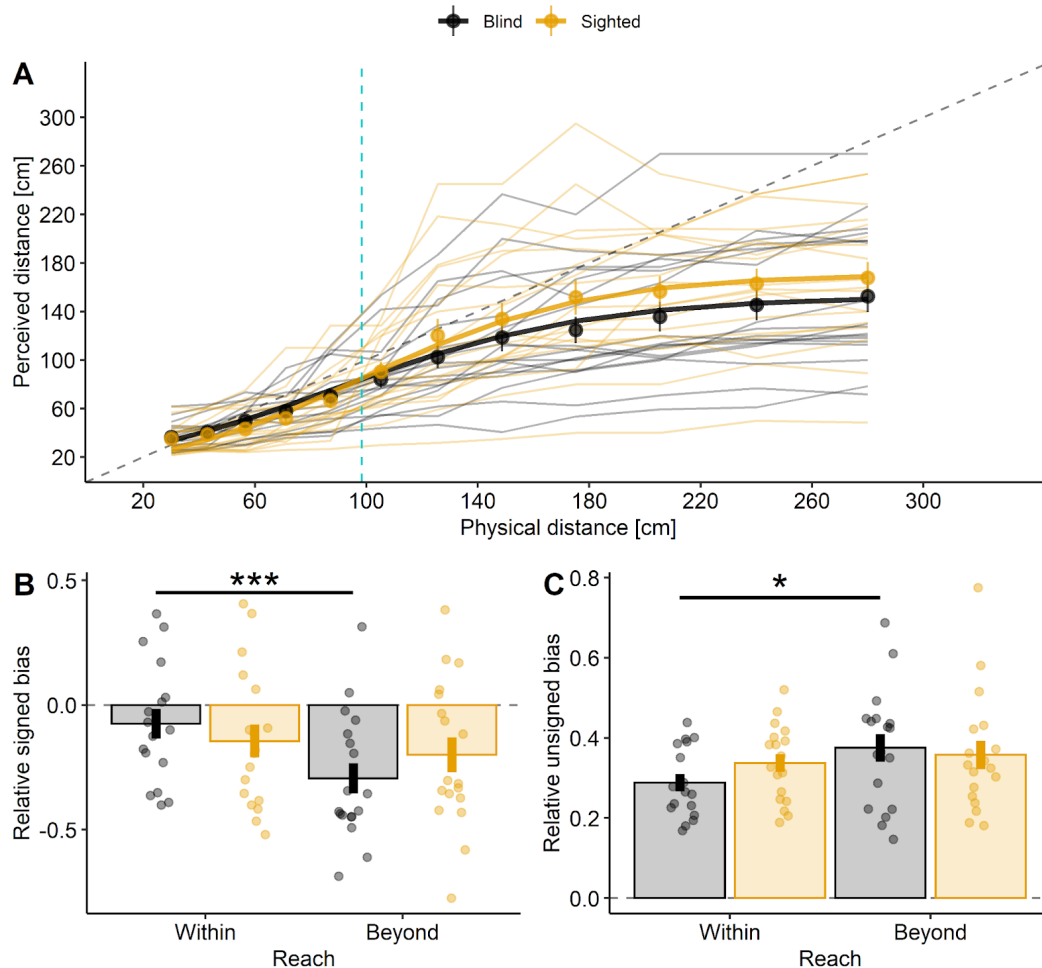


Figure 2. (a) Verbal Reported auditory distance of the target as a function of the target's distances. Mean responses ($\pm$ SEM: standard error of the mean) for the sighted - yellow - (or light grey in the printed version) and blind - black- participants are plotted as dots (and error bars) and solid lines fitted by non-linear mixed-effects model (nLME). Each thin curve represents a single subject. The grey dashed line indicates perfect performance (response = true distance). Light blue (or light grey in the printed version) dashed line indicates the average reach of the blind subjects (98.4 cm). (b) Relative signed bias and (c) relative unsigned bias collapsed across distances (mean $\pm$ SEM) for the verbal reported task. Results are split up into within- and beyond-reach target positions based on the individual maximum reachable distance obtained at the beginning of the experiment. Each point represents a single subject.

Bias analysis

For the bias analysis we splitted the responses between the targets within and beyond reach as described in the methods section. In Figure 2.b we show the collapsed signed relative bias for both groups and both reaching regions. We can see a consistent underestimation of the physical

distances for both groups, with larger values for sources beyond reach (Blind-Within: $M = -6.5\%$ 95% CI [-19.5, 6.4]%; Blind-Beyond: $M = -29.4\%$, 95% CI [-42.3, -16.6]%, Sighted-Within: $M = -14.5\%$, 95% CI [-27.3, -1.6]%, Sighted-Beyond: -20%, 95% CI [-32.9, -7.2]%). Figure 2.c shows the collapsed



unsigned relative bias for both groups and both reaching regions. We can see a consistent estimation error of the physical distances for both groups, with larger values for sources beyond reach (Blind-Within: $M = 25.4\%$ 95% CI [18.6, 32.1]%; Blind-Beyond: $M = 35.8\%$, 95% CI [29.2, 42.4]%, Sighted-Within: $M = 31.6\%$, 95% CI [25, 38.2]%, Sighted-Beyond: $M = 32.7\%$, 95% CI [26.1, 39.3]%). After fitting a linear mixed-effects model (for Signed and Unsigned bias) with visual condition and reaching region as fixed effects and random intercepts for each subject, we confirmed that targets were more underestimated when unreachable (Signed relative bias: $\beta = -22.9\%$, 95% CI [-32.6, -13.2]%, fixed-effect test: $F(1,33.3) = 16.9$, $p = 2.37 \times 10^{-4}$; Unsigned relative bias: $\beta = 10.4\%$ 95% CI [3.8, 17]%, fixed-effect test: $F(1,32.9) = 6.03$, $p = 0.019$). However, we cannot be conclusive whether blind participants worsened their performance significantly more than sighted participants when sources became unreachable. This result is consistent when analyzing signed bias ($\beta = 17.3\%$, 95% CI [3.7, 30.9]%, fixed-effect test: $F(1,33.3) = 6.28$, $p = 0.017$), but not when analyzing unsigned bias ($\beta = 9.3\%$, 95% CI [0.1, 18.1]%, fixed-effect test: $F(1,32.9) = 3.96$, $p = 0.054$). However, when making multiple comparisons between groups (using the Holm–Bonferroni adjustment), we only found significant differences in blind participants when sources became unattainable in both biases (Signed: $M = 23.3\%$, 95% CI [12.4, 34.1]%, $t(16) = 4.54$, $p = 0.0003$; Unsigned: $M = 11\%$, 95% CI [0.3, 18.3]%, $t(16) = 3.18$, $p = 0.005$).

4. DISCUSSION

In this study we compared how blind and sighted participants estimate the distance to sound sources located at both within- and beyond-reach distances. When asked to use reaching as the response method, blind listeners showed less biased responses, with slight overestimation for sources closer than 45 cm and underestimation for sources located at greater distances. In contrast, sighted participants underestimated the source distance for the entire tested distance range, resulting in a significant increase in both signed and

unsigned biases. This result agrees with Ashmead et al. [30], who observed that sighted participants underestimated the distance of real near sources to a greater extent than blind ones resulting in a significant increase in both signed and unsigned bias. On the other hand, when asked to verbally report the perceived distance, the estimates obtained for sources within reach were similar across both groups. Two previous studies reported results in the same line. Macé et al. [15] measured ADP in the near field and observed that blind participants were slightly more biased (~ 1 cm) than sighted ones. This difference does not appear to be of practical relevance. In fact, the authors concluded that, despite the lack of visual calibration of auditory cues, blind and sighted listeners performed the task with similar accuracy. Also, Wanet & Veraart [14] reported that the early-onset blind group was less accurate than both the late-onset blind and sighted groups to perceive the absolute distance to nearby sources. However, according to Kolarik et al. [3], these last differences would have been non-significant had the authors adjusted the significance level for multiple comparisons.

When we compared the ADP curves between both response methods, the near-field verbal report performance of blind and sighted participants appeared to be similar to that of the blind in the Reaching task. This observation was corroborated by comparing the signed bias across methods. The question that arises from these observations is whether the best reaching performance of the blind subjects is due to a better accuracy when estimating the auditory distance or because they have a greater ability to report the perceived distance using reaching in the dark. This possibility is feasible since blind subjects are more habituated to performing this action than sighted ones, who generally use vision to locate nearby objects. However, the comparison of the unsigned bias across methods showed that blind participants are less biased than sighted ones regardless of the task. The less compressed response of the sighted in the Verbal Report task can be explained by the fact that several participants overestimated the near-field auditory distance as opposed to the

Reaching task where most underestimated it. However, as shown in Fig. 2, the unsigned bias of the sighted was similar regardless of the task. This result suggests that the better performance of the blind in the Reaching task is not only due to an inability of the sighted to perform this task correctly. However, our experimental design does not allow us to be conclusive about the causes of this observation, so it would be interesting to design future experiments that can put light on this issue.

The fact that the near-field responses of the blind were less biased (in the Reaching task) or similar (in the Verbal Report task) than that of the sighted suggests that blind subjects were able to calibrate the ADP cues with non-visual spatial information. In everyday life, our arms and hands allow us to touch and/or grasp objects, many of which also emit sounds. In fact, in many situations, the hands themselves generate sounds (tapping with the fingers on a table, clapping hands, snapping the fingers, etc.), use an external element to generate it (noise of objects that one moves on a table, playing an instrument, etc.), or directly carry sound-emitting objects (mobile phones). We consider that this audio-motor information is very important for the blind since, in the absence of vision, it might be the main way they have to calibrate the auditory spatial cues with more accurate proprioceptive spatial information. The influence of proprioceptive information on the calibration of spatial auditory skills has been reported in numerous previous works [25-28]. For example, it has been observed that the auditory spatial perception of the blind can be improved with training based on multisensory feedback [28]. In the same line, experiments performed with sighted participants by Hüg et al. [25] showed that auditory distance cues can be calibrated by touching a fixed source that had previously emitted a short noise. The results obtained here support our first hypothesis, that is, when the sources are within reach, blind participants are able to perceive the auditory distance of the source with greater than or, at least, similar accuracy compared to the sighted participants. Furthermore, our results support the hypothesis that blind subjects will compensate for the lack of vision by using tactile-proprioceptive

information to calibrate the acoustic ADP cues. In summary, both the evidence reported here and the results of previous studies do not support the perceptual deficit hypothesis for ADP in the peripersonal space.

Verbal Report estimates of both blind and sighted participants were similar. Although in the far field the average curves showed greater underestimation by blind participants, we did not observe significant differences between groups neither in the signed nor in the unsigned bias. These results agree with two previous studies that did not observe differences in the response bias between blind and sighted in far-field absolute ADP of real sources [29-30]. These results disagree with the general idea that the blind show lower accuracy for absolute auditory distance judgments and are not consistent with the perceptual deficiency hypothesis. On the other hand, some measured parameters suggest that blind participants have difficulties perceiving the distance to sources located out of reach. For example, such participants showed a more compressive response, compared to the sighted. This difference can be explained by the lesser underestimation for near sources and larger underestimation for far sources. This result is in agreement with Kolarik et al. [16] where blind participants also showed more compressive responses in far-field auditory distance estimations. We can also see that blind participants' verbal estimates become less accurate (greater signed and unsigned bias) when the source is beyond than within reach while the sighted showed similar biases for sources located both inside and outside the peripersonal space. In summary, the results obtained using verbal reports are not conclusive.

5. CONCLUSIONS

For sources located within reach, the blind participants' responses were better (reaching) or similar (verbal report) compared to the sighted participants' responses. These results show robust evidence suggesting that blind participants can calibrate their distance estimations with proprioceptive spatial information. Taking into account the results



obtained here and those reported in previous studies, we consider that there is abundant evidence to bring into question the perceptual deficiency hypothesis for ADP when sources are located within reach. Our far-field results were contradictory. On the one hand, no differences were observed between groups, while both the unsigned and signed biases were similar compared across blind and sighted subjects. This result does not support the theory of perceptual deficit and does not agree with the general idea that the blind are less accurate than the sighted to perform absolute distance judgments in the far field.

6. ACKNOWLEDGEMENTS

The work was supported by grants from Universidad Nacional de Quilmes, Argentina (PUNQ 1394/15); Agencia Nacional de Promoción Científica y Tecnológica, Argentina (PICT 2016-0738); and Agencia Nacional de Promoción Científica y Tecnológica, Argentina (PICT 2018-4586).

REFERENCES

- [1] Alais, D., & Burr, D. (2004). The ventriloquist effect results from near-optimal bimodal integration. *Current biology*, 14(3), 257-262.
- [2] Voss, P. (2016). Auditory spatial perception without vision. *Frontiers in psychology*, 7, 1960. <https://doi.org/10.3389/fpsyg.2016.01960>
- [3] Kolarik, A. J., Pardhan, S., & Moore, B. C. (2021). A framework to account for the effects of visual loss on human auditory abilities. *Psychological Review*. <https://doi.org/10.1037/rev0000279>
- [4] Axelrod, S. (1959). Effects of early blindness: Performance of blind and sighted children on tactile and auditory tasks (Research Series No. 7). New York: American Foundation for the Blind.
- [5] Jones, B. (1975). Spatial perception in the blind. *British Journal of Psychology*, 66(4), 461-472. <https://doi.org/10.1111/j.2044-8295.1975.tb01481.x>
- [6] Lewald, J. (2002). Vertical sound localization in blind humans. *Neuropsychologia*, 40(12), 1868-1872. [https://doi.org/10.1016/S0028-3932\(02\)00071-4](https://doi.org/10.1016/S0028-3932(02)00071-4)
- [7] Voss, P., Tabry, V., & Zatorre, R. J. (2015). Trade-off in the sound localization abilities of early blind individuals between the horizontal and vertical planes. *Journal of Neuroscience*, 35(15), 6051-6056. <https://doi.org/10.1523/JNEUROSCI.4544-14.2015>
- [8] Zwiers, M. P., Van Opstal, A. J., & Cruysberg, J. R. M. (2001). A spatial hearing deficit in early-blind humans. *Journal of Neuroscience*, 21(9), RC142-RC142. <https://doi.org/10.1523/JNEUROSCI.21-09-j0002.2001>
- [9] Gori, M., Sandini, G., Martinoli, C., & Burr, D. C. (2014). Impairment of auditory spatial localization in congenitally blind human subjects. *Brain*, 137(1), 288-293. <https://doi.org/10.1093/brain/awt311>
- [10] Bertonati, G., Amadeo, M. B., Campus, C., & Gori, M. (2021). Auditory speed processing in sighted and blind individuals. *Plos one*, 16(9), e0257676. <https://doi.org/10.1371/journal.pone.0257676>
- [11] Finocchietti, S., Cappagli, G., & Gori, M. (2015). Encoding audio motion: spatial impairment in early blind individuals. *Frontiers in psychology*, 6, 1357. <https://doi.org/10.3389/fpsyg.2015.01357>
- [12] Cappagli, G., Finocchietti, S., Cocchi, E., & Gori, M. (2017). The impact of early visual deprivation on spatial hearing: a comparison between totally and partially visually deprived children. *Frontiers in Psychology*, 8, 467. <https://doi.org/10.3389/fpsyg.2017.00467>
- [13] Cappagli, G., Cocchi, E., & Gori, M. (2017). Auditory and proprioceptive spatial impairments in blind children and adults. *Developmental science*, 20(3), e12374. <https://doi.org/10.1111/desc.12374>
- [14] Wanet, M. C., & Veraart, C. (1985). Processing of auditory information by the blind in spatial localization tasks. *Perception & Psychophysics*, 38(1), 91-96. <https://doi.org/10.3758/BF03202929>
- [15] Macé, M. J. M., Dramas, F., & Jouffrais, C. (2012, July). Reaching to sound accuracy in the peri-personal space of blind and sighted humans. In *International Conference on Computers for Handicapped Persons* (pp. 636-643). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-31534-3_93
- [16] Kolarik, A. J., Pardhan, S., Cirstea, S., & Moore, B. C. (2017). Auditory spatial representations of the world are compressed in blind humans. *Experimental Brain Research*, 235(2), 597-606. <https://doi.org/10.1007/s00221-016-4823-1>
- [17] Kolarik, A. J., Moore, B. C., Cirstea, S., Raman, R., Gopalakrishnan, S., & Pardhan, S. (2021). Partial visual loss disrupts the relationship between judged room size and sound source distance. *Experimental Brain Research*, 1-16. <https://doi.org/10.1007/s00221-021-06235-0>
- [18] Miller, L. (1992). Diderot reconsidered: Visual impairment and auditory compensation. *Journal of Visual Impairment & Blindness*, 86(5), 206-210. <https://doi.org/10.1177/0145482X9208600504>
- [19] Teng, S., & Whitney, D. (2011). The acuity of echolocation: Spatial resolution in sighted persons compared to the performance of an expert who is blind.

- Journal of visual impairment & blindness, 105(1), 20-32. <https://doi.org/10.1177/0145482X1110500103>
- [20] Lessard, N., Paré, M., Lepore, F., & Lassonde, M. (1998). Early-blind human subjects localize sound sources better than sighted subjects. *Nature*, 395(6699), 278-280. <https://doi.org/10.1038/26228>
- [21] Cappagli, G., & Gori, M. (2016). Auditory spatial localization: developmental delay in children with visual impairments. *Research in developmental disabilities*, 53, 391-398. <https://doi.org/10.1016/j.ridd.2016.02.019>
- [22] Lewald, J. (2013). Exceptional ability of blind humans to hear sound motion: implications for the emergence of auditory space. *Neuropsychologia*, 51(1), 181-186. <https://doi.org/10.1016/j.neuropsychologia.2012.11.017>
- [23] Kolarik, A. J., Cirstea, S., & Pardhan, S. (2013). Evidence for enhanced discrimination of virtual auditory distance among blind listeners using level and direct-to-reverberant cues. *Experimental brain research*, 224(4), 623-633. <https://doi.org/10.1007/s00221-012-3340-0>
- [24] 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), 1734-1738. <https://doi.org/10.1016/j.cub.2004.09.051>
- [25] Hüg, M. X., Vergara, R. O., Tommasini, F. C., Etchemendy, P. E., Bermejo, F., & Fernandez, L. G. (2019). Reaching measures and feedback effects in auditory peripersonal space. *Scientific reports*, 9(1), 1-14. <https://doi.org/10.1038/s41598-019-45755-2>
- [26] Carlile, S. (2014). The plastic ear and perceptual relearning in auditory spatial perception. *Frontiers in neuroscience*, 8, 237. <https://doi.org/10.3389/fnins.2014.00237>
- [27] Cuppone, A. V., Cappagli, G., & Gori, M. (2019). Audio-motor training enhances auditory and proprioceptive functions in the blind adult. *Frontiers in neuroscience*, 13, 1272. <https://doi.org/10.3389/fnins.2019.01272>
- [28] Finocchietti, S., Cappagli, G., & Gori, M. (2017). Auditory spatial recalibration in congenital blind individuals. *Frontiers in neuroscience*, 11, 76. <https://doi.org/10.3389/fnins.2017.00076>
- [29] Lai, H. H., & Chen, Y. C. (2006). A study on the blind's sensory ability. *International journal of industrial ergonomics*, 36(6), 565-570. <https://doi.org/10.1016/j.ergon.2006.01.015>
- [30] Ashmead, D. H., Wall, R. S., Ebinger, K. A., Eaton, S. B., Snook-Hill, M. M., & Yang, X. (1998). Spatial hearing in children with visual disabilities. *Perception*, 27(1), 105-122. <https://doi.org/10.1068/p270105>
- [31] Kolarik, A. J., Moore, B. C., Zahorik, P., Cirstea, S., & Pardhan, S. (2016). Auditory distance perception in humans: a review of cues, development, neuronal bases, and effects of sensory loss. *Attention, Perception, & Psychophysics*, 78(2), 373-395. <https://doi.org/10.3758/s13414-015-1015-1>
- [32] Farina, A. (2000, February). Simultaneous measurement of impulse response and distortion with a swept-sine technique. In *Audio Engineering Society Convention 108*. Audio Engineering Society.