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Single Case Report

Using prism adaptation to alleviate perception of unilateral tinnitus: A case study

Clémence Bonnet [a,*], *Bénédicte Poulin-Charronnat* [b], *Yves Rossetti* [c], *Xavier Perrot* [d,e] and *Carine Michel-Colent* [a]

[a] *INSERM UMR1093-CAPS, Université de Bourgogne, UFR des Sciences du Sport, F-21000, Dijon, France*
[b] *LEAD — CNRS UMR5022, Université de Bourgogne, Dijon, France*
[c] *Inserm Unité Mixte de Recherche-Santé (UMR-S) 1028, CNRS UMR5292, ImpAct, Centre de Recherche en Neurosciences de Lyon, Université Lyon-1, Bron, France*
[d] *Hospices Civils de Lyon, Service d'Audiologie et Explorations Otoneurologiques, Lyon, France*
[e] *Université de Lyon, Université Lyon 1, Institut des Sciences et Techniques de la Réadaptation, Lyon, France*

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ABSTRACT

Tinnitus is described as an uncomfortable sound or noise heard by an individual in the absence of an external sound source. Treating this phantom perception remains difficult even if drug and nondrug therapies are used to alleviate symptoms. The present case study aimed to investigate whether prism adaptation could induce beneficial aftereffects in a tinnitus sufferer. A 75-year-old man, R. B., with chronic unilateral tinnitus in the left ear reported a self-estimation of parameters of his tinnitus—discomfort, pitch and loudness—and performed a manual line-bisection task to study the consequences of lateralized auditory disorder on spatial representation. Aftereffects of prism adaptation were assessed using a sensorimotor open-loop pointing task. In parallel, a control group completed the line-bisection task and the open-loop pointing task before and after lens exposure, under the same experimental condition as those of R. B. Throughout the pretests, the patient assessed his tinnitus at a constant medium pitch (around 3000 Hz), and he was biased toward the affected ear in both the sensorimotor task and the estimation of the subjective center in the manual line-bisection task. Although both optical deviations were effective, an exposure to prism adaptation to a rightward optical deviation (i.e., toward the unaffected ear) produced stronger aftereffects. In posttests, the tinnitus pitch decreased to 50 Hz and the subjective center was shifted toward the right side (i.e., unaffected ear side). Furthermore, the line-bisection task seemed to reflect the changes in the tinnitus perception, and spatial representation could be a new tool to assess tinnitus indirectly. Our findings suggest that prism adaptation may have benefits on unilateral tinnitus and open a new avenue for its treatment.

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* *Corresponding author*. INSERM UMR1093-CAPS, Université de Bourgogne, UFR des Sciences du Sport, 3 allée des Stades Universitaires, BP 27877, Dijon 21000, France.
E-mail address: clemence.bonnet@u-bourgogne.fr (C. Bonnet).

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1. Introduction

Tinnitus is the conscious perception of an uncomfortable sound or noise in one or both ears, without a corresponding real external sound source (for reviews see Baguley, McFerran, & Hall, 2013; Jastreboff, 1990). Between 10% and 15% of the adult population suffer from tinnitus, and the prevalence is higher in men and increases with age (Baguley et al., 2013). Although the origin of the auditory phantom sensation is still unclear, there is a consensus that tinnitus would be related to peripheral damage (i.e., cochlear disorders), leading to aberrant neuronal activity in the central auditory system (i.e., hyperexcitability and/or hypersynchrony; for reviews see Baguley et al., 2013; Jastreboff, 1990; Noreña, 2015). Most cases of tinnitus are associated with a hearing loss, induced by exposure to noise or linked to age (Baguley et al., 2013; Lockwood, Salvi, & Burkard, 2002). When hearing loss appears to be the main initial source of tinnitus, the consecutive cascade of neural changes in the auditory and nonauditory brain areas (i.e., frontal, parietal, and limbic networks) is likely to maintain the perception of tinnitus (for reviews see Baguley et al., 2013; De Ridder, Elgoyhen, Romo, & Langguth, 2011). Tonndorf (1987) and Møller (1997) consider that the phantom pain associated with limb amputation and the phantom sound in tinnitus share basic underlying mechanisms and similar typical symptoms. Similar to the map reorganization observed in the somatosensory areas due to amputation linked to phantom pain (Flor et al., 1995), one of the main features of tinnitus is the map reorganization observed in the auditory cortical areas due to the hearing loss at the pitch of the tinnitus (Mühlnickel, Elbert, Taub, & Flor, 1998; for a review see De Ridder et al., 2011).

To date, no effective treatments exist to treat tinnitus even if drug and nondrug therapies can alleviate associated symptoms (Lockwood et al., 2002). Attention training can relieve tinnitus symptoms (i.e., pitch and discomfort) and improve attentional skills (e.g., ability to shift attention between visual and auditory cues), which are often impaired in tinnitus sufferers, as assessed by the Comprehensive Attention Battery (Searchfield, Morrison-Low, & Wise, 2007; Spiegel et al., 2015). Similarly, prism adaptation, which consists in wearing prisms that shift the visual field (Stratton, 1896), produced beneficial aftereffects in right brain-damaged neglect patients by reallocating spatial attention in the auditory (Jacquin-Courtois et al., 2010; Matsuo et al., 2020) and visual modalities (e.g., Berberovic, Pisella, Morris, & Mattingley, 2004). This redistribution of spatial attention was also observed in patients suffering from complex regional pain syndrome (i.e., continuous pain following a limb injury, with or without nerve lesion, which is disproportionate to the injury; Merskey & Bogduk, 1994). Prism adaptation alleviated the phantom pain perception immediately after prism removal and for several days following prism exposure (Bultitude & Rafal, 2010; Sumitani et al., 2007). Furthermore, patients with phantom pain estimated their subjective body-midline toward their affected limb. Prism adaptation shifted this initial visual bias toward the unaffected side (i.e., in the direction of the optical deviation; Sumitani et al., 2007). A similar bias of attention orientation toward the phantom perception would also exist for tinnitus: several studies assumed that unilateral tinnitus would act as an attention attractor and patients would have difficulties in shifting their attention away from the tinnitus (Cuny, Noreña, El Massioui, & Chéry-Croze, 2004; Kandeepan et al., 2019; Leong et al., 2020; Lima et al., 2019; Schröger, 1996; for a review see Roberts, Husain, & Eggermont, 2013). The patients would have fewer attentional resources available for other tasks because they would involuntarily focus their attention on their tinnitus. For instance, they showed longer reaction times to perform a cognitive task compared to healthy control subjects (Trevis, McLachlan, & Wilson, 2016). From a therapeutic perspective for right brain-damaged neglect patients, a study suggested an intermodal beneficial effect of prism adaptation on pathological auditory processing (Jacquin-Courtois et al., 2010). All these findings suggest that prism adaptation to an optical deviation toward the unaffected body part reduces unilateral symptoms. Consequently, we could expect that prism adaptation to an optical deviation toward the unaffected ear could alleviate tinnitus perception (i.e., phantom sound) by acting on the right posterior parietal cortex, which mediates spatial attention distribution (for reviews see Jacquin-Courtois et al., 2013; Michel, 2006).

The present case study aimed to explore aftereffects of prism adaptation on tinnitus characteristics as assessed by pitch, loudness, and tinnitus discomfort. As spatial representation is modulated by spatial attention (e.g., Milner, Brechmann, & Pagliarini, 1992), we also investigated whether there was a link between spatial representation and tinnitus. Since tinnitus would act as an attention attractor, we assumed a representational bias toward the tinnitus side. Furthermore, we know that prism adaptation modifies spatial representation by modulating attention (Berberovic & Mattingley, 2003; Colent, Pisella, Bernieri, Rode, & Rossetti, 2000; Fortis, Goedert, & Barrett, 2011; Striemer & Danckert, 2010). We therefore hypothesized that prism adaptation should modify tinnitus perception by modulating attention, and consequently spatial representation should also be modified. More precisely, we suggested that prism adaptation to an optical deviation toward the unaffected ear would alleviate tinnitus perception by shifting spatial attention away from the side of the tinnitus.

2. Methods

We report how we determined the sample size of the control group, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

2.1. *Participants*

All participants were completely naïve with regard to prism adaptation and its aftereffects, and they were debriefed at the end of the third experimental session. After having been informed of the experimental procedure, the participants gave their informed consent to participate in the study.

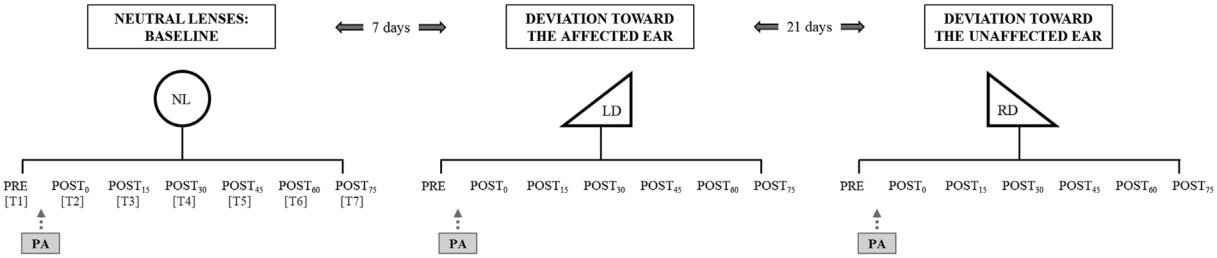

Fig. 1 – Experimental procedure. NL: Neutral lenses; LD: Leftward optical deviation; RD: Rightward optical deviation; PRE: Pretest; POST$_n$: The number corresponds to the period (in min) between the end of prism adaptation and the posttest; T1 to T7 correspond to the seven tests performed during the neutral-lens session; PA: Prism adaptation.

2.1.1. *Case report*

R. B. was a 75-year-old, right-handed man who had experienced unilateral tinnitus in his left ear for sixteen years. He described his tinnitus as a continuous complex noise, identical both night and day, with no variation in either pitch or loudness. R. B. had no history of known neurological and/or psychiatric disorders. According to the medical examination provided by an ear, nose and throat specialist, R. B. had normal vision and a drastic hearing loss beyond 2000 Hz [45 dB HL (decibel hearing level) and 60 dB HL in the right and left ear respectively].

2.1.2. *Control group*

The sample size of the control group was estimated using an a priori test according to the data of the published study by Tissieres, Elamly, Clarke, and Crottaz-Herbette (2017), $N = 17$, which aimed to investigate aftereffects of prism adaptation on the auditory neglect by comparing hemineglect patients with a control group of healthy participants. The results obtained by this control group during the sensorimotor task were used to define the sample size. Based on the mean difference of angular errors produced during the open-loop pointing task between pretest and posttest after a rightward prism adaptation (mean aftereffect: $-8.51°$; $SD = 2.61$), the effect size was estimated to be $dz = -3.26$. An a priori analysis for a dependent t-test comparison with $\alpha = .05$ and power $= .95$ indicated a required sample size equal to $N = 3$ with the effect size mentioned above (G*Power; Faul, Erdfelder, Lang, & Buchner, 2007). The current proposed sample size of $N = 5$ in the control group is higher than the required sample size obtained by the a priori analysis.

The control group included five healthy, older, right-handed participants (4 women, 1 man; age: $M = 77.4$ years old, $SD = 6.39$), who had normal or corrected-to-normal vision. None of them reported present or past tinnitus, or any neurological and/or psychiatric history. These inclusion/exclusion criteria were determined before data analysis.

2.2. *Experimental procedure*

The experimental procedure was in accordance with the Declaration of Helsinki (1964). No part of the study procedures or analyses was preregistered prior to the research being conducted.

R. B. and the participants of the control group were evaluated three times on three different days (in the following order: neutral lenses, leftward deviation, and rightward deviation) with the same experimental procedure for each session. The control condition (i.e., neutral-lens session) was the first to be conducted in order to estimate the participant's initial state by obtaining several basic values. There was a seven-day gap between the neutral-lens session and the leftward-prism adaptation session. A period of twenty-one days was fixed between the leftward-prism adaptation and the rightward-prism adaptation. This long period between leftward- and rightward-prism adaptation was chosen to avoid any aftereffects of the first adaptation on the second session (see Fig. 1). Leftward optical deviation was used because it is the only optical deviation that has been shown to shift attention toward the right side of participants without neurological lesions (Loftus, Vijayakumar, & Nicholls, 2009). The rightward optical deviation, directed toward the unaffected ear, was used because prism adaptation toward the unaffected side alleviated pathologic pain in patients with complex regional pain syndrome (Sumitani et al., 2007).

In a preliminary step, before the first session, a pure tone audiometry was carried out in order to assess R. B.'s auditory perception threshold. The control group did not carry out this preliminary step.

Four tasks were then used to test the aftereffects of prism adaptation: tinnitus spectrum assessment in pitch and loudness, discomfort assessment, manual line-bisection, and open-loop pointing task. Only R. B. conducted the tasks involving tinnitus spectrum and discomfort assessments. All participants completed the other tasks at different times during the experimental procedure (see Fig. 1): before prism adaptation (Pretest), and immediately after prism adaptation (Posttest_0), then at a regular 15-min intervals, i.e., 15 min (Posttest_{15}), 30 min (Posttest_{30}), 45 min (Posttest_{45}), 60 min (Posttest_{60}), and 75 min (Posttest_{75}) after prism adaptation. For the control condition, the seven baseline performance measures were described as follows: T1 referred to the neutral-lens pre-exposure phase, and T2 to T7 referred to the neutral-lens post-exposure phases.

2.3. *Pure tone audiometry*

The pure tone audiometry allowed R. B.'s auditory thresholds to be determined and an audiogram for each ear to be completed (Fig. 2). The audiometric test took place in a quiet room thanks to the Electronica AudiTest system, a CE medical device with an adjustable sound level (from −10 dB to 100 dB

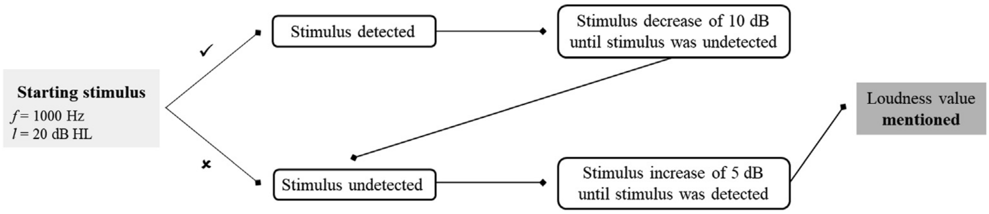

Fig. 2 – Procedure of the pure tone audiometry. f: frequency; l: loudness.

HL). Stimuli were pulsed pure tones lasting three seconds, presented through noise-isolating Sennheiser headphones (HD 202 model) over a range of eleven auditory frequencies (125 Hz, 250 Hz, 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz, 6000 Hz, and 8000 Hz). In a first step, R. B. was familiarized with the stimuli presented in each ear, with a frequency of 1000 Hz and a loudness of 20 dB HL. Then the perception threshold for each of the eleven frequencies was measured. Three blocks of stimuli were presented to each ear. Each block consisted of (1) a presentation of the reference frequency, which was always 1000 Hz, followed by (2) a presentation of increasing frequencies above 1000 Hz (i.e., 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz, 6000 Hz, and 8000 Hz), then (3) an intermediate test of 1000 Hz followed by (4) a presentation of decreasing frequencies below 1000 Hz (i.e., 750 Hz, 500 Hz, 250 Hz, and 125 Hz). For each auditory frequency tested, the starting loudness was fixed at 20 dB HL. If R. B. did not detect the stimulus, the experimenter increased the loudness by steps of 5 dB HL until the stimulus was perceived. If the stimulus was detected, the experimenter decreased the loudness by steps of 10 dB HL until the stimulus was no longer perceived. When the stimulus became undetected, the experimenter then increased the stimulus by steps of 5 dB HL until it was detected again by R. B. The loudness value of the last sound perceived was reported on an audiogram. After the presentation of the three blocks, the perception threshold was defined as the hearing level of the lowest decibel for which R. B. detected a frequency at least twice out of three (American National Standards Institute, 2004).

2.4. *Tinnitus spectrum assessment (tinnitus matching)*

The tinnitus spectrum was assessed by identifying its two main features: pitch and loudness. Tone Generator software (https://www.nch.com.au/tonegen/index.html), developed by NCH Software, is an easy-to-use program that can be used as a sound generator to conduct acoustic tests. The software creates pure tones for tonal tinnitus or white noise for complex tinnitus. It was combined with the WavePad plugin (https://www.nch.com.au/wavepad/fr/free-vst-plugins.html), an audio editor also developed by NCH Software to arrange sound recordings. The plugin is an equalizer, which allows the application of a band-pass filter to the auditory signal in order to match the generated sound to the pitch of the tinnitus. R. B. sat in a quiet room and did not see what was displayed on the computer screen. The generated sound was played through noise-isolating Sennheiser headphones (HD 202 model) in the unaffected ear only and the patient had to match both its pitch and loudness to his tinnitus. At the beginning, the experimenter played a white noise centered on 100 Hz. According to R. B.'s indications, the experimenter adjusted the band-pass filter in steps of 500 Hz. If the frequency exceeded that of the tinnitus, the experimenter decreased it in steps of 200 Hz. The frequency was then refined in steps of 100 Hz until it matched the auditory pitch of the tinnitus. After pitch matching, R. B. indicated to the experimenter whether to decrease or increase the sound volume to adjust the loudness of the tinnitus. A sound level meter Lutron SL-4001 indicated the loudness value from the headphones. The tinnitus loudness was expressed in dB SL (decibel sensation level), which corresponds to the individual intensity in relation to the patient's auditory threshold measured in dB HL for the tested frequency. Specifically, if a pure sound of 1000 Hz at 40 dB HL is presented to a subject A who has a threshold of 15 dB HL for this frequency, this corresponds to a loudness of 25 dB SL (40 minus 15). For another subject B who has a threshold of 5 dB HL, the same stimulus will correspond to 35 dB SL (40 minus 5).

2.5. *Discomfort assessment*

The discomfort was assessed by using the visual analog scale that we have developed (see Appendix 1). The scale was vertical to avoid attentional and representational spontaneous bias of pseudoneglect in the horizontal space (e.g., McCourt & Jewell, 1999), which can be modulated by prism adaptation (for a review see Michel, 2016). Moreover, the scale was two-sided. The part seen by R. B. was composed of seven smileys expressing seven levels of discomfort. The other part hidden from R. B. was a numerical scale graduated from 0 (i.e., no discomfort) to 10 (i.e., unbearable discomfort). R. B. did not carry out the task himself in order to avoid any deadaptation because of short-lived aftereffects. The experimenter slowly dragged the cursor, from 0 to 10, until R. B. told him to stop.

2.6. *Manual line-bisection task*

All participants performed a manual line-bisection task in order to study the impact of tinnitus on spatial representation and to evaluate the representational aftereffects of prism adaptation. The experimenter presented a series of ten 300-mm long and 1-mm wide lines on A3 sheets one by one. R. B. and the control group were given a pencil and had to place a mark at the center of each line presented by the experimenter. The participants were asked to carry out movements slowly to avoid contamination of the movement by the sensorimotor aftereffects.

2.7. Open-loop pointing task

To assess effective development of prism adaptation, all participants conducted the open-loop pointing task (ten trials) before prism adaptation (i.e., pretest) and after prism adaptation (i.e., posttests). They were asked to point a sagittal target (6-mm diameter black dot) placed 25 cm from the starting position of their right hand. In each trial, the experimenter first asked participants to look at the target. Then the participants closed their eyes and pointed at the target and kept their eyes closed as they executed the movement and between each trial. At the end of each pointing step, the experimenter passively replaced the participant's right index finger in the starting position. These precautions prevented the deadaptation of participants during the task by reducing all the visuo-spatial cues relative to sensorimotor realignment (Redding & Wallace, 1997).

2.8. Prism adaptation procedure

R. B. and the control group underwent the prism adaptation procedure immediately after the pretest. The first session was a control session, in which the participants wore neutral lenses, which did not modify their visual field. For the following two sessions, the participants wore prism goggles producing a 15° visual lateral shift of the visual field. They were exposed to a leftward optical deviation, seven days after the control session. They were then exposed to a rightward optical deviation, twenty-one days after exposure to the leftward optical deviation (see Fig. 1). In a horizontal working plan, nine visual-colored targets (6 mm diameter with a 4 cm inter-dot space) were placed 25 cm from the starting position of the participant's hand. The participants were then asked to point successively at each of the nine targets as fast as possible according to the order indicated by the experimenter. The procedure lasted about 20 min and involved four blocks of 81 pointing trials. The starting position of the hand could not be seen in order to ensure the optimal development of prism adaptation (Redding & Wallace, 1997).

2.9. Data analyses

No part of the study procedures or analyses was preregistered prior to the research being conducted. All data have been archived in the publicly accessible OSF website (DOI: 10.17605/OSF.IO/UNG7H; https://osf.io/ung7h/).

For all the participants, the results of the open-loop pointing task and the manual line-bisection task were expressed as means, and the pretests were compared to zero using a one-sample comparison.

For the data obtained by R. B., nonparametric statistical analyses were performed using a Mann–Whitney *U* test to compare the posttests with the pretest (e.g., Pretest *vs* Posttest$_0$). A correction of the *p*-values was achieved according to the Bonferroni method, and the *p*-values mentioned correspond to the adjusted *p*-values. This analyze could not be used for the tinnitus parameters measures (pitch, loudness, and discomfort) since we collected only one measurement per test (Pretest and Posttests). Therefore, these results are presented in a descriptive way.

For the data obtained by the control group, a Friedman ANOVA allowed repeated measures obtained during the open-loop pointing task and the line-bisection task to be compared. Due to the small sample size, R. B. and the control group were compared using descriptive analysis.

3. Results

3.1. Pure tone audiometry

As displayed in Fig. 3, R. B.'s audiogram shows a presbycusis pattern, with downward-sloping pure tone thresholds from 1500 Hz to 8000 Hz for both ears. The decline was more marked in the left ear from 2000 Hz to 4000 Hz. At 3000 Hz, corresponding to the frequency of R. B.'s tinnitus (see section *Measure of the tinnitus pitch* below), the hearing loss was 40 dB HL for the left ear (i.e., the affected ear), whereas it was 25 dB HL for the right ear (i.e., the unaffected ear).

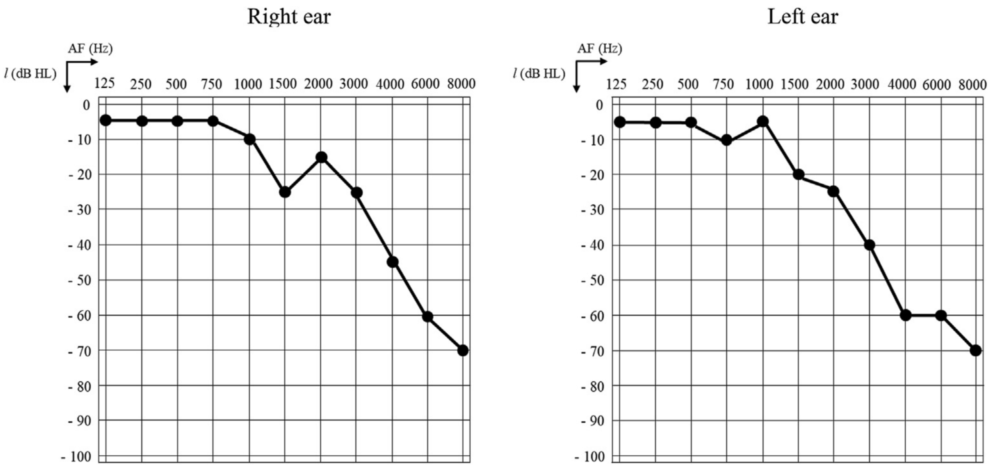

Fig. 3 – Audiogram of the participant R. B. AF: Auditory frequencies; l: Loudness; HL: Hearing level.

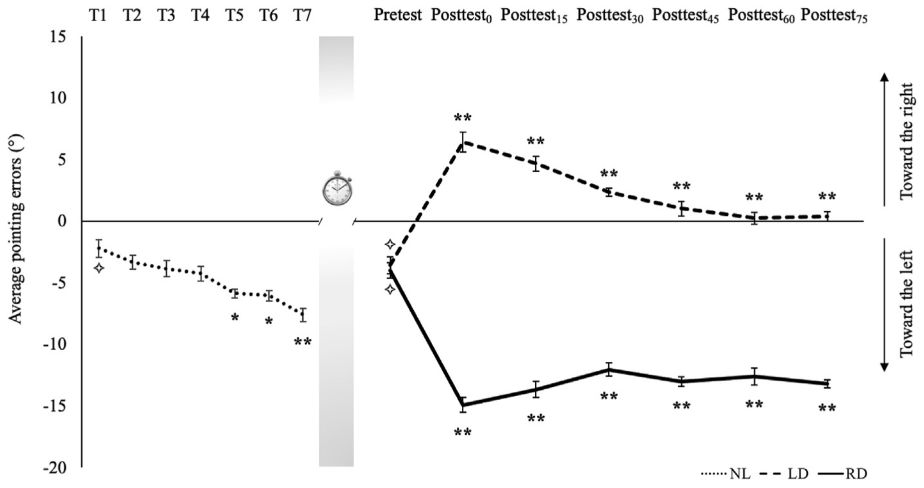

Fig. 4 – Average of pointing errors for pretest and posttests as a function of the deviation in R. B. NL: Neutral lenses; LD: Left deviation; RD: Right deviation. T1 to T7 correspond to the seven tests performed during the neutral-lens session: T1 was performed before goggle exposure, T2 to T7 were performed after goggle exposure. The gray band illustrates the time period between the neutral-lens session and each prism adaptation session (LD: 7 days; RD: 28 days). Each posttest was compared to the pretest; ****$p < .05$; *****$p < .01$**. Each pretest was compared to 0; ✧ $p < .01$.**

3.2. *Open-loop pointing task*

3.2.1. *The tinnitus sufferer R. B.*

In pretests, R. B. showed a bias toward the left side of space (negative values in Fig. 4), which differed significantly from 0 in each session [NL: $t(9) = -3.037$; $p = .014$; LD: $t(9) = -5.394$; $p < .001$; RD: $t(9) = -6.298$; $p < .001$]. A nonparametric Mann–Whitney *U* test was performed to compare the posttests with the pretest (e.g., neutral-lens session: T1 *vs* T2; prism adaptation: Pretest *vs* Posttest$_0$). In the neutral-lens session (NL; dotted line), a nonsignificant slight deviation was observed toward the left side of space throughout the first three testing phases in comparison to T1 (i.e., T2, T3, T4; all *ps* > .10). From T5 to T7, this leftward bias became significantly more marked in comparison to T1 (T5: $Z = 2.956$; $p = .019$; T6: $Z = 3.107$; $p = .011$; T7: $Z = 3.485$; $p = .003$). Adaptation to a leftward optical deviation (LD; dashed line) produced a significant shift toward the right side of space (positive values in Fig. 4), from Posttest$_0$ until the end of the experiment (Posttest$_0$: $Z = -3.746$; $p = .001$; Posttest$_{15}$: $Z = -3.747$; $p = .001$; Posttest$_{30}$: $Z = -3.747$; $p = .001$; Posttest$_{45}$: $Z = -3.399$; $p = .004$; Posttest$_{60}$: $Z = -3.191$; $p = .009$; Posttest$_{75}$: $Z = -3.191$; $p = .009$). Adaptation to a rightward optical deviation (RD; solid line) caused a significant shift toward the left side of space (negative values in Fig. 4), from Posttest$_0$ until the end of the experiment (Posttest$_0$: $Z = -3.746$; $p = .001$; Posttest$_{15}$: $Z = -3.746$; $p = .001$; Posttest$_{30}$: $Z = -3.747$; $p = .001$; Posttest$_{45}$: $Z = -3.747$; $p = .001$; Posttest$_{60}$: $Z = -3.747$; $p = .001$; Posttest$_{75}$: $Z = -3.747$; $p = .001$).

The presence of significant sensorimotor aftereffects in the opposite direction to the optical deviation from Posttest$_0$ to Posttest$_{75}$ indicates that R. B. adapted correctly to both optical deviations, and that the adaptation remained until the end of the experiment.

3.2.2. *The control group*

In pretests, the control group presented a bias directed toward the left part of space, which did not differ significantly from 0 in any session [NL: $t(4) = -.650$; $p = .551$; LD: $t(4) = -.879$; $p = .429$; RD: $t(4) = -1.786$; $p = .149$]. A Friedman ANOVA was performed to test sensorimotor performance across all testing phases (i.e., Pretest and Posttests). In the neutral-lens session (NL; dotted line), no significant sensorimotor time effect was observed ($p = .433$). Adaptation to a leftward optical deviation (LD; dashed line) produced a significant shift toward the right side of space (positive values in Fig. 5; time effect: $p < .001$), and adaptation to a rightward optical deviation (RD; solid line) caused a significant shift toward the left side of space (negative values in Fig. 5; time effect: $p = .014$).

3.3. *Manual line-bisection task*

3.3.1. *The tinnitus sufferer R. B.*

In pretests, R. B. showed a bias toward the left side of space, which differed significantly from 0 in each session [NL: $t(9) = -7.932$; $p < .001$; LD: $t(9) = -7.344$; $p < .001$; RD: $t(9) = -6.087$; $p < .001$]. A nonparametric Mann–Whitney *U* test was used to compare the posttests with the pretest (e.g., neutral-lens session: T1 *vs* T2; prism adaptation sessions: Pretest *vs* Posttest$_0$). In the neutral-lens session (NL; dotted line), the performances were stable around −1 cm from the center of the line, no significant change was observed between T1 and any posttest (all *ps* > .10). Adaptation to a leftward optical deviation (LD; dashed line) produced a nonsignificant shift toward the right (all *ps* > .10). Fig. 6 shows that adaptation to a rightward optical deviation (RD; solid line) caused a large shift toward the right side of space. The bias produced by prism adaptation then fluctuated, but remained further

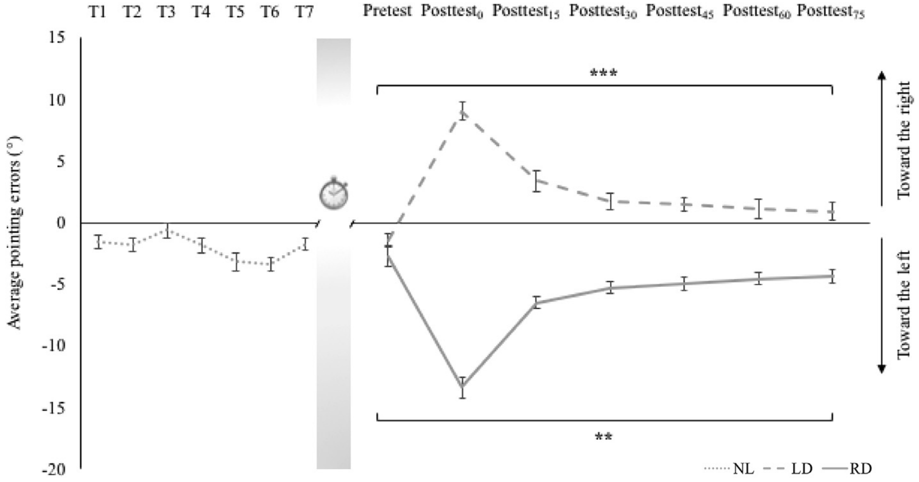

Fig. 5 – Average pointing errors for pretest and posttests as a function of the deviation in the control group. NL: Neutral lenses; LD: Left deviation; RD: Right deviation. T1 to T7 correspond to the seven tests performed during the neutral-lens session: T1 was performed before goggle exposure, T2 to T7 were performed after goggle exposure. The gray band illustrates the time period between the neutral-lens session and each prism adaptation session (LD: 7 days; RD: 28 days). Time effect: *****p* **< .01; ***** ***p*** **< .001.**

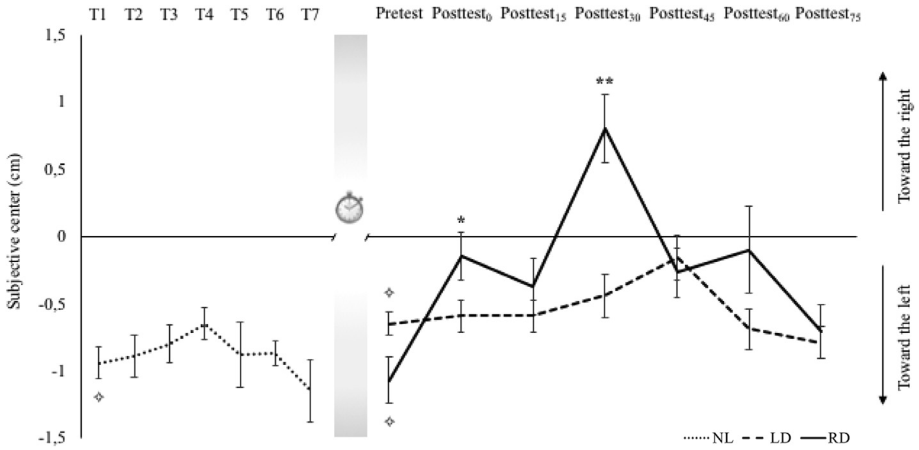

Fig. 6 – Subjective center of the lines for pretest and posttests as a function of the deviation in R. B. NL: Neutral lenses; LD: Left deviation; RD: Right deviation. T1 to T7 correspond to the seven tests performed during the neutral-lens session: T1 was performed before goggle exposure, T2 to T7 were performed after goggle exposure. The gray band illustrates the time period between the neutral-lens session and each prism adaptation session (LD: 7 days; RD: 28 days). Each posttest was compared to the pretest; ****p* **< .05; *****p*** **< .01. Each pretest was compared to 0; ✧** ***p*** **< .001.**

toward the right than the pretest. This relative rightward bias compared to the pretest lasted until one hour after prism removal. Statistically, adaptation to a rightward optical deviation significantly shifted the subjective center of R. B. toward the right compared to the pretest immediately after prism adaptation in Posttest$_0$ (.92 cm right of the pretest; $Z = -2.849$; $p = .026$), and 30 min after prism removal (1.87 cm right of the pretest; $Z = -3.593$; $p = .002$). The aftereffects in Posttest$_{45}$ were almost significantly different to the Pretest (.80 cm right of the pretest; $Z = -2.613$; $p = .054$). In Posttest$_{15}$ (.70 cm right of the pretest), Posttest$_{60}$ (.97 cm right of the pretest) and Posttest$_{75}$ (.36 cm right of the pretest), the shift of the subjective center toward the right side of space was no longer significant (all *ps* > .10).

Adaptation to a rightward optical deviation shifted the estimation of the center of horizontal lines toward the right side of space compared to the pretest, and the effects were early, large, and present until 30 min after prism removal.

3.3.2. *The control group*

In pretests, the control group presented a trend directed toward the left part of space, which did not differ significantly from 0 in any session [NL: $t(4) = -1.527$; $p = .201$; LD: $t(4) = -2.612$; $p = .059$; RD: $t(4) = -.914$; $p = .413$]. A Friedman

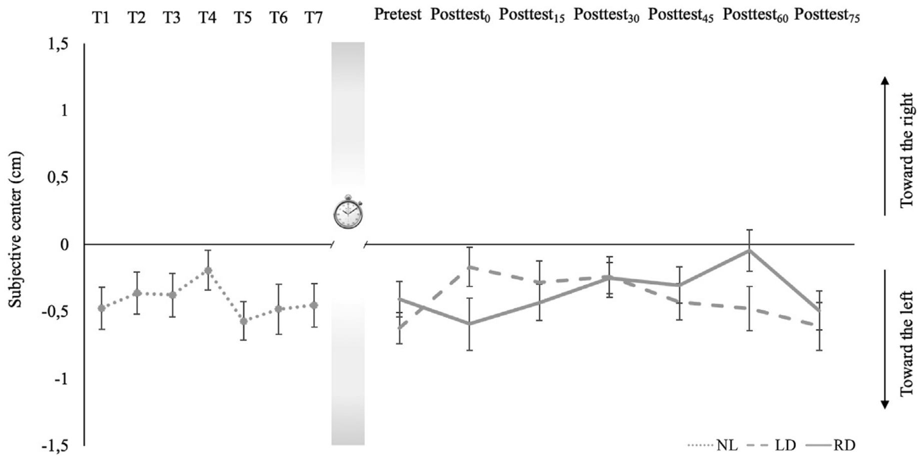

Fig. 7 – Subjective center of the lines for pretest and posttests as a function of the deviation in the control group. NL: Neutral lenses; LD: Left deviation; RD: Right deviation. T1 to T7 correspond to the seven tests performed during the neutral-lens session: T1 was performed before goggle exposure, T2 to T7 were performed after goggle exposure. The gray band illustrates the time period between the neutral-lens session and each prism adaptation session (LD: 7 days; RD: 28 days).

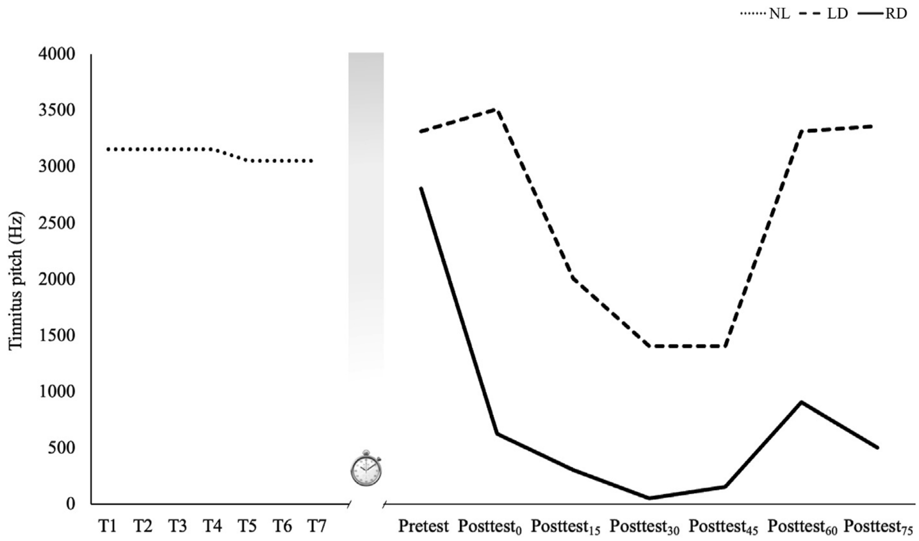

Fig. 8 – Estimation of the tinnitus pitch for each test throughout the three experimental sessions. NL: Neutral lenses; LD: Left deviation; RD: Right deviation. T1 to T7 correspond to the seven tests performed during the neutral-lens session: T1 was performed before goggle exposure, T2 to T7 were performed after goggle exposure. The gray band illustrates the time period between the neutral-lens session and each prism adaptation session (LD: 7 days; RD: 28 days).

ANOVA was performed to test effects of prism adaptation on the line-bisection task. Exposure to neutral lenses (NL; dotted line) and adaptation to a rightward optical deviation did not produce a significant time effect (NL: $p = .515$; RD: $p = .281$). Adaptation to a leftward optical deviation (LD; dashed line) tended to shift the line bisection toward the right in Posttest$_0$, and the performance returned to its baseline. However, statistically, no significant time effect was observed ($p = .860$).

3.4. *Measure of the tinnitus pitch*

In pretests, the values of the estimated tinnitus pitch were relatively constant (NL: 3150 Hz; LD: 3300 Hz; RD: 2800 Hz). No variation was observed either among the seven tests of the neutral-lens session (NL: T1 to T7), nor between the seven tests of the neutral-lens session and the pretests of the two prism adaptation sessions (LD and RD). These results support

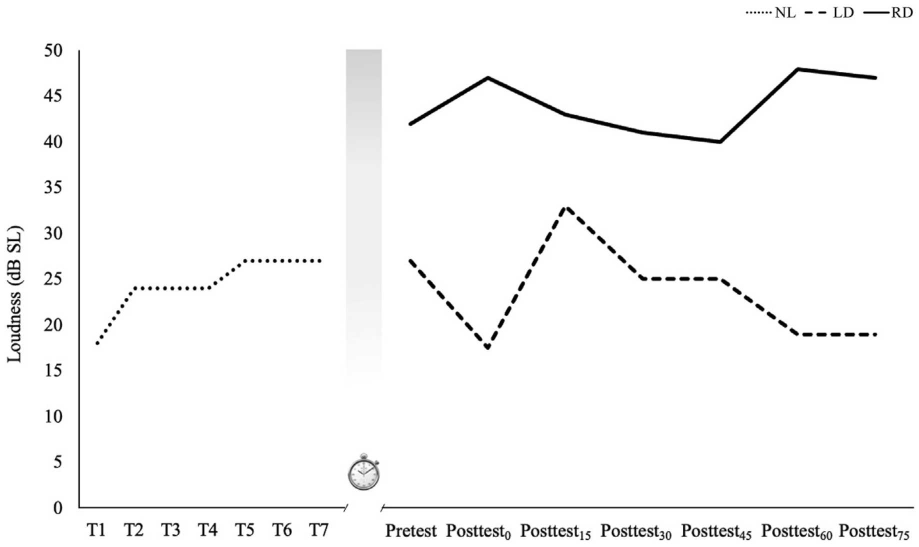

Fig. 9 – Estimation of the loudness of tinnitus for pretest and posttests as a function of the deviation. NL: Neutral lenses; LD: Left deviation; RD: Right deviation. T1 to T7 correspond to the seven tests performed during the neutral-lens session: T1 was performed before goggle exposure, T2 to T7 were performed after goggle exposure. The gray band illustrates the time period between the neutral-lens session and each prism adaptation session (LD: 7 days; RD: 28 days).

a stable tinnitus pitch assessment by R. B. (see left side of Fig. 8). A time effect occurred during each prism adaptation session (see right side of Fig. 8). Adaptation to a leftward optical deviation (LD; dashed line) produced a decrease in pitch 15 min after prism removal (Posttest$_{15}$: 2000 Hz, i.e., 1300 Hz less than in Pretest). The drop lasted in Posttest$_{30}$ and in Posttest$_{45}$ (Posttest$_{30}$ and Posttest$_{45}$: 1400 Hz, i.e., 1900 Hz less than in Pretest), and the pitch returned to its baseline level in Posttest$_{60}$ and Posttest$_{75}$. Adaptation to a rightward optical deviation (RD; solid line) caused an early dramatic decrease in pitch, immediately after adaptation (Posttest$_0$: 625 Hz, i.e., 2175 Hz less than in Pretest), which lasted in Posttest$_{15}$ (300 Hz, i.e., 2500 Hz less than in Pretest). The pitch reached its minimum value 30 min after prism removal (Posttest$_{30}$: 50 Hz, i.e., 2750 Hz less than in Pretest), and slightly increased until the end of the experiment, staying far from its baseline value (Posttest$_{45}$: 150 Hz, i.e., 2650 Hz less than in Pretest; Posttest$_{60}$: 900 Hz, i.e., 1900 Hz less than in Pretest; Posttest$_{75}$: 500 Hz, i.e., 2300 Hz less than in Pretest).

Prism adaptation to both optical deviations decreased the value of the perceived pitch, but the effects were earlier, larger and more durable after adaptation to a rightward optical deviation with a spike 30 min after prism removal, as for the manual line-bisection task.

3.5. *Measure of the tinnitus loudness*

The tinnitus loudness was higher in pretest for the rightward-prism adaptation session (42 dB SL) compared to the other two sessions (NL: 18 dB SL; LD: 27 dB SL). The tinnitus loudness increased slightly throughout the seven tests of the neutral-lens session (NL; T1: 18 dB SL to T7: 27 dB SL; see left side of Fig. 9). Adaptation to a leftward optical deviation (LD; dashed line; see right side of Fig. 9) decreased loudness immediately after prism removal (Posttest$_0$: 9.5 dB SL less than in Pretest). A peak occurred 15 min after prism removal (6 dB SL than in Pretest), and the loudness returned to its baseline in Posttest$_{30}$ and Posttest$_{45}$. Loudness slightly decreased until the end of the experiment (Posttest$_{60}$ and Posttest$_{75}$: 19 dB SL). After adaptation to a rightward optical deviation (RD; solid line; see right side of Fig. 9), only slight fluctuations of loudness were observed during the experiment.

3.6. *Discomfort assessment*

In the three sessions, the discomfort level was the same and remained constant throughout the sessions. It reached level 5 on the scale, corresponding to a moderate discomfort. Despite the regular results on the discomfort scale, R. B. spontaneously reported being less bothered by his tinnitus as the experiment progressed, during the prism adaptation sessions (i.e., LD, RD).

4. Discussion

The current case study provides three fundamental results concerning tinnitus: 1) the expression of tinnitus throughout sensorimotor behavior during an open-loop pointing task and a line-bisection task, 2) the aftereffects of adaptation to a rightward optical deviation on the line-bisection task, and 3) the aftereffects of prism adaptation on tinnitus features.

First, the performances of R. B. in the open-loop pointing task and in the manual line-bisection task were biased toward the left side of space in pretests, that is, toward the side of his tinnitus. Although, it was not significant, an initial leftward bias also tended to be present for both these tasks in the control group, but it appeared less pronounced than for R. B. Named pseudoneglect in the line-bisection task (for a review see Jewell & McCourt, 2000), this bias is frequently observed in healthy people and explained by the dominance of the right hemisphere in visuo-spatial processes (Corballis, 2003; Fink et al., 2000; Fink, Marshall, Weiss, & Zilles, 2001; Zago et al., 2017). However, the leftward bias observed in our study could be surprising because of the participants' advanced age (i.e., 75 years old for R. B. and an average 77 years old for the control group). It has previously been reported that in elderly people, pseudoneglect is suppressed or reversed to a bias toward the right side of space (Schmitz & Peigneux, 2011; for a review see Jewell & McCourt, 2000). The bias of pointing and the representational bias observed in R. B. could be explained by an attentional bias toward the affected ear. A similar bias has been observed in an auditory attentional task in which tinnitus sufferers showed difficulties in diverting their attention from the affected ear (e.g., Cuny et al., 2004; Trevis et al., 2016). It is thus worth mentioning that for the open-loop pointing task the leftward bias in pretest could also reflect the attentional bias toward the affected ear for two reasons. First, the initial leftward bias increased through the neutral-lens session for R. B., whereas the performance of the control group remained stable. Second, after prism adaptation to a rightward optical deviation, the pointing performance of the control group decreased 15 min after prism removal (i.e., classical sensorimotor deadaptation), whereas this was not the case for R. B., who continued to show marked sensorimotor aftereffect (i.e., absence of sensorimotor deadaptation). All this information indicates that tinnitus would seem to draw the spatial attention toward the side of the affected ear. A larger study involving sufferers of unilateral tinnitus (in either the left or right ear) should allow this point to be clarified, in particular by dissociating the manifestations of pseudoneglect from the attentional and representational bias related to the tinnitus-affected ear.

The second interesting result was the shift in the estimation of the center of the line in a manual line-bisection task to the right compared to pretest after prism adaptation to a rightward optical deviation (i.e., optical deviation toward the unaffected ear), with an immediate, long, strong, and significant aftereffect. Only the rightward optical deviation produced representational aftereffects toward the right part of space in R. B., whereas only leftward optical deviation caused these aftereffects in healthy participants (e.g., Colent et al., 2000; for a review see Michel, 2016). The control group tended to bisect the line toward the right part of space in comparison to their initial performance after adaptation to a leftward optical deviation, but no significant aftereffects were observed. This result could be explained by the very small sample size ($N = 5$), and/or the nonsignificant initial leftward bias, whose presence conditions the development of aftereffects in the line-bisection task after prism adaption to a leftward optical deviation (e.g., Goedert, LeBlanc, Tsai, & Barrett, 2010). The divergence observed in R. B. between sensorimotor aftereffects (i.e., opposite to the optical deviation) and line-bisection aftereffects (i.e., in the same direction as the rightward optical deviation) suggests a potential specific reaction to prism adaptation in patients with tinnitus in a spatial representational task. The aftereffects observed after adaptation to a rightward optical deviation could be therapeutic, like those shown in phantom pain (Foncelle et al., 2021; Sumitani et al., 2007). In a recent study investigating the influence of prism adaptation in a patient suffering from phantom pain in the left hand, adaptation to a rightward optical deviation shifted proprioceptive straight-ahead toward the right only when the patient performed the experimental tasks with her left hand (Foncelle et al., 2021). Similarly, Sumitani and collaborators (2007) used the visual subjective body-midline task and observed similar outcomes. Altogether with our results, this suggests that prism adaptation to an optical deviation toward the unaffected side might rebalance the distribution of spatial attention initially focused on the affected side.

The third powerful result is that for the first time we demonstrated prism adaptation aftereffects on unilateral tinnitus. Both optical deviations decreased the perceived tinnitus pitch, with an earlier and larger effect after adaptation to a rightward optical deviation (i.e., toward the unaffected ear). The aftereffects lasted approximatively 30 min after adaptation to a leftward optical deviation, and until the end of the experiment for the rightward optical deviation (i.e., 75 min). Whatever the optical deviation used, prism exposure only resulted in weak fluctuations of the tinnitus loudness. In tinnitus, there is an aberrant neuronal activity accompanied by a reorganization of the cortical auditory areas (Mühlnickel et al., 1998; for a review see De Ridder et al., 2011). Exposure to prism adaptation to a deviation toward the unaffected ear could act on this plasticity in a transitory way by reducing tinnitus perception.

Concerning the discomfort caused by the tinnitus, according to the visual analog scale, no change was observed whatever the experimental session. However, during the sessions of prism adaptation (i.e., LD, RD), R. B. mentioned a decrease in his tinnitus perception, as if he had “forgotten” his tinnitus. The spontaneous feeling freely reported by R. B. differed from the data obtained with the scale despite all the precautions taken, probably because the discomfort assessment with the scale was not sensitive enough. Moreover, in the literature, the correlation between discomfort assessment and the audiological characteristics of tinnitus (i.e., pitch and loudness) is still unclear. Concerning loudness, some authors suggest a dissociation between tinnitus experience and loudness matching. Namely, high tinnitus loudness perceived by patients is not systematically linked to high discomfort (Colagrosso, Fournier, Fitzpatrick, & Hébert, 2019; Noroozian et al., 2017), whereas others assume the opposite (Al-Swiahb et al., 2016; da Nascimento et al., 2019). Concerning pitch, although no link between pitch and discomfort has been reported in the literature (e.g., Colagrosso et al., 2019), Key and Payne (1981) observed that high frequencies would be more annoying than low frequencies. Our results suggest that the decrease in pitch observed after prism exposure to both optical deviations led to a decreased in R. B.'s tinnitus perception, in line with the decreased disturbance he spontaneously reported.

As already mentioned, tinnitus seems to be linked to disturbed attention. In comparison with healthy participants, tinnitus sufferers showed reduced performance in attentional tasks (e.g., Cuny et al., 2014; Leong et al., 2020; Stevens, Walker, Boyer, & Gallagher, 2007; Trevis et al., 2016), as well as decreased attentional network activity at rest (Kandeepan et al., 2019) and during attentional tasks (Husain, Akrofi, Carpenter-Thompson, & Schmidt, 2015; Lima et al., 2019). Attention appears to be crucial when experiencing tinnitus; directing patients' attention away from tinnitus by focusing on another stimulus would decrease their tinnitus perception (Colagrosso et al., 2019). Although weaker than the decrease observed in our study, attentional training has already reduced the tinnitus pitch by directing attention toward auditory stimuli that differ from the tinnitus (Spiegel et al., 2015). Our results associated with those of Spiegel et al. (2015) suggest that modulating attention of tinnitus sufferers could be an effective way to reduce their tinnitus perception.

Finally, the results obtained for the tinnitus pitch match those obtained in the manual line-bisection task, especially after adaptation to a rightward optical deviation: the minimum perceived pitch and the maximum shift of the subjective center toward the right side were observed 30 min after rightward prism removal. Our results suggest a link between the modulation of spatial representation and the modulation of the perceived tinnitus pitch. The line-bisection task seemed to reflect changes in tinnitus perception and could be an interesting tool to assess tinnitus indirectly.

In summary, our preliminary results provide the first demonstration that prism adaptation to an optical deviation toward the unaffected side influences tinnitus perception and might represent a therapeutic approach to alleviate tinnitus. Although both optical deviations were effective, an exposure to prism adaptation toward the unaffected ear (in the present case, to a rightward optical deviation) resulted in a larger decrease in the tinnitus pitch. The initial representational bias observed toward the tinnitus side in the line-bisection task in pretests could suggest attention focused toward the tinnitus side. Prism adaptation toward the unaffected ear (in the present case, to a rightward optical deviation) shifted the bias toward the unaffected ear. According to these results, spatial representation could be a new tool to assess tinnitus indirectly. A limitation of our study was the difference in the initial loudness level between the three experimental conditions (see Fig. 7) and the overall weak discomfort perceived by the patient. This might have prevented the observation of significant aftereffects on these parameters. Further studies including more tinnitus sufferers are needed to confirm our preliminary results. To conclude, the current study suggests that prism adaptation may have benefits on unilateral tinnitus and opens a new avenue for its treatment.

Author note

Clémence Bonnet and Carine Michel-Colent, INSERM UMR1093-CAPS, Université de Bourgogne, UFR des Sciences du Sport, 3 allée des Stades Universitaires, BP 27877, 21000 Dijon, France; Bénédicte Poulin-Charronnat, LEAD – CNRS UMR5022, Université de Bourgogne, Pôle AAFE, 11 Esplanade Erasme, 21000 Dijon, France; Yves Rossetti, CRNL – INSERM UMR-S 1028 – CNRS UMR5292, Centre Hospitalier Le Vinatier Bâtiment 452, 95 Boulevard Pinel, 69500 Bron, France; Xavier Perrot, Hospices Civils de Lyon, Service d'Audiologie et Explorations Otoneurologiques, Hôpital Edouard Herriot, Pavillon U, 5 Place d'Arsonval, 69003 Lyon, France.

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CRediT authorship contribution statement

CB: Conceptualization; Formal analysis; Investigation; Methodology; Writing – original draft; Writing – review & editing.

BPC and CMC: Conceptualization; Formal analysis; Funding acquisition; Methodology; Supervision; Validation; Writing – review & editing.

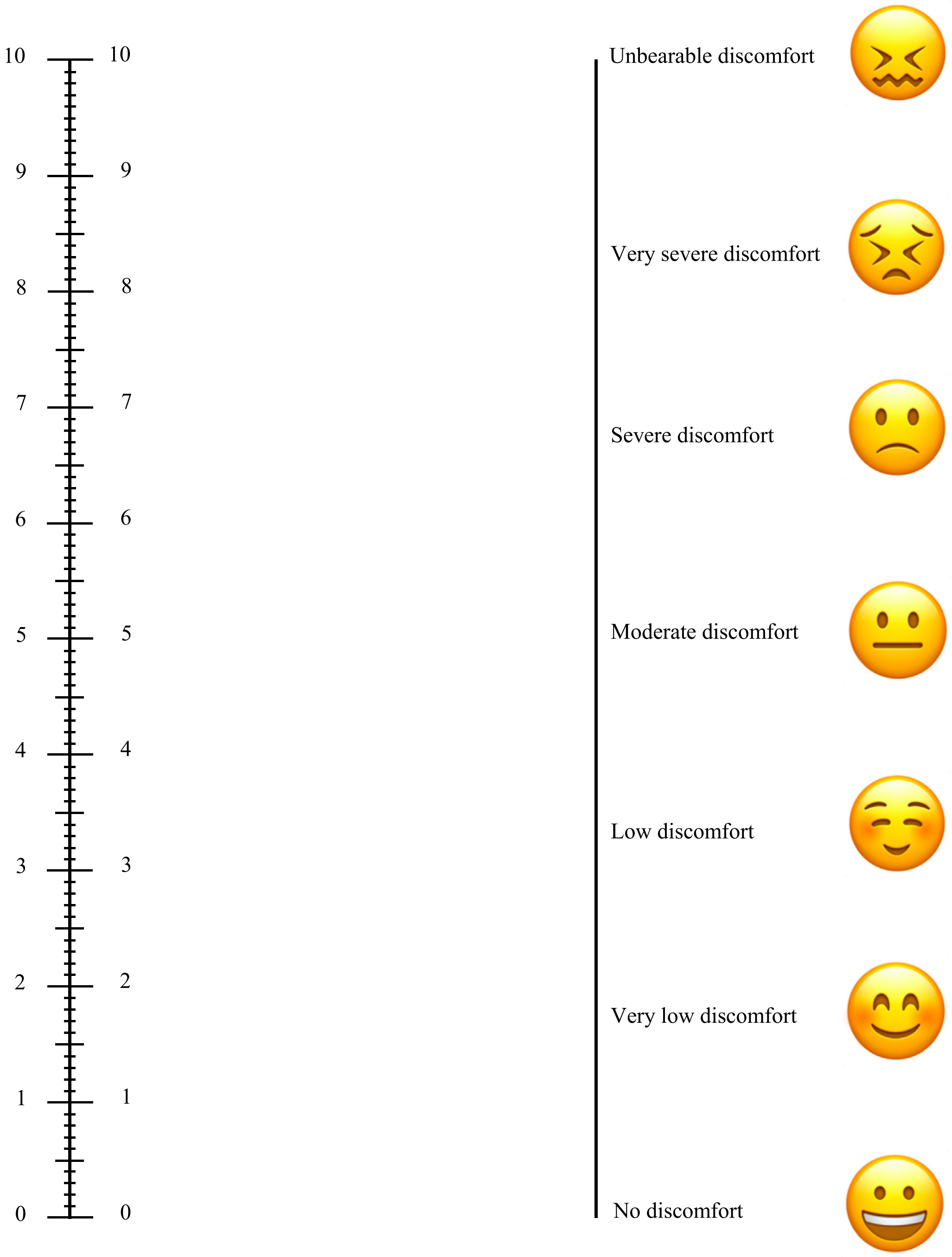
XP: Conceptualization; Validation; Writing – review & editing.

YR: Conceptualization; Validation.

Open practices

The study in this article earned Open Data and Open Materials badges for transparent practices. Materials and data for the study are available at https://osf.io/ung7h/

Appendix 1. Visual analog scale for discomfort assessment.



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