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Cross-Modal Aftereffects of Visuo-Manual Prism Adaptation: Transfer to Auditory Divided Attention in Healthy Subjects

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Objective: Prism adaptation was shown to modify auditory perception. Using a dichotic listening task, which assesses auditory divided attention, benefits of a rightward prism adaptation were demonstrated in neglect patients (i.e., a syndrome following right hemisphere brain damage) by reducing their left auditory extinction. It is currently unknown whether prism adaptation affects auditory divided attention in healthy subjects. In the present study, we investigated the aftereffects of prism adaptation on dichotic listening. ***Method:*** A sample of 47 young adults performed a dichotic listening task, in which pairs of words were presented with two words sounded simultaneously, one in each ear. Three parameters were measured: The percentage of recalled words, the percentage of correctly recalled words, and the laterality index (LI). ***Results:*** Prism adaptation to a leftward optical deviation (L-PA) significantly increased the overall percentage of recalled words ($p = .044$) and that from the right ear ($p = .002$), and the overall LI ($p = .049$). ***Conclusions:*** For the first time, these findings demonstrate that L-PA produced an orientation of the auditory divided attention in favor of the right ear in healthy participants. This asymmetrical aftereffect provides a new argument in favor of the cross-modal dimension of prism adaptation, although an acclimatization effect of the dichotic listening task is also discussed. Our study opens up a new avenue for using prism adaptation in the field of auditory rehabilitation requiring a modulation of auditory attention.

Key Points

Question: Does prism adaptation act on auditory divided attention in healthy people? ***Findings:*** Prism adaptation to a leftward optical deviation produces aftereffects on auditory divided attention in favor of the right ear. ***Importance:*** Prism adaptation produces auditory cross-modal aftereffects. ***Next Steps:*** Using prism adaptation in auditory rehabilitation requiring a modulation of auditory attention.

Keywords: prism adaptation, dichotic listening, auditory divided attention, cross-modal aftereffects

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Prism Adaptation and Space Representation

The orientation of spatial attention modulates space representation (e.g., Milner et al., 1992). Our ability to orient our visuo-spatial attention to the left and right sides of space is asymmetrical. A spatial bias has been widely observed using the line-bisection task, a reliable tool to study space representation. In this task, the participant has to determine the center of a horizontal line by manually setting a mark (e.g., Colent et al., 2000) or perceptively (e.g., Milner et al., 1992). In healthy subjects, the subjective center is placed slightly to the left of the objective center of the line (e.g., Jewell & McCourt, 2000). This leftward bias is assumed to reflect the dominance of the right hemisphere in visuo-spatial functions (Corballis, 2003; Corbetta & Shulman, 2002; Fink et al., 2001; Zago et al., 2017). Called pseudoneglect, mirroring the rightward bias of neglect (i.e., a neurological deficit of attention, perception, and action in the left part of space following a right brain lesion; Bowers & Heilman, 1980), this behavior is explained by an over-representation of the left part of space and an under-representation of the right part (e.g., McCourt & Jewell, 1999). Prism adaptation consists in pointing at visual targets while wearing prisms that change the visual field (e.g., Stratton, 1896). In healthy subjects, prism adaptation to a leftward optical deviation (L-PA) shifts the estimation of the center of the line to the right of the objective center, producing a neglect-like behavior (Berberovic & Mattingley, 2003; Colent et al., 2000; Fortis et al., 2011; Michel, 2006, 2016; Michel, Pisella, et al., 2003; Striemer & Danckert, 2010).

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Clémence Bonnet played equal role in conceptualization, formal analysis, writing of original draft and writing of review and editing. Bénédicte Poulin-Charronnat played equal role in conceptualization, formal analysis, methodology, supervision, and writing of review and editing. Corentin Vinot played equal role in investigation. Patrick Bard played equal role in formal analysis and software. Carine Michel played equal role in conceptualization, formal analysis, methodology, supervision, and writing of review and editing.

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Prism Adaptation and Space Associated Elements

Space representation is not only restricted to physical stimuli but also concerns mental lines along which spatially valued elements are mentally represented. Dehaene et al. (1993) showed the existence of a mental numerical scale with a left-to-right organization whereby small numbers are associated with the left part of a mental horizontal line and large numbers with the right part. Similarly, the mental alphabetic line also has a left-to-right organization, with letters at the beginning of the alphabet on the left side and letters toward the end of the alphabet on the right side (i.e., A–Z; Gevers et al., 2003). A spatial association is also present in the auditory domain. It has been shown that auditory frequencies are mentally represented along a horizontal line with low frequencies on the left and high frequencies on the right (Ishihara et al., 2013; Rusconi et al., 2006). Like for physical horizontal lines, pseudoneglect affects all these mental horizontal lines involving an overestimation of the left-sided associated elements. This left-sided bias is observed when healthy subjects have to bisect numbers (i.e., toward small numbers; Loftus, Nicholls, et al., 2009; Longo & Lourenco, 2007), letters (i.e., toward the beginning of the alphabet; Nicholls & Loftus, 2007) or auditory frequencies (i.e., toward low frequencies; Michel et al., 2019). After an L-PA, the bias is shifted more toward the right-sided associated elements. As for the physical line-bisection task, the pseudoneglect becomes a neglect-like behavior illustrated by an overestimation of the features with right-sided association, that is to say toward large numbers (Loftus et al., 2008) and letters toward the end of the alphabet (Nicholls et al., 2008). A bias toward high auditory frequencies has also been observed after an L-PA (Bonnet et al., 2021; Michel et al., 2019). In addition to mental scales, many studies have demonstrated aftereffects of an L-PA on a wide range of tasks such as spatial attention (Loftus, Vijayakumar, et al., 2009), visual and auditory time bisection (Magnani et al., 2012, 2020), hierarchical processing (Bultitude & Woods, 2010), or haptic exploration (Girardi et al., 2004). All together, these results suggest that prism adaptation can affect higher levels of spatial representation and modify elements not directly linked to sensorimotor processes involved in the development of visuo-manual adaptation.

Prism Adaptation and Auditory Attention

Prism adaptation to a rightward optical deviation (R-PA), used as a rehabilitative procedure in neglect patients with right hemisphere brain damage (Rossetti et al., 1998), has been shown to improve a wide range of deficits such as drawing, reading, line-cancellation performance, and line-bisection performance (Jacquin-Courtois et al., 2013; Rode et al., 1998; Rossetti & Rode, 2002; Rossetti et al., 1998). Jacquin-Courtois and collaborators (Jacquin-Courtois et al., 2010) have demonstrated aftereffects of an R-PA in neglect patients with a left auditory extinction. These authors used a dichotic listening task, which is an experimental paradigm allowing the study of auditory divided attention. Dichotic listening consists in presenting two different auditory stimuli simultaneously, one stimulus to the left ear and the other to the right ear of the participant (e.g., Broadbent, 1952; Kimura, 1967). After an R-PA, the left auditory extinction was observed to decrease in patients. This aftereffect of prism adaptation was illustrated by a decrease in the lateralization index (i.e., a sensitive measure of auditory asymmetry) corresponding to an increase in words recalled from the left ear (Jacquin-Courtois et al., 2010; Tissieres et al., 2017). Audition is a sensory modality not involved in the development of visuo-manual adaptation (unlike proprioception and vision) and verbal responses do not require visuo-manual coordination, these results therefore highlight the cross-modal effect of prism adaptation.

To the best of our knowledge, the aftereffects of prism adaptation on dichotic listening in healthy subjects have not been investigated to date. In the present study, we investigated whether the attentional aftereffects were restricted to neglect patients because of their particular brain plasticity following brain damage (Jacquin-Courtois et al., 2013), or whether the aftereffects also manifest in healthy subjects. Assessing the aftereffects of prism adaptation on auditory attention in healthy subjects will provide a better understanding of the mechanisms of sensorimotor plasticity transfer into the auditory system. The novel results of the present study could have positive repercussions in the clinical field for rehabilitation processes involving auditory attention.

In the present study, the dichotic listening task was performed with words. Participants were assigned to three groups: One group wore neutral lenses (i.e., control group; NL group), one group was adapted to a leftward optical deviation (L-PA group), and the other group was adapted to a rightward optical deviation (R-PA group). A right-ear advantage (REA) was predicted before the prism adaptation procedure because of the dominance of the left hemisphere in language functions (e.g., Kimura, 1967; Michel et al., 1986) and the preactivation of the left hemisphere in the processing of verbal stimuli (Kinsbourne, 1970). Although we predicted this initial rightward bias, different from the classical initial leftward representational bias of pseudoneglect (e.g., McCourt & Jewell, 1999), an increase in the REA was expected only after an L-PA. Due to the attentional nature of the dichotic listening task, a shift of the orientation of spatial attention to the right was assumed following an L-PA (Michel, 2016). Nevertheless, aftereffects following an R-PA were not completely excluded for two reasons. First, on representational spatial tasks, asymmetrical aftereffects depend on preexisting attentional biases: If the initial representational bias is oriented toward the left side of space, then adaptation to an L-PA would produce greater aftereffects in comparison to an R-PA, and vice versa (Goedert et al., 2010). Second, asymmetrical aftereffects are less obvious according to the age (Magnani et al., 2012, 2020) or the experimental paradigm used (Frassinetti et al., 2009; Ronga et al., 2018; Schintu et al., 2017).

Material and Methods

Participants

From the study of Jacquin-Courtois et al. (2010; effect size: $\eta_p^2 =$ .27), we performed a sample size estimation based on an a priori analysis (α = .05 and power = .80). The required sample size for such effect size was $N = 8$ per group of optical deviation (G*Power 3.1. Software; Faul et al., 2007).

The present study involved 47 healthy participants (23 females, 24 males, $M_{age} = 23.63$, $SD = 4.08$ years). The participants were allocated to a neutral lens group (i.e., control group; NL group: 16 participants), or to prism adaptation to a leftward or rightward optical deviation group (respectively, L-PA group: 16 participants; R-PA group: 15 participants). None of the participants reported any visual, auditory, or neurological deficits. According to the

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Edinburgh Handedness Inventory, all participants were right-handed (M = .61; SD = .23) except 13 participants who were ambidextrous (NL group: 3; L-PA group: 7; R-PA group: 3). After having been informed of the experimental procedures, all the participants gave their informed consent prior to their inclusion in the study. Although ethical review and approval was not required for the present study, in line with the local legislation and institutional requirements, the experimental protocol was carried out in accordance with the Declaration of Helsinki (1964).

Experimental Procedure

The experimental procedure was divided into three phases: Pretest (before prism adaptation), prism adaptation, and posttest (after prism adaptation). Pretest and posttest consisted of the same tasks: A dichotic listening task and an open-loop pointing task (see Figure 1). At the end of the experiment, a last open-loop pointing task was conducted to ensure that the participants were still adapted, and that sensorimotor aftereffects were maintained until the end of the experiment.

Dichotic Listening Task

Participants sat in a quiet room, and stimuli were played through headphones.

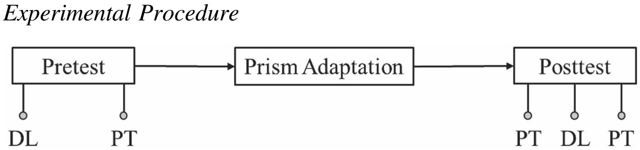
A first step was to ensure that none of the participants had an obvious hearing deficit. Participants listened to 10 pure tones of different frequencies (60 Hz, 345 Hz, 630 Hz, 915 Hz, and 1200 Hz), which were all played randomly in each ear, and they had to indicate in which ear they heard the tones. We also questioned the participants to ensure that the intensity of the stimuli was equivalently perceived by both ears.

Next, the dichotic listening task was performed. This involved pairs of words being presented with the two words sounded simultaneously, one in the left and the other in the right ear. Eighty pairs of bisyllabic words were constituted (i.e., 160 words). The 160 words were chosen from the French database “Lexique” (New et al., 2001), which classifies French words according to their frequency of occurrence. The film frequencies of the selected words were comprised between 41.34 and 583.45 occurrences per million. As far as possible, the pairs of words were created by associating words with similar frequencies.

In both the pretest and posttest, 40 pairs of words were presented to each participant in ten blocks of four pairs (two different sets of 80 words were presented in pretest and posttest, respectively). For each pair of words, one word was presented in the left ear, while the other was presented simultaneously in the right ear (i.e., dichotic listening). To avoid word effect, all the same words were presented in all the conditions across the participants. To that end, the lists of words were yoked by eight participants. First, two lists were created, each containing 40 pairs of words. Participant S1 received list 1 for the pretest and list 2 for the posttest. Participant S2 also received list 1 in pretest and list 2 in posttest, but the ear in which the words were presented was reversed compared to Participant S1. The words presented in the left ear for Participant S1 were presented in the right ear for Participant S2, and vice versa. Participant S3 also received list 1 in pretest and list 2 in posttest, but this time the ear from which the recall was requested was reversed. The words to be recalled from the left ear for Participant S3, were the words to be recalled from the right ear for Participant S1, and vice versa. Finally, Participant S4 received the same list as Participant S2, but the ear to recall was reversed. Then Participants S5 to S8 were yoked respectively with Participants S1–S4, with list 1 (with the same ears for presenting and requesting words) presented in posttest and list 2 presented in pretest. With this kind of yoked design, all the words were presented in both pretest and posttest, in both left and right ears, and were recalled from both left and right ears. Thus, no influence of word properties could have influenced participant performance. The other participants were yoked by eights in a similar way to Participants S1 to S8, but the pairs of words were presented in a new random order across blocks.

The dichotic listening task began with a training block to ensure that participants had understood the instructions well. The training block was similar in all respect to the experimental blocks. Within the blocks, the word pairs were presented at 1000-ms intervals. To avoid a strategy of lateralized memorization, during each block the participants had to pay attention to all the words because they did not know from which ear they would be asked to recall the words. At the end of each block, the participants were asked to recall as many words as possible heard by a specific ear and told not to recall the words from the other ear. From the 10 blocks, 40 words had to be recalled in pretest and posttest. The left and right ear heard 20 words each (i.e., five blocks each; see Figure 2).

Figure 1
Experimental Procedure



Note. DL = dichotic listening; PT = open-loop pointing task.

Prism Adaptation Procedure

Following the pretest, participants underwent the prism adaptation procedure. The visual field was not modified in the control group (NL group), which used neutral lenses. In the other two groups, the visual field was displaced laterally by 15° to the left (L-PA group) or to the right (R-PA group), using optical wedge-prisms. The adaptation procedure was achieved with the right hand, and vision of the starting position of the hand was occluded to ensure optimal development of adaptation (Redding & Wallace, 1997). The participants performed a simple pointing task (four blocks of 81 pointing trials) for 20 min. They were asked to point as fast and accurately as possible at the nine colored visual targets (diameter: 6 mm). These targets were horizontally placed (interdot spaces: 4 cm) on a horizontal plane, with the sagittal central target aligned 35 cm from the starting point. Four targets were placed on the left and four others were placed on the right of the central target. The effective development of adaptation was checked using sensorimotor aftereffects measured during the open-loop pointing. Before and after the prism adaptation procedure, participants were required to point with the right hand toward a sagittal black visual target (diameter: 6 mm) placed 35 cm from the starting position and without visual feedback during movement execution. To avoid de-adaptation, participants were asked to keep their eyes closed

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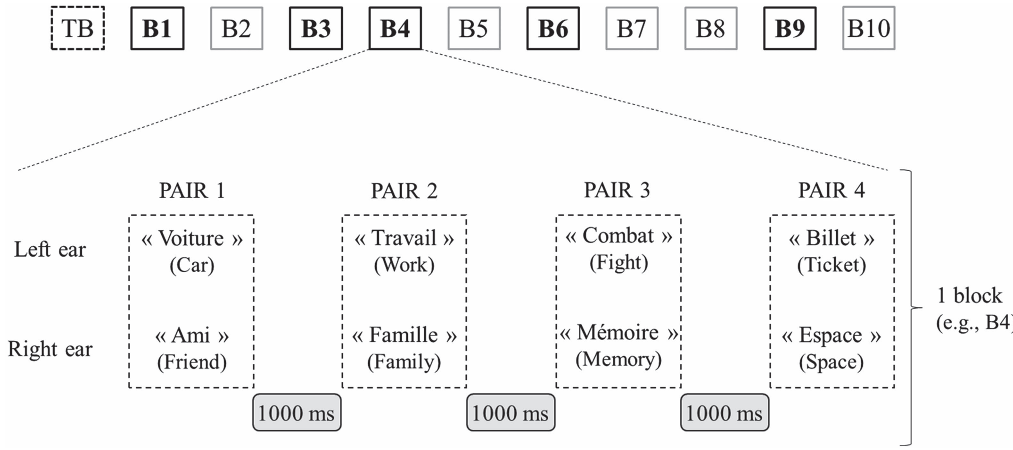
Figure 2
Dichotic Listening Task Design



Note. TB = training block; B1, . . . , B10: Block 1 to Block 10, experimental blocks; The bold black square and the gray square represent the recall side, left and right, respectively.

between each trial, and the experimenter passively placed the participants' right index finger at the starting position. The same experimental procedure was used at the end of the experiment to ensure that sensorimotor aftereffects persisted during all the experiment. All arm movements were recorded using three TV-cameras connected to an optoelectronic system of motion analysis (Smart, B.T.S., Italy).

Analysis

Open-Loop Pointing Task

To assess sensorimotor aftereffects, angular pointing errors from the sagittal target were computed. Expressed in degrees, the errors were calculated as the difference between the starting position to target position vector and the starting position to final index fingertip position vector. Negative values corresponded to leftward errors and positive values to rightward errors.

Dichotic Listening Task

Three parameters were applied three times, one for both ears together (overall) and then for each ear separately, resulting in nine different measures (i.e., two percentages and LI, for both ears (overall), and separately for the left and right ears).

The first parameter was the percentage of recalled words, which corresponds to the percentage of all the recalled words, whether or not correctly recalled according to the requested ear. Measuring the percentage of recalled words allowed the total number of words recalled to be assessed, including lateralization errors. The overall percentage corresponded to: (the number of words recalled from the right ear plus the number of words recalled from the left ear) divided by (the total number of words presented) multiplied by 100. In other words, it was equal to $100 \times (R + L)/80$, where R and L were the number of recalled words from the right and left ear, respectively. For each ear, the percentage corresponded to: (the number of words recalled from the right or left ear) divided by (the number of words presented per ear) multiplied by 100. In other words, it was equal to $(100 \times R)$ or $(100 \times L)/40$.

The second parameter was the percentage of correctly recalled words, which corresponded to the percentage of correctly recalled words according to the requested ear. Measuring the percentage of correctly recalled words allowed a more precise evaluation of the lateralized restitution ability. The overall percentage corresponded to: (the number of correctly recalled words from the right ear plus the number of correctly recalled words from the left ear) divided by (the total number of words to be recalled) multiplied by 100. In other words, it was equal to $100 \times (R_C + L_C)/40$, where R_C and L_C were the number of correctly recalled words from the right and left ear, respectively. For each ear, the percentage corresponded to: (the number of words correctly recalled from the right or left ear) divided by (the number of words to be recalled per ear) multiplied by 100. In other words, it was equal to $(100 \times R_C)$ or $(100 \times L_C)/20$.

The third parameter was the laterality index (LI), which quantified a possible asymmetry in the recall of words. The overall LI corresponded to: (the number of words recalled from the right ear minus the number of words recalled from the left ear) divided by (the number of words recalled from the right ear plus the number of words recalled from the left ear) multiplied by 100. In other words, the overall LI was equal to $100 \times (R - L)/(R + L)$, where R and L were the number of recalled words from the right and left ear, respectively. A positive value represented an advantage for the right ear, while a negative value represented an advantage for the left ear. The LI was measured for each ear with the same formula as the overall LI by considering only the blocks to be recalled from the requested ear.

Statistical Analysis

The present study investigated the aftereffects of prism adaptation on the dichotic listening task (i.e., Posttest vs. Pretest). Because this is usual in prism adaptation research and because different aftereffects occur after prism adaptation according to the optical deviation used, separate analyses were carried out for each optical

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deviation to highlight potential asymmetrical effects. The threshold for statistical significance was set at $\alpha = .05$. The analyses were conducted with Statistica software (Version 13.3), and effect sizes were computed with JASP software (Version 0.11.1).

Sensorimotor Aftereffects. Sensorimotor measures followed a normal distribution (Shapiro–Wilk: all *ps* > .05). To ensure that participants were well adapted, a repeated measures analysis of variance (ANOVA) with Session (pretest, posttest, late-test) as within-subject factor was conducted separately for each optical deviation. Posttest and late-test were then compared to pretest with paired *t* tests. The same procedure was completed for the control group (NL group).

Dichotic Listening Task. For each group (NL, L-PA, and R-PA), the overall data (i.e., combining left and right ear performance) were analyzed using paired comparisons. When results followed a normal distribution, a Student's *t* test was computed; otherwise, a Wilcoxon test was used. Furthermore, for each group (NL, L-PA, and R-PA), we used a repeated measures ANOVA with Session (pretest, posttest) and Ear (left ear, right ear) as within-subject factors. Posttest was then compared to pretest with paired *t* tests for each ear when data followed a normal distribution; otherwise, a Wilcoxon test was used.

Results

Sensorimotor Aftereffects on Open-Loop Pointing Task

For each group, sensorimotor data followed a normal distribution (Shapiro–Wilk: all *ps* > .05).

Neutral Lenses

A repeated measures ANOVA with Session (pretest, posttest, late-test) as within-subject factor showed no significant effect of Session, $F(2, 30) = .490$, $p = .617$, $\eta_p^2 = .032$. Compared to the pretest, the pointing performance remained constant until the end of the experiment.

Leftward Optical Deviation

A repeated measures ANOVA with Session (pretest, posttest, late-test) as within-subject factor showed a significant main effect of Session, $F(2, 28) = 86.624$, $p = .000$, $\eta_p^2 = .861$. Compared to pretest, the pointing performance was significantly shifted toward the right (positive values in Table 1) in posttest, $t(15) = -14.966$, $p = .000$, $d = -3.741$, and in late-test, $t(14) = -8.568$, $p = .000$, $d = -2.212$. All participants remained adapted until the end of the experiment.

Rightward Optical Deviation

A repeated measures ANOVA with Session (pretest, posttest, late-test) as within-subject factor showed significant main effect of Session, $F(2, 28) = 83.765$, $p = .000$, $\eta_p^2 = .857$. Compared to pretest, the pointing performance was significantly shifted toward the left (negative values in Table 1) in posttest, $t(14) = 12.233$, $p = .000$, $d = 3.159$, and in late-test, $t(14) = 7.804$, $p = .000$, $d = 2.015$. All participants remained adapted until the end of the experiment.

Aftereffects of Prism Adaptation on the Dichotic Listening Task

The following analyses compared the performance on the dichotic listening task before and after prism adaptation (pretest vs. posttest) according to the ear, for each optical deviation (i.e., NL group, L-PA group, and R-PA group) and for each parameter (i.e., percentage of recalled words, percentage of correctly recalled words, laterality index). For all parameters, baseline measurements in pretest indicated no difference between L-PA and R-PA groups (all *ps* > .10). However, the NL group significantly recalled less words and less correct words than the L-PA and R-PA groups in pretest for all measures (i.e., Overall, Left ear, Right ear; all *ps* < .05).

Percentage of Recalled Words

The percentage of recalled words corresponds to the percentage of all the words recalled, whether or not they were recalled correctly according to the ear they were requested from (Table 2).

Neutral Lenses. In each session, data of the percentage of recalled words followed a normal distribution overall and also for each ear (Shapiro–Wilk test: all *ps* > .05). No significant difference was observed for the overall percentage of recalled words between pretest and posttest, $t(15) = -1.916$, $p = .075$, $d = -0.479$. A repeated measures ANOVA with Session (pretest, posttest) and Ear (left ear, right ear) as within-subject factors showed a significant effect of Session, $F(1, 15) = 4.618$, $p = .048$, $\eta_p^2 = .235$, a significant effect of Ear, $F(1, 15) = 8.156$, $p = .012$, $\eta_p^2 = .352$, but no significant Session × Ear interaction, $F(1, 15) = 0.124$, $p = .729$, $\eta_p^2 = .008$. Paired *t* tests showed no significant variation between pretest or posttest for each ear, Left ear: $t(15) = -0.648$, $p = .527$, $d = .162$; Right ear: $t(15) = -1.662$, $p = .117$, $d = -0.416$.

Leftward Prism Adaptation. First, the data of the overall percentage of recalled words did not follow a normal distribution

Table 1
Means and SDs of Sensorimotor Data for Each Group

	Average pointing errors (°)					
	Pretest		Posttest		Late-test	
Exposure session	*M*	*SD*	*M*	*SD*	*M*	*SD*
Neutral lenses	−0.689	3.153	−0.182	3.042	−0.581	3.094
Leftward prism adaptation	−1.315	2.509	9.757	3.744	5.462	3.402
Rightward prism adaptation	−0.234	3.505	−10.081	3.123	−8.114	2.922

Note. Positive values indicate rightward pointing errors; negative values indicate leftward pointing errors.

Table 2
Means and SDs of the Percentage of Recalled Words for Each Experimental Group

Test	Percentage of recalled words								
	Leftward prism adaptation			Neutral lenses			Rightward prism adaptation		
	Overall	Left ear	Right ear	Overall	Left ear	Right ear	Overall	Left ear	Right ear
Pretest	32.688	30.438	35.250	26.375	23.813	28.938	34.333	32.733	36.067
SD pretest	6.183	9.893	6.486	6.761	9.558	7.261	3.904	6.041	5.800
Posttest	35.375	28.813	42.188	28.688	25.563	32.125	36.067	33.533	38.400
SD posttest	5.596	6.534	7.565	7.418	10.991	8.123	3.595	6.105	5.138

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in posttest (Shapiro–Wilk test: $p < .05$). A Wilcoxon test revealed a significant aftereffect of leftward prism adaptation for the overall data ($Z = 2.016$; $p = .044$), illustrating an increase in the overall percentage of recalled words after L-PA. Second, the data for the percentage of recalled words followed a normal distribution for both ears in each session (Shapiro–Wilk test: all $ps > .05$), except the data from the right ear which tended not to be normal in posttest (Shapiro–Wilk test: $p = .045$). A repeated measures ANOVA with Session (pretest, posttest) and Ear (left ear, right ear) as within-subject factors showed a significant effect of Session, $F(1, 15) = 5.311$, $p = .036$, $\eta_p^2 = .261$, a significant effect of Ear, $F(1, 15) = 21.281$, $p = .000$, $\eta_p^2 = .587$, and a significant Session × Ear interaction, $F(1, 15) = 7.991$, $p = .013$, $\eta_p^2 = .348$. More words were significantly recalled from the right ear after L-PA than before adaptation, $t(15) = -3.817$, $p = .002$, $d = -0.954$, whereas no significant variation was observed for the left ear, $t(15) = .819$, $p = .426$, $d = .205$.

Rightward Prism Adaptation. The percentage of recalled words followed a normal distribution overall and also for each ear, in each session (Shapiro–Wilk test: all $ps > .05$). The overall percentage of recalled words did not significantly change after adaptation to a rightward optical deviation, $t(14) = -1.216$, $p = .244$, $d = -0.314$. A repeated measures ANOVA with Session (pretest, posttest) and Ear (left ear, right ear) as within-subject factors showed a significant Session × Ear interaction, $F(1, 14) = 4.760$, $p = .047$, $\eta_p^2 = .254$, although no significant difference was observed in posttest compared to pretest for either the left ear, $t(14) = -0.462$, $p = .651$, $d = -0.119$] or the right ear, $t(14) = -1.769$, $p = .099$, $d = -0.457$. No significant main effects of Session, $F(1, 14) = 1.094$, $p = .313$, $\eta_p^2 = .073$, or Ear, $F(1, 14) = 3.539$, $p = .081$, $\eta_p^2 = .202$, were observed.

In summary, L-PA improved the overall performance. More specifically, the word recall performance from the right ear was increased, while none of the exposure to optical deviations significantly affected the performance of the left ear. As for the NL group, the R-PA group did not show a change in the percentage of recalled words, either overall or when each ear was considered separately.

Percentage of Correctly Recalled Words

To complete the previous analysis, the percentage of correctly recalled words (i.e., the percentage of words correctly recalled according to the requested ear) was analyzed before and after prism adaptation for each group of optical deviation (see Table 3). Except for the overall percentage of correctly recalled words in pretest and that from the right ear in posttest, data did not follow a normal distribution in the NL group (Shapiro–Wilk test: all $ps < .05$). Normality was confirmed in the L-PA and R-PA groups, as well as for each ear, in each session (Shapiro–Wilk test: all $ps > .05$).

Neutral Lenses. Overall, the participants significantly recalled more correct words in posttest than in pretest ($Z = 2.582$, $p = .010$). The percentage did not significantly change in posttest, regardless of the ear to be recalled (Left ear: $Z = 1.549$, $p = .121$; Right ear: $Z = 1.443$, $p = .149$).

Leftward Prism Adaptation. The overall recall performance significantly increased after L-PA, $t(15) = -2.390$, $p = .030$, $d = -0.597$. A repeated measures ANOVA with Session (pretest, posttest) and Ear (left ear, right ear) as within-subject factors revealed a significant effect of Session, $F(1, 15) = 5.880$, $p = .028$, $\eta_p^2 = .282$, and a significant effect of Ear, $F(1, 15) = 30.484$, $p = .000$, $\eta_p^2 = .670$. Although there was no significant Session × Ear interaction, $F(1, 15) = 2.621$, $p = .126$, $\eta_p^2 = .149$, the present study aimed to investigate the potential differential effects of the Ear factor, relevant to our a priori hypotheses. L-PA significantly increased the percentage of correctly recalled words from the right ear, $t(15) = -2.819$, $p = .013$, $d = -0.705$, and no significant

Table 3
Means and SDs of the Percentage of Correctly Recalled Words for Each Experimental Group

Test	Percentage of correctly recalled words								
	Leftward prism adaptation			Neutral lenses			Rightward prism adaptation		
	Overall	Left ear	Right ear	Overall	Left ear	Right ear	Overall	Left ear	Right ear
Pretest	45.188	40.313	49.688	33.867	29.333	38.000	46.067	43.000	48.667
SD pretest	7.565	11.470	9.031	6.266	9.612	6.761	9.067	10.488	11.412
Posttest	49.500	40.938	57.813	40.200	37.000	43.000	52.667	49.667	55.000
SD posttest	10.589	11.863	12.776	9.814	17.300	8.409	12.799	14.936	13.363

change was observed from the left ear, $t(15) = -0.209$, $p = .837$, $d = -0.052$.

Rightward Prism Adaptation. No significant aftereffects of R-PA were observed for the overall percentage of correctly recalled words even though the effect of session nearly reached significance, $t(14) = -2.135$, $p = .051$, $d = -0.551$. A repeated measures ANOVA with Session (pretest, posttest) and Ear (left ear, right ear) as within-subject factors indicated a statistical trend for the main effects of Session, $F(1, 14) = 4.387$, $p = .055$, $\eta_p^2 = .239$, and Ear, $F(1, 14) = 3.429$, $p = .085$, $\eta_p^2 = .197$, but no significant Session × Ear interaction, $F(1, 14) = .019$, $p = .892$, $\eta_p^2 = .001$. In posttest, there was only a trend for an increase in words correctly recalled from each ear, Left ear: $t(14) = -1.939$, $p = .073$, $d = -0.501$; Right ear: $t(14) = -1.969$, $p = .069$, $d = -0.508$.

In summary, adaptation to a leftward optical deviation and exposure to neutral lenses produced a significant overall improvement in the ability to correctly recall words in relation to the ear requested. More specifically, this improvement reached significance only for the right ear in the L-PA group. No significant effect by ear was observed with neutral lenses, while both the left and right ear showed an improvement trend for the R-PA.

Laterality Index

The LI allows the detection and quantification of a possible asymmetry in the recall of words presented to both ears (Bellmann et al., 2001; see Table 4). Regardless of the optical deviation used, a REA was observed in pretest with a positive average overall LI, significantly different from zero, $M = 8.617$, $SD = 17.654$, $t(46) = 3.346$, $p = .002$, $d = .488$. Except for the left ear LI in posttest in the NL group (Shapiro–Wilk test: $p = .029$), the LI data followed a normal distribution overall and also for each ear, in each session (Shapiro–Wilk test: all $ps > .05$).

Neutral Lenses. The overall LI was unchanged after exposure to neutral lenses, $t(15) = -0.183$, $p = .857$, $d = -0.046$. A repeated measures ANOVA with Session (pretest, posttest) and Ear (left ear, right ear) as within-subject factors indicated only a significant main effect of Ear, $F(1, 15) = 73.185$, $p = .000$, $\eta_p^2 = .830$. No significant effect of Session, $F(1, 15) = .537$, $p = .475$, $\eta_p^2 = .035$, or of significant Session × Ear interaction, $F(1, 15) = 1.107$, $p = .309$, $\eta_p^2 = .069$, were observed. The LI was not changed in posttest, although a trend was observed for the right ear, Left ear: $Z = .517$, $p = .605$; Right ear: $t(15) = -2.051$, $p = .058$.

Leftward Prism Adaptation. When overall LI was compared between pretest and posttest with a paired t test, there was a significant increase in overall LI after adaptation to a leftward optical deviation, $t(15) = -2.138$, $p = .049$, $d = -0.534$. A repeated measures ANOVA with Session (pretest, posttest) and Ear (left ear, right ear) as within-subject factors showed a significant effect of Session, $F(1, 15) = 6.515$, $p = .022$, $\eta_p^2 = .303$, a significant effect of Ear, $F(1, 15) = 90.121$, $p = .000$, $\eta_p^2 = .857$, but no significant Session × Ear interaction, $F(1, 15) = .014$, $p = .908$, $\eta_p^2 = .001$. LI was not significantly modulated for either the left ear, $t(15) = -1.143$, $p = .271$, $d = -0.286$, or the right ear, $t(15) = -1.703$, $p = .109$, $d = -0.426$.

Rightward Prism Adaptation. The overall LI was not significantly modified after adaptation to a rightward prism adaptation, $t(14) = -1.819$, $p = .090$, $d = -0.470$. A repeated measures ANOVA with Session (pretest, posttest) and Ear (left ear, right ear) as within-subject factors revealed a significant effect of Session, $F(1, 14) = 5.622$, $p = .033$, $\eta_p^2 = .287$, a significant effect of Ear, $F(1, 14) = 39.466$, $p = .000$, $\eta_p^2 = .738$, but no significant Session × Ear interaction, $F(1, 14) = 2.807$, $p = .116$, $\eta_p^2 = .167$. No significant effect was observed after adaptation to a rightward optical deviation for the left ear, $t(14) = 1.091$, $p = .294$, $d = .282$, and there was only a trend for the right ear, $t(14) = -2.142$, $p = .051$, $d = -0.553$.

In summary, only adaptation to a leftward optical deviation significantly increased the overall LI. The left ear LI and the right ear LI were not significantly changed in any group after goggles exposure.

Discussion

The present study aimed to investigate the effect of prism adaptation on dichotic listening in healthy subjects. Exposure to an L-PA modified the participants' performances. The overall percentage of recalled words, the overall percentage of correctly recalled words and the overall LI all increased after an L-PA. L-PA produced a significant improvement in the percentage of recalled words and the percentage of correctly recalled words only for the right ear. Our innovative findings demonstrate that an L-PA modifies auditory divided attention and support the cross-modal aftereffects of prism adaptation in modalities not directly involved in the adaptation process.

Modification of Dichotic Listening Performance by Prism Adaptation: The First Time This Has Been Demonstrated in Healthy Subjects

Dichotic listening is a tool to assess auditory divided attention (Westerhausen & Kompus, 2018). In pretest, the average LI was positive, meaning that participants reported more of the words

Table 4
Means and SDs of the Laterality Index for Each Experimental Group

	Laterality index								
	Leftward prism adaptation			Neutral lenses			Rightward prism adaptation		
Test	Overall	Left ear	Right ear	Overall	Left ear	Right ear	Overall	Left ear	Right ear
Pretest	8.938	−34.875	45.375	11.688	−28.688	46.875	5.000	−31.600	38.733
SD pretest	18.717	27.765	27.782	21.093	33.627	28.458	12.130	32.483	26.935
Posttest	19.188	−22.313	59.875	13.250	−28.938	59.750	7.000	−38.800	53.533
SD posttest	13.403	31.797	28.284	24.689	40.285	25.666	12.984	34.935	28.950

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presented to the right ear. Called right-ear advantage, this asymmetry indicates a left-hemispheric specialization in language processing (Kimura, 1967), and results from a preactivation of the left hemisphere, which orients the auditory attention toward the right (Kinsbourne, 1970).

Altogether, our novel results can be interpreted as attentional aftereffects of prism adaptation on the REA. Exposure to an L-PA produced an increase in the overall LI, the overall percentage of recalled words and the overall percentage of correctly recalled words. More specifically, an L-PA modified the performance of the right ear, by increasing the percentage of words recalled and the percentage of words correctly recalled, without decreasing the performance from the left ear.

Attentional factors have already been shown to modulate the REA (Hiscock et al., 1999). Hugdahl et al. (2000) have shown this modulation especially when the participants were required to focus their attention toward the left or the right ear. The present experiment showed that the focus of the participants, following prism adaptation, was not intentional and occurred without the participants' knowledge. The increase in the overall recall (measured by the percentage of words recalled), and the improvement of the lateralized auditory processing (measured by the percentage of words correctly recalled) could correspond to the rise in auditory attention. After L-PA, there was a significant increase in both percentages only for the right ear. The fact that an L-PA helped more words to be recalled from the right ear, and more specifically more correct words, suggests an increase in auditory attention of the right ear, which is consistent with the increase in the overall LI. Adaptation to an L-PA modified auditory divided attention by enhancing the REA.

Prism Adaptation, a Procedure With Cross-Modal Aftereffects

As mentioned in the Introduction section, aftereffects of prism adaptation extend to cognitive processes (Michel, 2016). An L-PA produces a rightward shift in spatial representation assessed with line-bisection tasks (Berberovic & Mattingley, 2003; Colent et al., 2000; Fortis et al., 2011; Striemer & Danckert, 2010), in orientation of spatial attention assessed with the luminance judgment task (Loftus, Vijayakumar, et al., 2009), in body posture assessed with a force platform (Michel, Rossetti, et al., 2003), and in spatially valued elements (numbers, Loftus et al., 2008; letters, Nicholls et al., 2008; auditory frequencies, Michel et al., 2019). These cognitive aftereffects cannot be explained by sensorimotor aftereffects of prism adaptation, but rather by high-level effects on spatial cognition involving spatial attention and representation (Michel, 2006, 2016). Following L-PA, processes of plasticity may lead to an interhemispheric imbalance to the detriment of the right hemisphere or in favor of the left hemisphere at the parietal level, leading to an orientation of visuo-spatial attention toward the right side of space (Magnani et al., 2014; Michel, 2006, 2016; Panico et al., 2020). The current aftereffects observed at the auditory level also seem to be related to the attentional shift toward the right: The shift of attention would enhance the REA initially present. This may account for aftereffects of prism adaptation on hearing, which is a sensory modality not involved in the development of prism adaptation.

Our results are directly in line with previous findings of Jacquin-Courtois et al. (2010), which demonstrated the benefits of an R-PA in neglect patients (i.e., a neurological deficit of perception of stimuli in left hemispace; Heilman et al., 2000). Before prism adaptation, these patients had left ear extinction. After an R-PA, left ear extinction was reduced with a decrease in IL indicating that the detection asymmetry in favor of the right ear was reduced. Similarly, aftereffects of an R-PA were observed in a haptic discrimination task in neglect patients (Revol et al., 2020). An R-PA corrected the initial error bias of the neglect patients, suggesting an increase in haptic divided attention in the left side. For the first time, the present study showed aftereffects of prism adaptation on auditory divided attention in healthy subjects. This means that these effects are independent of the patient's recovery plasticity.

Modifying Auditory Attention in Healthy Subjects: A Neuroanatomical Point of View

Studies of neural substrates at play during prism adaptation have shown a crucial role of the cerebellum and the parietal cortex in error correction and spatial realignment as well as a consistent involvement of the temporal cortex during the late phase of exposure (Chapman et al., 2010; Luauté et al., 2009; Panico et al., 2020). The cerebellum includes areas involved in auditory processing, in particular crus I area activated regardless the nature of the auditory task (Baumann & Mattingley, 2010; Petacchi et al., 2005). The parietal cortex and the temporal cortex comprise multimodal neurons, which process information from different sensory modalities (Stein & Stanford, 2008). It is worth noting that these two brain areas are also involved in visual and auditory processing. Studies have shown that the parietal cortex is directly involved in both the orientation of visual (Fierro et al., 2000; Fink et al., 2001) and auditory spatial attention (Cohen, 2009; Tissieres et al., 2018), while the temporal cortex is known to be the site of auditory processing (Hall & Plack, 2009). Tissieres et al. (2017) demonstrated the key role of the parietal and the temporal cortex in the emergence of aftereffects of prism adaptation in auditory divided attention. According to the literature, the current aftereffects of prism adaptation in auditory divided attention would involve the cerebellum as well as the parietal and temporal cortex (i.e., multimodal structures; Michel, 2016).

Unexpected Aftereffects: Are They Real or Not?

A seemingly surprising significant increase in the overall percentage of correctly recalled words was observed after exposure to neutral lenses (i.e., control group). Similarly, exposure to an R-PA tended (a) to enhance the ability of the participants to recall correct words overall and (b) to emphasize the LI of the right ear.

In the literature, aftereffects on spatial attention have been observed only after exposure to an L-PA in healthy participants (Loftus, Vijayakumar, et al., 2009; for review see Michel, 2016), and after exposure to an R-PA only in brain-damaged patients (Jacquin-Courtois et al., 2013). As the dichotic listening task assesses attentional mechanisms, the lateralized effect of prism adaptation observed in the present study (i.e., asymmetrical aftereffects in favor of L-PA) is in accordance with the literature of attentional aftereffects of prism adaptation.

In the present study, exposure to an R-PA tended to increase the LI for the right ear. Considering the literature referring to tasks that are not intrinsically attentional, such as representational line-bisection tasks, a decreased LI could have been expected after

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exposure to an R-PA, due to the presence of an REA from the pretest linked to the use of words in the dichotic listening task. However, the improvement trend observed in the present study would be difficult to explain within the framework of the literature on prism adaptation.

Another explanation for the improvement observed in the NL and R-PA groups could be that familiarization with the dichotic listening task was not long enough. Although participants performed one training block to familiarize themselves with the dichotic listening task, it is likely that they still encountered difficulties in accomplishing this task in the first blocks. One block was maybe insufficient for participants to get used to hearing two different words simultaneously and it is possible that during the first training blocks, they progressively developed more attention to the stimuli, and improved in the task by recalling more correct words. A limitation of the present study could thus be the use of only a single training block programmed at the beginning of each session (i.e., pretest and posttest). In order to avoid this effect, several training blocks should be provided to get the participants used to the dichotic listening task. The combination of the REA and the acclimatization of the participants to the dichotic listening task could account for the improvement observed in the NL and R-PA conditions. However, it is worth noting that L-PA was the only one to reach a significance threshold probably because of its aftereffects on auditory attention.

Finally, the percentage of recalled words and the overall LI seem to be the most sensitive parameters to assess the aftereffects of prism adaptation in a dichotic listening task in healthy participants. These two parameters take into account the incorrectly recalled words that could be recalled because of increased attention on the right-side following adaptation to a leftward optical deviation. These two parameters should be considered for future studies involving dichotic listening; they would be a more precise way to evaluate prism adaptation aftereffects in a dichotic listening task than a measure based on correctly recalled words only.

Conclusion

For the first time, the present study in healthy subjects extended the aftereffects of an L-PA to auditory divided attention by using a dichotic listening task. An L-PA increased auditory attention only to the right ear without decreasing the performance from the left ear. This asymmetrical aftereffect in the auditory domain provides a new argument in favor of the cross-modal influence of prism adaptation. The effect of an L-PA on dichotic listening can be explained partly by a strengthening of auditory divided attention, which enhanced the REA. Our findings give a theoretical approach to mechanisms involved in prism adaptation aftereffects in the auditory modality. Our study opens up a new avenue for using prism adaptation in the field of auditory rehabilitation requiring a modulation of auditory attention.

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