

# Prominent reflexive eye-movement orienting associated with deafness

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Profound deafness affects orienting of visual attention. Until now, research focused exclusively on covert attentional orienting, neglecting whether overt oculomotor behavior may also change in deaf people. Here we used the pro- and anti-saccade task to examine the relative contribution of reflexive and voluntary eye-movement control in profoundly deaf and hearing individuals. We observed a behavioral facilitation in reflexive compared to voluntary eye movements, indexed by faster saccade latencies and smaller error rates in pro- than anti-saccade trials, which was substantially larger in deaf than hearing participants. This provides the first evidence of plastic changes related to deafness in overt oculomotor behavior, and constitutes an ecologically relevant parallel to the modulations attributed to deafness in covert attention orienting. Our findings also have implications for designers of real and virtual environments for deaf people and reveal that experiments on deaf visual abilities must not ignore the prominent reflexive eye-movement orienting in this sensory-deprived population.

**Keywords:** Deafness; Eye movements; Cortical plasticity.

The lack of one sensory modality can cause substantial plastic changes in the remaining sensory abilities. In case of profound deafness, for instance, vision becomes crucial for interactions with the environment and for interpersonal communication. Such cross-modal plastic changes have been extensively documented by research on deaf cognition (Bavelier & Neville, 2002; Mitchell & Maslin, 2007; Pavani & Bottari, in press) and have been primarily associated with the orienting of attentional selection resources in space (Bavelier, Dye, & Hauser, 2006). Deaf individuals are faster at reorienting visual processing resources when triggered by an abrupt visual onset (Colmenero, Catena, Fuentes, & Ramos, 2004; Parasnis & Samar, 1985) and are more easily distracted by task-irrelevant flankers, particularly when these occur toward the

periphery of the visual field (Chen, Zhang, & Zhou, 2006; Proksch & Bavelier, 2002). In addition, deaf individuals are better at dividing visual attention resources, compared to hearing controls, when both peripheral and central portions of the visual field are simultaneously attended (Dye, Hauser, & Bavelier, 2009). Finally, enhanced discrimination performance has been observed when deaf participants are asked to selectively attend to visual targets presented at peripheral locations in the visual field (Neville & Lawson, 1987).

All previous studies on selective attention in the deaf instructed participants to keep fixation throughout the experimental session. As a consequence, these works characterized only the covert aspect of visual attention, but neglected *overt* orienting of attentional

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resources. This is most surprising, given that overt behavior and ocular movements in particular are fundamental to our interactions with the environment. Our visual system actively perceives the world by pointing the fovea of our eyes, where visual acuity is best, toward a single part of the scene at a time, and does this several times per second. Yet, no study examined directly whether basic oculomotor behavior is altered in deaf people, and to what extent cross-modal plastic changes occurring for covert attentional orienting are paralleled by modified eye-movement control. Note that the very few studies to date that have measured eye movement in deaf people examined only the strategic aspect of visual scanning during sign-language observation (Agrafiotis et al., 2006; Emmorey, Thompson, & Colvin, 2009; Muir & Richardson, 2005).

In the present study, we examined the oculomotor behavior of deaf and hearing individuals, using a well-characterized paradigm in the eye-movement literature: the pro- and anti-saccade task (Everling & Fischer, 1998; Hallett, 1978). In this paradigm, participants are presented with lateralized visual targets and are required to switch on a trial-by-trial basis between two different saccadic tasks: a pro-saccade task, in which they are required to saccade directly to the target, and an anti-saccade task, in which they are asked to inhibit the reflexive saccade to the target and saccade instead to the opposite side of fixation. The pro-saccadic behavior represents the automatic (or reflexive) form of overt orienting. By contrast, the anti-saccadic behavior taps onto inhibitory and voluntary mechanisms of oculomotor control. We hypothesized that enhanced reorienting of covert attention in deaf individuals should also result in modified oculomotor behavior in deaf individuals compared to hearing controls. Furthermore, given the adaptive relevance of fast responses to visual events in the profoundly deaf (Colmenero et al., 2004; Loke & Song, 1991; Parasnis & Samar, 1985; Pavani & Bottari, in press), we expected a prominent role of reflexive over voluntary overt orienting. This should emerge as facilitation in pro-saccadic rather than anti-saccadic behavior, specifically in deaf individuals.

## METHODS

Thirteen profoundly deaf participants (mean age = 37 years,  $SD = 7$ , range 24–55 years old; 7 females) were recruited through two associations of deaf individuals (Ente Nazionale Sordi, Trento; and Associazione Sordi Trentini) to participate in the study. All deaf participants had uncorrected bilateral profound hearing loss (HL) (>90 dB HL). Five were congenitally deaf, five

acquired deafness before the age of 2, and one before the age of 5. None of the participants had neurological disorders or meningitis associated with deafness. All participants used sign language as preferred communication mode: Four had learned sign language from deaf parents (starting at birth), five before the age of 10, and four in adolescence before the age of 18. Six out of 13 deaf participants currently used hearing aids. All deaf participants were also proficient in lip reading, and could communicate with the experimenter also without a sign-language interpreter. Thirteen hearing controls (mean age = 36 years,  $SD = 7$ , range 26–52 years old; 6 females) were also recruited to take part in the study. All participants had normal or corrected-to-normal vision, were right-handed by self-report, and gave their informed consent to the study, which was approved by the ethics panel of the University of Trento.

Visual fixation was a small circle covering  $0.5^\circ$  of visual angle, presented at the center of a black screen throughout the experimental session. Two empty, white, rectangular boxes covering  $1.5^\circ$  of visual angle served as place-holders and were positioned on opposite sides with respect to fixation. In the target display, one box became internally white. The boxes were placed at either  $3^\circ$  or  $7^\circ$  from fixation. From now on, we will refer to locations at  $3^\circ$  as perivoveal and at  $7^\circ$  as peripheral. The choice of different target eccentricities was motivated by the fact that visual attention abilities differ between deaf and hearing individuals mostly for targets in the visual periphery (e.g., Bavelier et al., 2006; Neville & Lawson, 1987). The specific eccentricities adopted in this study were chosen to be consistent with our own previous work (e.g., Bottari, Nava, Ley, & Pavani, 2010). All stimuli were presented on a standard 19-inch monitor, with  $1024 \times 768$  pixels resolution, and 100-Hz refresh rate. The experiment was programmed with Matlab (<http://www.mathworks.com/>) and Psychtoolbox (Brainard, 1997; Pelli, 1997). An EyeLink II infrared system (SR Research, Ontario, Canada), with sampling rate of 500 Hz and spatial resolution of less than  $0.01^\circ$ , was used for ocular movements recording. Participants sat at a distance of approximately 65 cm from the computer monitor, with their head and chin resting on dedicated support.

Each trial began with a color change of fixation and presentation of the two place-holders. The saccadic task was instructed by the color of the circle: A green circle required participants to perform a pro-saccade; a red circle instructed them to perform an anti-saccade. Before the experiment, the experimenter checked that each participant could readily distinguish the two color cues. After 1000 ms from the color instruction, one of the place-holders became completely white (target). In the pro-saccade task, participants were required to

make a saccade to the center of the target. In the anti-saccade task, participants were required to make a saccade to the center of the place-holder opposite to the target. They were also required to gaze back to the fixation point upon completion of the saccade. The task (pro-saccade or anti-saccade) switched unpredictably between trials, whereas target eccentricity (perifoveal or peripheral) changed between experimental blocks (data were collected separately for each block). The rest time between trials (i.e., the time between the end of a saccade and the begin of the following trial) was 1 s. Participants learned the color-coding of the task prior to the experimental session and completed a practice block of 20 trials before data recording.

The experimental session was divided into two blocks, each comprising 100 trials and lasting approximately 15 min. The entire experimental session lasted approximately 30 min. Between blocks, participants were invited to take a break. We used a  $2 \times 2 \times 2$  factorial design, with Task (pro-saccade or anti-saccade) and Target eccentricity (perifoveal or peripheral) as within-participant factors, and Group (deaf individuals or hearing controls) as between-participants factor. Before the beginning of the experimental session, a standard 9-point calibration of the EyeLink system was always performed.

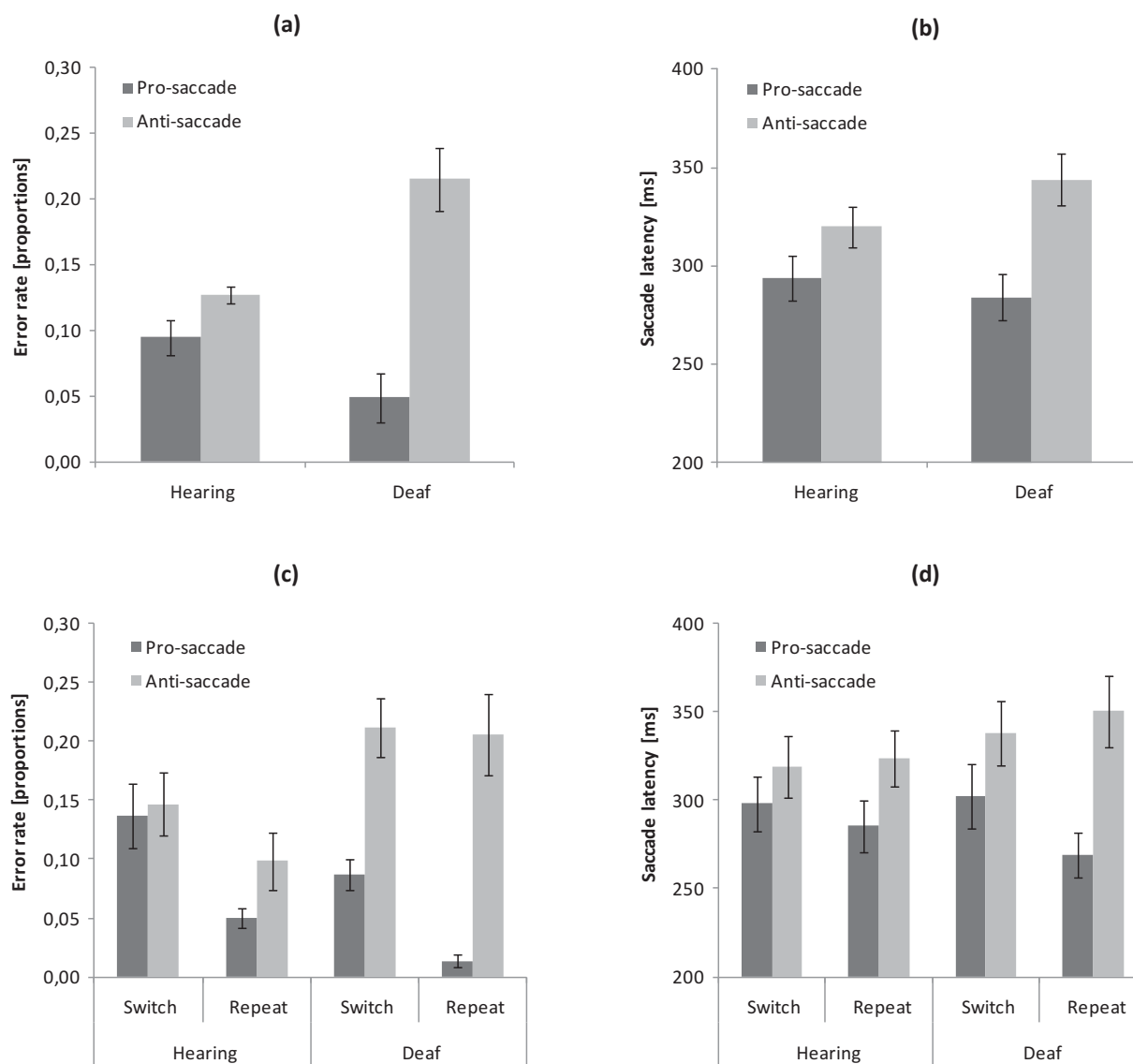
All trials in which no saccade was executed or in which the saccade did not cover at least half the distance between fixation and target were removed. Subsequently, the following parameters of the ocular movement were taken into account: error rate (i.e., percentage of trials in which participants moved their eyes in the opposite direction with respect to the instruction), saccade latency (i.e., time from target onset to saccade execution, calculated on correct trials only), peak-velocity amplitude (a simple kinematic descriptor of the saccade), landing point precision (i.e., the standard deviation of horizontal landing point expressed in degrees of visual angle and thus a measure of variability over trials), and landing point accuracy (i.e., the horizontal distance between the average landing point and the target in degrees of visual angle; positive values indicate overshoots, and negative values indicate undershoots). All these descriptors have been traditionally used to characterize oculomotor behavior in the pro- and anti-saccade task (e.g., Everling & Fischer, 1998; Hutton & Ettinger, 2006). Outliers were removed by the nonrecursive method described by Van Selst and Jolicour (1994). All measures were then entered into separate repeated-measure ANOVAs with Task (pro-saccade or anti-saccade) and Target eccentricity (perifoveal or peripheral) as within-participant factors and Group as between-participant factor. When appropriate, post-hoc comparisons were conducted by the Tukey test.

## RESULTS

Overall we removed 8.1% of trials (not including the trials with saccades in the direction opposite to the target), of which 7% were undershoot and 1.2% trials in which the saccade was not executed or the saccade started outside the central area around fixation. The proportion of trials removed for undershoot was 5.73% for hearing controls and 8.19% for deaf subjects

The analysis on peak velocity did not reveal any significant difference between groups (all  $F_s < 1$ ). Both groups reached higher peak velocities for anti-saccade compared to pro-saccade trials,  $F(1, 24) = 30.6, p < .001$ , and for peripheral compared to perifoveal target eccentricities,  $F(1, 24) = 732.8, p < .0001$ . Similarly, landing point accuracy was comparable between groups, regardless of the experimental conditions (all  $F_s < 1.6$ ). All participants produced more overshoots for perifoveal than peripheral targets,  $F(1, 24) = 14.9, p < .01$ . Finally, the analysis on landing point precision showed that end-point variability between trials was comparable in both groups—main effect of Group,  $F(1, 24) = 2.8, p = .11$ ; interactions involving the Group factor, all  $F_s < 1$ . All participants were less precise when producing anti-saccades compared to pro-saccades,  $F(1, 24) = 28.0, p < .0001$ , and when executing an eye movement toward peripheral compared to the perifoveal targets,  $F(1, 24) = 77.4, p < .0001$ . These results indicate that deaf individuals and hearing controls display comparable functionality of the oculomotor system, as documented by the absence of between-group differences in the measures of ocular movement kinematic and landing accuracy or precision.

A difference between deaf and hearing participants emerged instead when analyzing the error rates; that is, the percentage of trials in which participants moved their eyes in the opposite direction with respect to that requested by the task. Overall, participants made more errors in the anti-saccade task compared to the pro-saccade task,  $F(1, 24) = 30.3, p < .0001$ . In addition, there was a marginally significant trend to produce more errors for targets at perifoveal than peripheral eccentricities,  $F(1, 24) = 3.9, p = .06$ . Most importantly, the interaction between Task and Group was significant,  $F(1, 24) = 13.7, p < .001$ . As shown in Figure 1a, deaf participants made more errors in the anti-saccade compared to the pro-saccade task ( $p < .0001$ ), whereas hearing controls performed comparably in the two tasks ( $p = .6$ ). When comparing the error rate between groups, deaf participants made more errors than hearing participants specifically in the anti-saccade task ( $p < .02$ ), whereas in the pro-saccade task deaf individuals produced statistically comparable errors to the hearing controls ( $p = .4$ ). Note that no



**Figure 1.** (a) Error rates in pro-saccade and anti-saccade tasks. Deaf participants made more errors in the anti-saccade compared to the pro-saccade task. (b) Saccade latency in pro-saccade and anti-saccade tasks. Deaf individuals showed longer latencies in the anti-saccade compared to the pro-saccade task. (c) Error rates as a function of Trial type (repeat or switch) and Task (pro-saccade or anti-saccade). The three-way interaction (Group, Trial type, and Task) was not significant, suggesting that the higher proportion of errors in the anti- than pro-saccade task in deaf participants was not merely driven by larger task switching cost. (d) Saccade latency as a function of Trial type (repeat or switch) and Task (pro-saccade or anti-saccade). In deaf participants the latency advantage for pro-saccade was larger in repeat (81 ms) than switch trials (36 ms) while in hearing controls it was comparable (21 ms and 38 ms respectively).

main effect of group emerged ( $F < 1$ ), indicating that performance of deaf individuals was not overall worse.

The analysis on saccade latency provided further support to the error pattern. The interaction between Task and Group was significant,  $F(1, 24) = 4.4$ ,  $p < .05$ . Deaf individuals showed longer latencies in the anti-saccade compared to the pro-saccade task ( $p < .001$ ), whereas in hearing controls this was only a marginally significant trend ( $p = .06$ ; see Figure 1b). No other between-group post hoc comparisons were

significant, indicating that the deaf were not significantly faster than hearing controls at producing pro-saccades, despite the evident numerical trend. The main effect of Task was also significant,  $F(1, 24) = 34.6$ ,  $p < .0001$ .

To further investigate the difference in error rates and saccade latency between groups, we separated trials in which the task remained the same over successive trials (repeat trials) from trials in which the task changed from one trial to the next (switch trials). Our

rationale was that voluntary control demands are relatively reduced in repeat compared to switch trials, resulting in more prominent reflexive eye-movement orienting specifically in repeat trials. Error rate and saccade latency measures divided according to this criterion were entered separately in a repeated-measure ANOVA with Trial type (repeat or switch) and Task (pro-saccade or anti-saccade) as within-participants factors, and Group as between-participant factor.

The follow-up analysis on error rates showed that participants made fewer errors in repeat than switch trials overall,  $F(1, 24) = 13.3, p < .001$ . This facilitation for repeat compared to switch trials, however, was larger for pro-saccade (3% vs. 11% errors, respectively;  $p = .0001$ ) than for anti-saccades (14% vs. 18% errors, respectively;  $p = .04$ ), resulting in a significant interaction between Trial type and Task,  $F(1, 20) = 5.2, p < .04$ . Interestingly, although Figure 1c seems to suggest a reduced error rate, specifically on repeat pro-saccade trials in the deaf group, the three-way interaction between Group, Trial type, and Task was not significant,  $F(1, 20) = 0.4, p = .6$  (see Figure 1c). For this reason, this three-way interaction was not analyzed further. Note, however, that the lack of significance in this interaction indicates that the higher proportion of errors in the anti- than pro-saccade task in deaf participants was not driven by larger task-switching cost in this population.

The follow-up analysis on saccade latency revealed instead a significant three-way interaction,  $F(1, 24) = 4.2, p = .05$ , reflecting a different saccade latency advantage in pro- than anti-saccade trials as a function of trial type in the two groups (see Figure 1d). In hearing controls, the latency advantage for pro-saccades was comparable in switch (21 ms) and repeat trials (38 ms;  $p = .7$ ). By contrast, in deaf participants, the latency advantage for pro-saccade was larger in repeat (81 ms) than switch trials (36 ms;  $p = .001$ ).

## DISCUSSION

The present results provide the first evidence of changes in the overt oculomotor behavior of individuals with profound deafness. In particular, they suggest a possible alteration of the balance between voluntary and reflexive eye-movement orienting. We observed a behavioral facilitation in reflexive compared to voluntary eye movements, indexed by faster saccade latencies and smaller error rates in pro- than anti-saccade trials. This behavioral facilitation was substantially larger in deaf participants than in hearing controls, resulting in more errors in anti-saccade trials for deaf than hearing individuals. This result was not driven by the fact that deaf

individuals had difficulty in learning or maintaining the task set, because this would have produced more errors overall compared to hearing controls. Notably, the prominent reflexive eye-movement orienting associated with deafness emerged in a context of comparable functionality of the oculomotor system in deaf and hearing individuals, as documented by the absence of between-group differences in the measures of ocular movement kinematic and landing accuracy/precision.

Given the known link between the saccadic oculomotor system and the neural system responsible for the covert orienting of attention (e.g., Moore, Armstrong, & Fallah, 2003), this reweighting of oculomotor behavior in favor of its reflexive component is compatible with the existing data on faster reorienting of visual attention in deaf individuals (Colmenero et al., 2004; Parasnis & Samar, 1985). One further aspect of the data in line with the existing literature on visual abilities in deaf individuals emerged from our follow-up analysis on repeat and switch trials. Profound deafness enhances reactivity to visual events in simple detection tasks (Bottari et al., 2010; Loke & Song, 1991; Pavani & Bottari, in press). The paradigm adopted here requires stronger inhibitory control than a simple detection task. This may explain why no overall enhanced reactivity in deaf participants emerged in saccadic latency. However, our results show that response in deaf participants was faster in those trials in which inhibitory control was reduced (i.e., repeat compared to switch trials). One aspect of the present study, however, diverges with respect to the previous literature on deafness. Although we expected larger between-group differences for peripheral than perifeveal targets, no evidence in this direction emerged. This unexpected finding could result from the choice of keeping target eccentricity constant within each experimental block, and/or from the limited eccentricity of our peripheral targets. If this is the case, the preponderance of reflexive over voluntary orienting in saccades may increase as a function of target eccentricity when this variable is made unpredictable and eccentricity more peripheral. Note that increasing target eccentricity would also allow probing visual locations that are relevant in face-to-face oral or sign communication, thus increasing further the ecological validity of our paradigm.

Our behavioral evidence that deaf individuals show a dominance of reflexive over voluntary eye movements may suggest a functional and anatomical reorganization in the brain. Voluntary and reflexive ocular movements depend on distinct neural structures (e.g., Johnston & Everling, 2008; Munoz & Everling, 2004). Reflexive saccades are driven by the direct input from the superior colliculus to occipital and parietal cortical regions,

whereas voluntary eye-movement control depends upon frontal cortical areas and the basal ganglia. Our finding indicates that in individuals with profound deafness a reweighting of the relative strength of voluntary and reflexive control may take place, with changes occurring specifically for the functionality of these oculomotor brain networks. However, whether these changes should be attributed specifically to long-term auditory deprivation, or may instead reflect plastic changes occurring as a result of sign-language or lip-reading experience, remains an open question. It would be of great interest to disentangle the contribution of these concurring factors for overt orienting, in a similar way to what has been done in covert attentional orienting (e.g., Bosworth & Dobkins, 2002; Proksch & Bavelier, 2002). In this respect, future research should evaluate overt orienting also in hearing native signers (CODAs: children of deaf adults) to control for any specific modulation induced by sign language per se.

The present results also have two important implications for applied and basic research on deaf cognition. First, given the prevalence of reflexive saccades in deaf individuals, designers of real or virtual (web-based) environments should aim to remove or limit distracting events that could trigger saccades. Second, careful monitoring of eye movement is critical in deaf research, because the assumption that deaf individuals can comply with the fixation request in a similar fashion to hearing controls is largely unwarranted.

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