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Differential influences of prism adaptation on reflexive and voluntary covert attention

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Abstract

Recent research has demonstrated some beneficial effects in patients with neglect using rightward shifting prismatic lenses. Despite a great deal of research exploring this effect, we know very little about the cognitive mechanisms underlying prism adaptation in neglect. We examined the possibility that prism adaptation influences visual attention by having healthy participants complete either a reflexive or a voluntary covert visual attention cuing paradigm before and after adaptation to leftward, rightward, or sham (no shift) prisms. The results for reflexive orienting demonstrated that a subset of participants with large cuing effects before prism adaptation were faster to reorient attention away from an invalid cue on the side of space opposite the prismatic shift post adaptation. For voluntary orienting, left prisms increased the efficiency of voluntary attention in both left and right visual space in participants with a small cuing effect before prism adaptation. In contrast, right prisms decreased the efficiency of voluntary attention in both left and right space for participants with a large cuing effect before prism adaptation. No significant effects were observed in the sham prism groups. These results suggest that prism adaptation may exert a variety of influences on attentional orienting mechanisms. (*JINS*, 2006, *12*, 337–349.)

Keywords: Neglect, Parietal lobes, Visuomotor adaptation, Spatial representation, Perceptual disorders, Sensory motor performance

INTRODUCTION

Lesions of the right parietal cortex or the superior temporal gyrus often lead to the disorder of neglect in which patients fail to attend or respond to stimuli in contralesional space (Driver & Mattingley, 1998; Karnath et al., 2001; Mort et al., 2003). Neglect is generally considered an attentional disorder (Danckert & Ferber, 2006; Husain & Rorden, 2003) with many attempts at rehabilitation focusing on cuing the patient to attend to left space (Robertson, 1999).

Rossetti and colleagues (1998) recently developed a means of ameliorating some symptoms of neglect using prismatic lenses. Before wearing prisms, the patient points to a subjective position straight ahead of their body's midline while blindfolded. Typically, patients with neglect point to the right of true center. Patients are then asked point to left and right targets while wearing prismatic lenses that shift vision 10 degrees to the right. The visual displacement caused by the prisms necessitates a compensatory visuomotor transformation such that patients must adjust their pointing movements to the left to compensate for the rightward shift in vision (for review, see Redding & Wallace, 2006). After prism adaptation (PA), straight-ahead pointing movements are typically shifted closer to the true midline (Rossetti et al., 1998). Perhaps more interesting are the after effects that PA has on patients such that, after PA, they bisect lines closer to the objective center and demonstrated less neglect on figure copying. In addition, recent studies have shown that PA leads to beneficial after-effects in visual imagery (Rode et al., 2001), postural imbalance (Tilikete et al., 2001), tactile extinction (Maravita et al., 2003), and temporal order judgments (Berberovic et al., 2004).

A similar "neglect-like" effect has been demonstrated in healthy individuals using leftward PA. Leftward PA necessitates a visuomotor transformation that results in a rightward shift in the subjective notion of straight-ahead, similar to the rightward bias in those same judgments exhibited by patients with neglect before adaptation. Such neglect-like patterns of behavior have been observed for line bisection (Colent et al., 2000; Michel et al., 2003a), postural control

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(Michel et al., 2003b), and haptic space exploration (Girardi et al., 2004).

Although the observed effects on tasks such as line bisection, visual imagery, and tactile extinction suggest that PA influences higher level spatial representations, we still know very little about the cognitive and neural mechanisms underlying this effect. One hypothesis is that PA might influence mechanisms involved in visual attention. To examine this hypothesis, we had healthy participants complete either a reflexive or a voluntary covert orienting of visual attention task (COVAT) after adaptation to 15 degrees left, 15 degrees right, or sham (no shift) prisms. The COVAT measures response time (RT) to cued (valid) and non-cued (invalid) targets while maintaining central fixation (Posner, 1980). Generally, RTs are faster for valid trials when compared with RTs on invalid trials. This finding is thought to reflect the fact that, in valid trials, attention has already been allocated to the cued location thereby decreasing RT, whereas invalid trials lead to slower RTs because a participant must first "disengage" attention from the cued location and reorient attention to the non-cued (invalid) location (Posner, 1980; Posner et al., 1984).

METHODS

Participants

For the reflexive orienting task, 20 participants (7 male) wore leftward shifting prisms, 20 (9 male, 2 left-handed) wore rightward shifting prisms, and 20 (6 male, 3 left-handed) completed the experiment using sham (no shift) prisms. For the voluntary orienting task, 26 participants (9 males, 1 left-handed) wore leftward shifting prisms, 25 participants (7 males, 1 left-handed) wore rightward shifting prisms, and 20 participants (10 males, 1 left-handed) completed the experiment with sham prisms. None of the participants in this experiment participated in more than one condition. Participants were undergraduate students recruited from the University of Waterloo. All participants had normal or corrected to normal visual acuity. Informed consent was obtained before commencing the experiment and the experimental protocol was approved by the University of Waterloo ethics committee in accordance with the Helsinki Declaration.

Apparatus and Procedure

For the reflexive COVAT, we used noninformative (i.e., 50% valid) abrupt onset peripheral cues. Target locations were indicated by green circles subtending 2.2 degrees and presented 12.4 degrees to the left and right of fixation. A cue consisted of the brightening of one peripheral landmark. Targets consisted of filled red circles presented entirely within the peripheral landmark.

Reaction times to detect targets were measured by external button press. All COVAT tasks were presented on an IBM compatible Pentium IV computer with a 19-inch CRT monitor (refresh rate, 75 Hz) and were created using Superlab software. Participants were seated 50 cm from the monitor, with their head in a chin rest. Participants were told to maintain central fixation.[a] A trial began with fixation, and after a variable time period one peripheral landmark was brightened. This cue remained present until the participant responded. After a stimulus onset asynchrony (i.e., the time between cue onset and target onset; SOA) of 50 ms, 150 ms, or 300 ms, a target appeared at either the cued (valid) or noncued (invalid) location. We also included uncued trials to measure RTs for simple target detection in the absence of cuing. Participants performed five practice trials before completing the COVAT.

For the voluntary COVAT, we used the exact same procedure, the only critical difference is that we used a highly predictive (i.e., 80% valid) central arrow cue subtending 4.6 degrees of visual angle. For voluntary orienting tasks using central arrow cues, previous research suggests that longer SOAs (i.e., SOAs $>$ 200 ms) are required to observe significant cuing effects (Muller & Rabbitt, 1989). The need for longer SOAs is thought to reflect the amount of time required by the participant to interpret the meaning of the cue (i.e., left or right) as well as the time required to voluntarily allocate attention to that location. This is in contrast to reflexive orienting paradigms where the cues attract attention "reflexively" and, thus, lead to the largest facilitatory effects at earlier SOAs (Klein, 2000). Thus, for the voluntary COVAT, we used longer SOAs of 300 ms and 500 ms to ensure that we would be able to observe a significant cuing effect.[b]

The PA procedure used was adapted from Rossetti and colleagues (1998). Before adaptation, participants sat with their head in a chin rest and made five pointing movements to a subjective position straight-ahead of their body's midline with their eyes closed. The experimenter recorded the endpoints of these movements, which were used to calculate each participant's pre-PA notion of straight-ahead. Participants then wore wedge base prismatic lenses (Optique Peter, France), which shifted visual perception 15 degrees to the left or right or induced no shift at all (sham prisms). Participants always used their right hand to point during adaptation. While wearing the prisms, they were asked to point to targets to the left and right of an objective straight-ahead position once every 3–4 seconds for a period of 15 minutes. Immediately after PA and again at the conclusion of the experiment, participants were asked to close their eyes and point to where they thought straight-ahead was

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[a] Although fixation was not strictly monitored, all participants reported having no difficulty maintaining fixation throughout. Furthermore, saccadic eye movements take around 200 ms to initiate such that eye movements to cued locations would not be possible at SOAs of 50 and 150.

[b] Different SOAs are used for the reflexive and voluntary COVAT based on prior research that demonstrated the largest RT advantage for validly cued targets in a reflexive orienting task occurs at early SOAs (~50 ms; Maruff et al., 1999), whereas RT advantages only arise at SOAs of around 200 to 300 ms in a voluntary COVAT (Muller & Rabbitt, 1989). It was important, therefore, to use these different SOAs in each task to ensure that a reliable cuing effect was observed in each task before adaptation takes place.

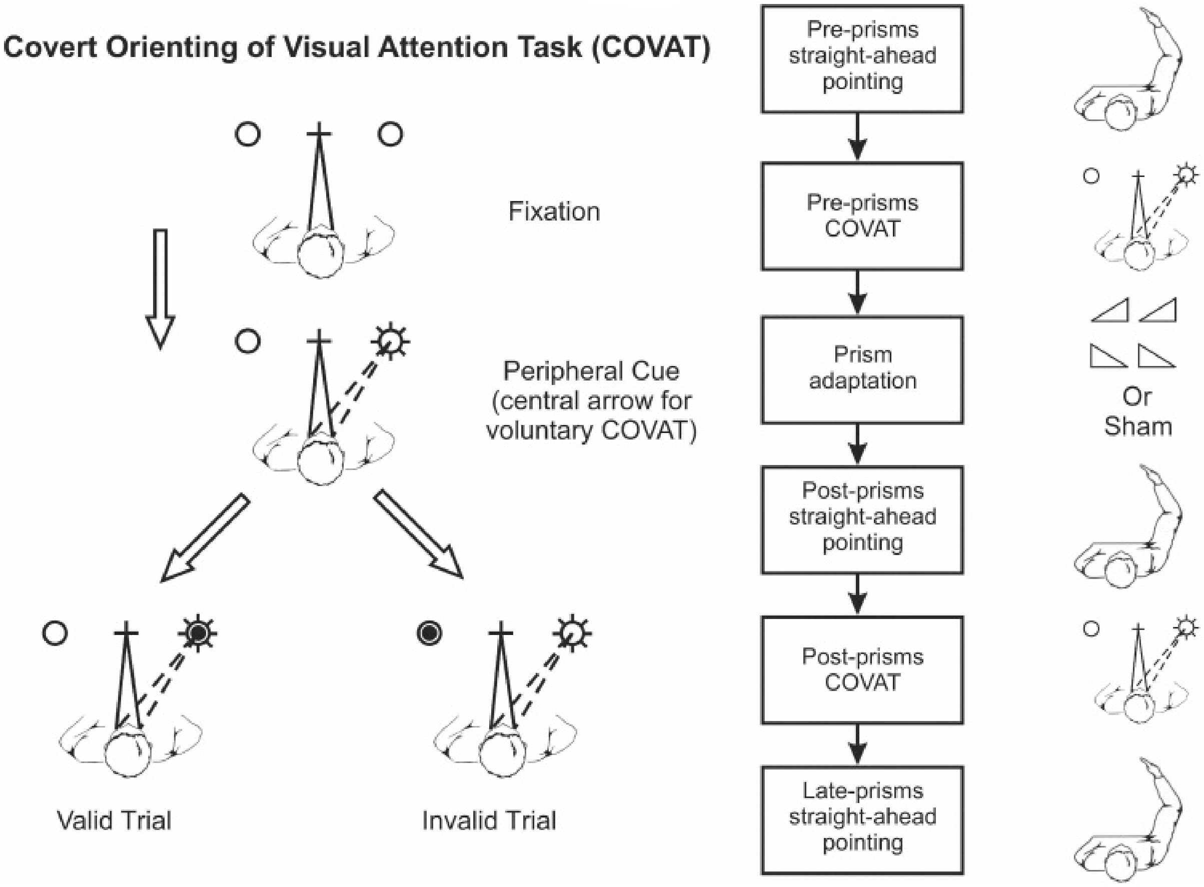

Fig. 1. To the left of the figure is a schematic depicting the sequence of events (from top to bottom) in a single trial of the reflexive covert orienting of visual attention task (COVAT). Solid lines indicate where the participant's eyes are fixated, dotted lines indicate where the participant's covert attention is directed. In a valid trial, the target appears in the same location as the cue (bottom left), whereas for invalid trials, targets appear in the opposite location (bottom right). The schematic to the right of the figure shows the sequence of events for the entire experiment.

five times. The endpoints of these pointing movements were recorded by the experimenter to determine the degree of adaptation to the prisms (post session) and how much participants had de-adapted from the prisms by the end of the experiment (late session; Figure 1).

Data Analysis

Average RTs were calculated for each trial type for each participant. Response times were discarded if they were 2 standard deviations above the participant's overall mean or if they were less than 150 ms. To analyze the effects of PA on covert attention, we calculated cue-effect sizes (CES) by subtracting the average RTs for valid trials from the average RTs for invalid trials at each SOA, with a positive score indicative of an RT advantage for valid trials, and a negative score indicative of an RT advantage for invalid trials. To examine whether or not PA had exerted a direction-specific effect on covert orienting, we calculated the CES for leftward and rightward shifts of attention at each SOA before and after PA. For leftward shifts, the CES was calculated by subtracting RTs for validly cued right visual field targets from invalidly cued left visual field targets. Similarly, for rightward shifts, the CES was calculated by subtracting RTs to validly cued left visual field targets from invalidly cued right visual field targets. For both left and right attention shift CES calculations, the initial component of each trial type is identical, that is, a shift of attention to a cue in the left or right visual field. The only difference is the need to reorient attention in the opposite direction to detect invalidly cued targets (see bottom panels of Figure 3).

After initial analyses of CES sizes pre- and post-PA suggested there was little or no influence of prisms on covert orienting, we decided to repeat the analysis this time separating each group according to the magnitude of their CES before adaptation. We deemed this strategy to be necessary based on the possible influence of ceiling or floor effects in pre-adaptation CES. That is, it is highly unlikely that an increase in CES will be observed post-PA among individuals who demonstrate a large CES before adaptation (i.e., a ceiling effect may prevent the CES from getting any larger). Conversely, it is also highly unlikely that a reduction in CES will be observed in those individuals whose pre-adaptation CES is already low (i.e., a floor effect may prevent the CES from getting any smaller). If both effects were observed (i.e., a reduction in the large CES group post-PA and an increase in the small CES group post-adaptation), these effects would cancel one another out in the whole group analysis. Therefore, each group (leftward shifting, rightward shifting, and sham prisms) were further split into large and small CES groups according to their pre-adaptation CES at the 50-ms SOA in the reflexive COVAT and the 300-ms SOA in the voluntary COVAT using a median split procedure. That is, participants with a CES above the median were placed in the large CES group, whereas participants with a CES below the median were placed in the small CES group. These CES data were then analyzed separately for each large and small CES group using a three-way within-subject analysis of variance (ANOVA) with session (pre- *vs.* post-PA), direction of attentional shift (left, right), and SOA (50, 150, 300 for reflexive; 300, 500 for voluntary) as within-subject factors. Significant effects were evaluated using the Greenhouse-Geisser (1959) correction for conservative degrees of freedom. Post hoc comparisons were carried out where appropriate using paired samples t tests, with Bonferroni corrections for the number of comparisons made.

Planned Comparisons

Previous research suggests that patients with parietal injury (with or without neglect) demonstrate a characteristic pattern of performance on the reflexive COVAT. Specifically, when the cue appears in the their right (ipsilesional) visual field and the target appears in their left (contralesional) visual field, it takes them an abnormally long time to detect the target (Bartolomeo et al., 2001; Morrow & Ratcliff, 1988; Posner et al., 1984, 1987). Furthermore, this effect, referred to as the "disengage deficit" is largest at short SOAs (~50 ms; Losier & Klein, 2001). Given that parietal lesions result in direction-specific deficits in covert orienting that are largest at the shortest SOAs, we used planned comparisons to examine the possibility that PA may affect covert orienting in a similar manner. That is, we were interested in testing for direction-specific effects of PA at the 50 ms SOA in which spatially specific *deficits* after parietal injury are *most likely* to be found (Losier & Klein, 2001). To be conservative, we used a Bonferroni correction to correct for the number of planned comparisons in each analysis (corrected p value of .025). Effect sizes for the planned comparisons are reported using Cohen's d statistic (Rosnow & Rosenthal, 1996).

Straight-Ahead Pointing

Data from each pointing trial for each session (pre-PA, post-PA, and late) were converted to degrees of visual angle for each individual participant. Pointing to the left of midline was coded as negative, whereas pointing to the right of midline was coded as positive. The mean deviation for each individual was then submitted to a one-way within-subject ANOVA followed by post hoc comparisons using paired sampled t tests with Bonferroni correction ($p = .016$). Separate analyses were conducted for each group.

RESULTS

Reflexive Orienting

Straight-ahead pointing

For the leftward shifting prism group, ANOVA indicated a significant difference between the three pointing sessions ($F(1.83, 34.73) = 38.11$; $p = .0001$). Post hoc comparisons demonstrated a significant rightward shift in pointing post-adaptation (3.33 degrees pre *vs.* 12.17 degrees post; $t(19) = 8.44$; $p = .0001$) demonstrating that participants adapted successfully to the prisms. In addition, there was no difference in pointing for post (12.17 degrees) and late (11.73 degrees) sessions ($t(19) = .42$; $p = .68$), indicating that participants remained adapted for the duration of the experiment (Figure 2).

For the rightward shifting prism group, there was also an effect of pointing session ($F(1.75, 33.23) = 101.35$; $p = .0001$) such that participants had a significant leftward shift in straight-ahead pointing post-PA (2.03 degrees pre *vs.* −11.55 degrees post; $t(19) = 13.49$, $p = .0001$), which was maintained at the late pointing session (−11.55 degrees post *vs.* −9.60 degrees; $t(19) = 1.62$; $p = .12$), confirming that participants remained adapted to the prisms throughout the experiment (Figure 2).

In the sham group, ANOVA indicated no significant difference between the three pointing sessions ($F(1.76, 33.44) = 1.65$; $p = .210$; 0.29 degrees pre, 0.14 degrees post, and −0.85 degrees late).

Cue-Effect Size Analysis

Leftward shifting prisms

Mean RTs for the large and small CES groups are presented in Table 1. The median CES at the 50-ms SOA for the whole group pre-adaptation was 33 ms. For the large CES group ($N = 10$), analysis revealed a significant session × SOA interaction ($F(1.92, 17.30) = 4.15$; $p = .035$) such that there was a large reduction in CES at the 50-ms SOA post-PA (31 ms) relative to pre-PA (50 ms; $t(9) = 3.36$; $p = .008$). Although the three-way interaction between session, direction of attentional shift, and SOA was nonsignificant ($F(2,18) = 1.50$; $p = .25$), we still carried out our planned comparisons to test for directional effects of PA at the 50-ms SOA. These comparisons revealed that post-PA, there was a significant decrease in CES at the 50-ms SOA for leftward shifts (45-ms pre *vs.* 18-ms post; $t(9)=2.72$; $p = .024$; $d = .86$) but not rightward shifts of attention (55-ms pre *vs.* 45-ms post; $t(9) = 1.08$; $p = .307$; $d = .34$; Figure 3). In addition, there was no difference in RT for left and right for validly cued targets at the 50-ms SOA post-adaptation

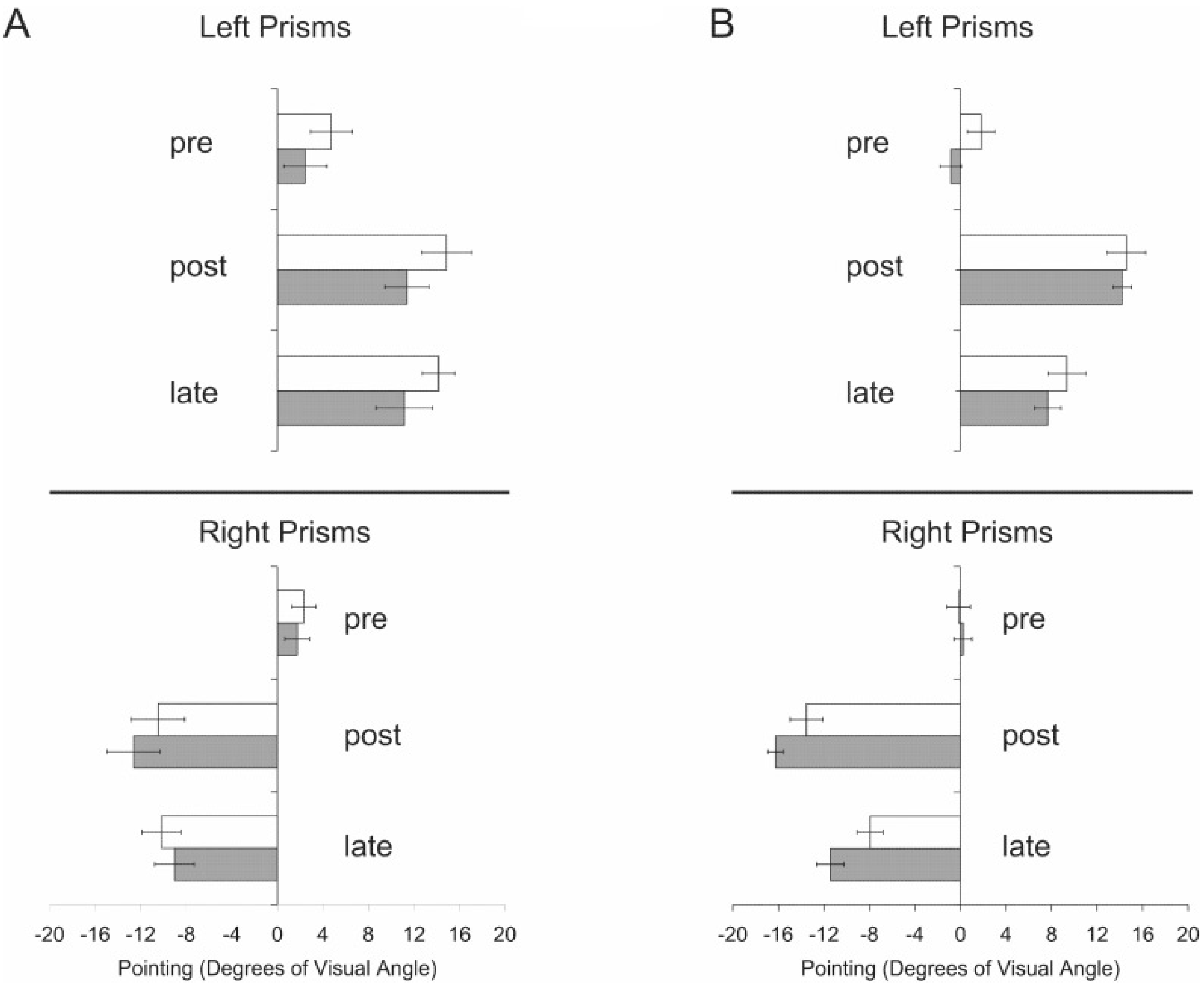

Fig. 2. Pointing data in degrees of visual angle for reflexive (panel A) and voluntary (panel B) orienting for the leftward (top) and rightward (bottom) shifting prism groups as a function of pointing session. Open bars represent the small cue-effect size (CES) group, whereas gray bars represent the large CES group.

Table 1. Mean response times and standard deviations (in brackets) for reflexive orienting in the leftward shifting prism group as a function of target side, cue validity, stimulus onset asynchrony (SOA), and session (pre- *vs.* post-prism)[a]

	Left target						Right target					
	Valid			Invalid			Valid			Invalid		
SOA	50	150	300	50	150	300	50	150	300	50	150	300
						Pre-prism						
Large CES group	346(21)	338(13)	338(23)	384(18)	350(14)	330(14)	340(13)	341(15)	340(17)	401(15)	370(14)	344(18)
Small CES group	357(23)	346(27)	345(20)	376(17)	340(18)	334(21)	370(30)	345(25)	338(20)	380(27)	358(24)	332(26)
Whole group	352(24)	342(23)	341(23)	380(17)	345(16)	332(19)	355(30)	343(21)	339(19)	391(22)	364(20)	338(22)
						Post-prism						
Large CES group	333(20)	321(13)	318(6)	364(29)	330(26)	322(16)	346(15)	325(12)	318(18)	378(19)	340(24)	322(25)
Small CES group	324(30)	314(20)	312(32)	343(24)	304(16)	298(19)	327(19)	302(23)	311(28)	348(29)	322(21)	307(36)
Whole group	329(25)	318(16)	315(22)	354(27)	318(23)	310(19)	337(17)	314(20)	315(23)	363(27)	331(23)	314(31)

[a] The standard deviations reported reflect the between-subject variability.
Note. CES = cue-effect size.

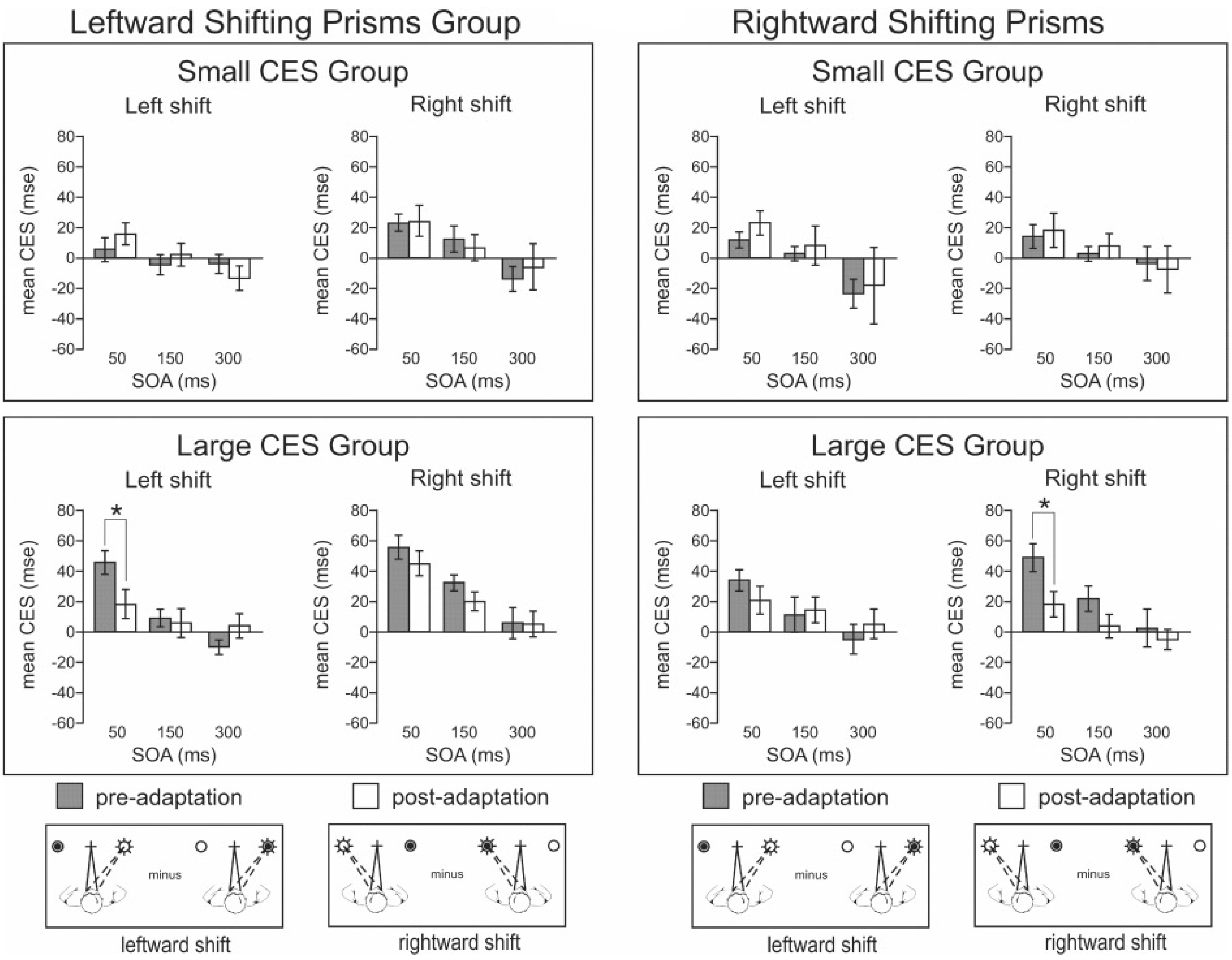

Fig. 3. Data from the leftward (left panels) and rightward (right panels) shifting prism groups for reflexive orienting. Data from the small cue effect size (CES) groups are presented in the top two panels, whereas data from the large CES groups are presented in the bottom two panels. Within each group CES, data are presented separately for leftward and rightward attentional shifts. All data are in milliseconds, and error bars represent between subject variance. An asterisk indicates a statistically significant difference. Gray bars represent pre-adaptation CES data, and open bars represent post-adaptation CES data. At the bottom of the figure is a schematic representing the calculation made for leftward and rightward attentional shifts. SOA = stimulus onset asynchrony.

(334 ms *vs.* 346 ms; $t(9) = 1.83$; $p = .10$). There was also no difference in RT for left and right uncued trials post-adaptation (368 ms *vs.* 376 ms; $t(9) = 1.04$; $p = .32$). This finding suggests that leftward PA has not led to faster RTs for detecting *any* target in the left visual field. Instead, PA led to faster reorienting of attention away from an invalid cue in the right visual field to detect a target in the left visual field.

The CES analysis in the small CES group ($N = 10$) revealed a significant main effect of SOA ($F(1.76, 15.89) = 9.70$; $p = .002$), with the CES being largest at the 50-ms SOA (17 ms). There were no main effects or interactions involving session, suggesting that PA had no effect in the small CES group (Figure 3). Planned comparisons examining directional effects of PA at the 50-ms SOA revealed no significant differences for leftward (5-ms pre *vs.* 16-ms post; $t(9) = 1.29$; $p = .228$; $d = .40$) or rightward shifts of attention (22-ms pre *vs.* 23-ms post; $t\ (9) = .134$; $p = .896$; $d = .04$).

Rightward shifting prisms

Mean RTs for the large ($N = 10$) and small ($N = 10$) CES groups are presented in Table 2 (median CES at the 50-ms SOA for the whole group before adaptation = 28 ms). The outcome of the CES analysis was identical to that of the large CES group in the leftward shifting prism group in that there was a significant session × SOA interaction ($F(1.87, 16.81) = 4.54$; $p = .029$). Post hoc tests revealed a significant decrease in CES at the 50-ms SOA after PA (41-ms pre *vs.* 19-ms post; $t(9) = 4.87$; $p = .001$). Again, although the three-way interaction between session, shift, and SOA was nonsignificant ($F(2, 18) = .016$; $p = .984$), we carried out our planned comparisons to test for directional effects of PA on the CES at the 50-ms SOA. There was a significant reduction in CES at the 50-ms SOA post-PA for rightward (48-ms pre *vs.* 18-ms post; $t(9) = 3.66$; $p = .005$; $d = 1.16$) but not leftward shifts of attention (34-ms pre, *vs.* 21-ms post; $t(9) = 1.43$; $p = .186$; $d = .45$). This effect mirrors the effect found in the large CES group after leftward PA (Figure 3). In addition, there was no difference in RTs for left and right validly cued targets postadaptation (365-ms pre *vs.* 359-ms post; $t(9) = .76$; $p = .469$) or for left and right uncued targets post-adaptation (387-ms pre *vs.* 392-ms post; $t(9) = .617$; $p = .552$).

For the small CES group ($N = 10$), ANOVA indicated a significant main effect of SOA ($F(1.67, 15.06) = 7.76$; $p = .007$), with CES being largest at the 50-ms SOA (16 ms). There were no interactions involving session (pre *vs.* post). Planned comparisons also failed to reveal any significant directional effects of PA at the 50-ms SOA for leftward (11-ms pre *vs.* 23-ms post; $t(9) = 1.19$; $p = .263$; $d = .37$) or rightward shifts of attention (14-ms pre, *vs.* 18-ms post; $t(9) = .32$; $p = .756$; $d = .10$; Figure 3).

Sham prisms

Mean RT data for the large and small CES groups are presented in Table 3 (median CES at the 50-ms SOA for the whole group before adaptation = 34 ms). For the large CES group ($N = 10$), ANOVA indicated a marginally significant main effect of session ($F(1, 9) = 5.46$; $p = .044$), with CES being smaller post-PA (23-ms pre *vs.* 18-ms post). In addition, there was a main effect of SOA ($F(2, 18) = 38.46$; $p = .001$), with CES at the 50-ms SOA (38 ms) being larger than CES at the 150-ms (22-ms) and 300-ms (2-ms) SOAs. There were no other main effects or interactions.

For the small CES group ($N = 10$), analysis revealed a significant main effect of SOA ($F(1.9, 17.12) = 13.5$; $p = .0001$), with CES at the 50-ms SOA (18-ms) being larger than CES at either then 150-ms (3-ms) or 300-ms (5-ms) SOAs. No other main effects or interactions were significant.

Voluntary Orienting

Straight-ahead pointing

For the leftward shifting prism group, analysis indicated a significant difference between pointing sessions

Table 2. Mean response times and standard deviations (in brackets) for reflexive orienting for the rightward shifting prism group as a function of target side, cue validity, stimulus onset asynchrony (SOA), and session (pre- *vs.* post-prism)[a]

	Left target						Right target					
	Valid			Invalid			Valid			Invalid		
SOA	50	150	300	50	150	300	50	150	300	50	150	300
						Pre-prism						
Large CES group	345(20)	341(18)	350(30)	391(29)	352(33)	341(41)	357(30)	340(27)	346(26)	393(29)	363(29)	352(50)
Small CES group	365(26)	359(14)	346(30)	372(31)	353(19)	338(18)	361(25)	351(22)	362(25)	379(21)	362(23)	343(22)
Whole group	355(25)	350(19)	348(29)	382(31)	353(26)	340(31)	359(27)	346(25)	354(26)	386(26)	362(25)	348(38)
						Post-prism						
Large CES group	365(31)	339(36)	341(19)	379(39)	358(27)	340(26)	358(32)	343(24)	335(24)	383(30)	343(29)	336(16)
Small CES group	350(23)	331(22)	346(41)	368(19)	346(28)	333(44)	346(23)	339(25)	352(63)	368(34)	339(17)	339(24)
Whole group	357(28)	335(29)	344(31)	374(30)	352(28)	337(35)	352(28)	341(24)	344(47)	375(32)	341(24)	338(20)

[a]The standard deviations reported reflect the between-subject variability.
Note. CES = cue-effect size.

Table 3. Mean response times and standard deviations (in brackets) for reflexive orienting for the sham prism group as a function of target side, cue validity, stimulus onset asynchrony (SOA), and session (pre- *vs.* post-prism)[a]

	Left target						Right target					
	Valid			Invalid			Valid			Invalid		
SOA	50	150	300	50	150	300	50	150	300	50	150	300
	Pre-prism											
Large CES group	339(17)	343(15)	341(18)	389(18)	360(19)	343(20)	355(20)	343(16)	351(15)	398(14)	376(16)	345(15)
Small CES group	345(35)	336(17)	336(19)	358(14)	333(12)	317(17)	349(16)	335(14)	335(25)	367(19)	343(17)	334(19)
Whole group	342(29)	340(16)	339(19)	374(17)	347(17)	330(19)	352(18)	339(16)	343(20)	383(18)	360(18)	339(16)
	Post-prism											
Large CES group	342(28)	334(12)	331(19)	379(19)	346(14)	336(20)	355(26)	328(15)	330(22)	377(28)	353(19)	338(17)
Small CES group	341(25)	314(24)	319(19)	357(15)	316(18)	305(21)	336(26)	320(17)	305(24)	360(16)	326(11)	317(28)
Whole group	341(27)	324(18)	325(19)	368(17)	331(17)	321(21)	346(26)	324(16)	318(23)	369(22)	339(16)	327(22)

[a] The standard deviations reported reflect the between-subject variability.
Note. CES = cue-effect size.

($F(1.85,46.45) = 121.12$; $p \leq .0001$). Post hoc tests indicated that participants had a significant rightward shift in straight-ahead pointing (.44 degrees pre *vs.* 13.35 degrees post; $t(25) = 13.87$, $p \leq .0001$). This shift in pointing had begun to diminish by the late pointing session (13.35 degrees post *vs.* 7.88 degrees late; $t(25) = 7.47$, $p \leq .0001$); however, participants were still significantly adapted compared to the pre-adaptation session (.440 degrees pre *vs.* 7.88 degrees late; $t(25) = 9.03$, $p \leq .0001$; Figure 2).

In the rightward shifting prism group, ANOVA also indicated a significant difference between the three pointing sessions ($F(1.94,46.62) = 158.71$; $p \leq .0001$). Post hoc analyses revealed that participants had a significant leftward shift in pointing post-adaptation (.04 degrees pre *vs.* −14.93 degrees post; $t(24) = 19.27$; $p \leq .0001$). Similar to the leftward shifting prism group, participants had begun to de-adapt by the end of the experiment (−14.93 degrees post *vs.* −9.75 degrees late; $t(24) = 5.83$; $p \leq .0001$); however, they remained adapted when compared with baseline pointing (.04 degrees pre *vs.* −9.75 degrees late; $t(24) = 10.98$; $p \leq .0001$; Figure 2).

For the sham prism group, analysis indicated that there were no significant differences between the three pointing sessions (1.04 degrees pre, −0.62 degrees post, −1.43 degrees late).

Cue-Effect Size Analysis

Leftward shifting prisms

Response time data for the leftward shifting prism group are presented in Table 4. The median CES for the whole group at the 300-ms SOA before PA was 28 ms.

In the large CES group ($N = 13$), ANOVA indicated a significant main effect of shift ($F(1,12) = 13.43$; $p = .003$), with rightward shifts of attention (44 ms) having a larger overall CES than leftward shifts of attention (24 ms; Fig-

Table 4. Mean response times and standard deviations (in brackets) for voluntary orienting for the leftward shifting prism group as a function of target side, cue validity, stimulus onset asynchrony (SOA), and session (pre- *vs.* post-prism)[a]

	Left target				Right target			
	Valid		Invalid		Valid		Invalid	
SOA	300	500	300	500	300	500	300	500
	Pre-prism							
Large CES group	306(21)	295(23)	344(18)	334(29)	314(21)	305(17)	366(23)	335(29)
Small CES group	314(26)	309(40)	330(28)	330(31)	312(22)	306(22)	319(25)	328(29)
Whole group	310(25)	302(34)	337(23)	332(30)	313(21)	305(20)	342(32)	332(28)
	Post-prism							
Large CES group	296(20)	292(14)	320(31)	316(30)	301(23)	292(19)	339(34)	334(31)
Small CES group	299(27)	293(26)	338(22)	316(21)	302(22)	303(21)	332(30)	319(19)
Whole group	297(24)	292(21)	329(29)	316(26)	301(22)	297(21)	335(32)	327(25)

[a] The standard deviations reported reflect the between-subject variability.
Note. CES = cue-effect size.

ure 4). There were no significant effects involving session, suggesting that PA did not influence voluntary covert attention in the large CES group.

For the small CES group ($N = 13$), ANOVA revealed a significant session × SOA interaction ($F(1,12) = 9.14$; $p = .011$) due to a significant *increase* in CES post-PA at the 300-ms SOA (11-ms pre *vs.* 34-ms post; $t(12) = 3.72$; $p = .003$). There was not a significant session × shift × SOA interaction ($F(1.92, 23.12) = .159$; $p = .854$), suggesting that PA increased the CES post-adaptation equally for leftward and rightward shifts of attention (Figure 4). Given that planned comparisons examining the direction of shift were conducted for reflexive shifts of attention despite a similar lack of a three-way interaction, we performed those same analyses here. This result confirmed that the increase in CES was equivalent for leftward (18-ms pre *vs.* 36-ms post; $t(12) = 2.83$; $p = .015$; $d = .79$) and rightward (4-ms pre *vs.* 33ms post; $t(12) = 2.97$; $p = .012$; $d = .82$) shifts of attention at the 300-ms SOA.

Rightward shifting prisms

Response time data for the rightward shifting prism group are presented in Table 5. The median CES for the whole group at the 300-ms SOA before PA was 29 ms.

For the large CES group ($N = 13$), ANOVA revealed a marginally significant session × SOA interaction ($F(1,12) = 5.15$; $p = .042$). This finding appeared to result from a *decrease* in CES at the 300-ms post-PA (48-ms pre *vs.* 24-ms post; $t(12) = 2.69$; $p = .019$). There was not a significant session × shift × SOA interaction (Figure 4), suggesting that the slight decrease in CES post-PA was equal for leftward and rightward shifts of attention ($F(1,12) = .003$; $p = .96$). Planned comparisons for left and right shifts of attention revealed that the decrease in SOA at the 300-ms SOA was not significant following the Bonferroni correction for either leftward (47-ms pre *vs.* 23-ms post; $t(12) = 2.41$; $p = .032$; $d = .67$) or rightward (51-ms pre *vs.* 25-ms post; $t(12) = 1.63$; $p = .128$; $d = .45$) shifts of attention. Thus, the reduction in CES after PA was not reliably different for left or right shifts of attention.

In the small CES group ($N = 12$), ANOVA revealed a significant main effect of shift ($F(1,11) = 8.12$; $p = .016$) with rightward shifts of attention (34 ms) having a larger CES than leftward shifts of attention (15 ms). There was also a main effect of SOA ($F(1,11) = 5.72$; $p = .036$), with CES at the 500-ms SOA (30 ms) being larger than CES at the 300-ms SOA (18 ms; Figure 4). There were no significant effects involving session, suggesting that rightward PA had no effect on voluntary covert orienting in the small CES group.

Sham prism group

Response time data for the sham prism group are presented in Table 6. The median CES for the whole group at the 300-ms SOA before PA was 28 ms.

For the large CES group ($N = 10$), there was a significant shift × SOA interaction ($F(1,9) = 6.91$; $p = .027$), with CES for rightward shifts of attention being larger than leftward shifts of attention at the 500-ms SOA (27-ms left shift *vs.* 54-ms right shift; $t(9) = 2.31$; $p = .046$). However, this difference was not significant after Bonferroni correction. There were no other significant main effects or interactions. In the small CES group ($N = 10$), ANOVA did not reveal any significant main effects or interactions. This finding suggests that sham adaptation had no effect on voluntary covert orienting for either the large or small CES groups.

DISCUSSION

Recent research suggests that PA may influence higher level spatial representations in patients with neglect. Despite several studies examining the effects of PA on these patients,

Table 5. Mean response times and standard deviations (in brackets) for voluntary orienting for the rightward shifting prism group as a function of target side, cue validity, stimulus onset asynchrony (SOA), and session (pre- *vs.* post-prism)[a]

	Left target				Right target			
	Valid		Invalid		Valid		Invalid	
SOA	300	500	300	500	300	500	300	500
				Pre-prism				
Large CES group	321(13)	307(26)	368(30)	339(29)	321(14)	309(23)	372(23)	354(22)
Small CES group	298(23)	293(30)	313(22)	324(22)	309(19)	299(26)	325(16)	335(30)
Whole group	310(18)	300(28)	341(31)	332(25)	315(17)	304(25)	350(24)	345(25)
				Post-prism				
Large CES group	323(24)	305(26)	347(31)	348(45)	324(15)	315(27)	348(38)	353(29)
Small CES group	296(18)	291(22)	317(49)	305(30)	303(13)	289(21)	324(23)	329(22)
Whole group	310(21)	298(24)	332(40)	327(40)	314(14)	303(24)	337(31)	341(26)

[a] The standard deviations reported reflect the between-subject variability.
Note. CES = cue-effect size.

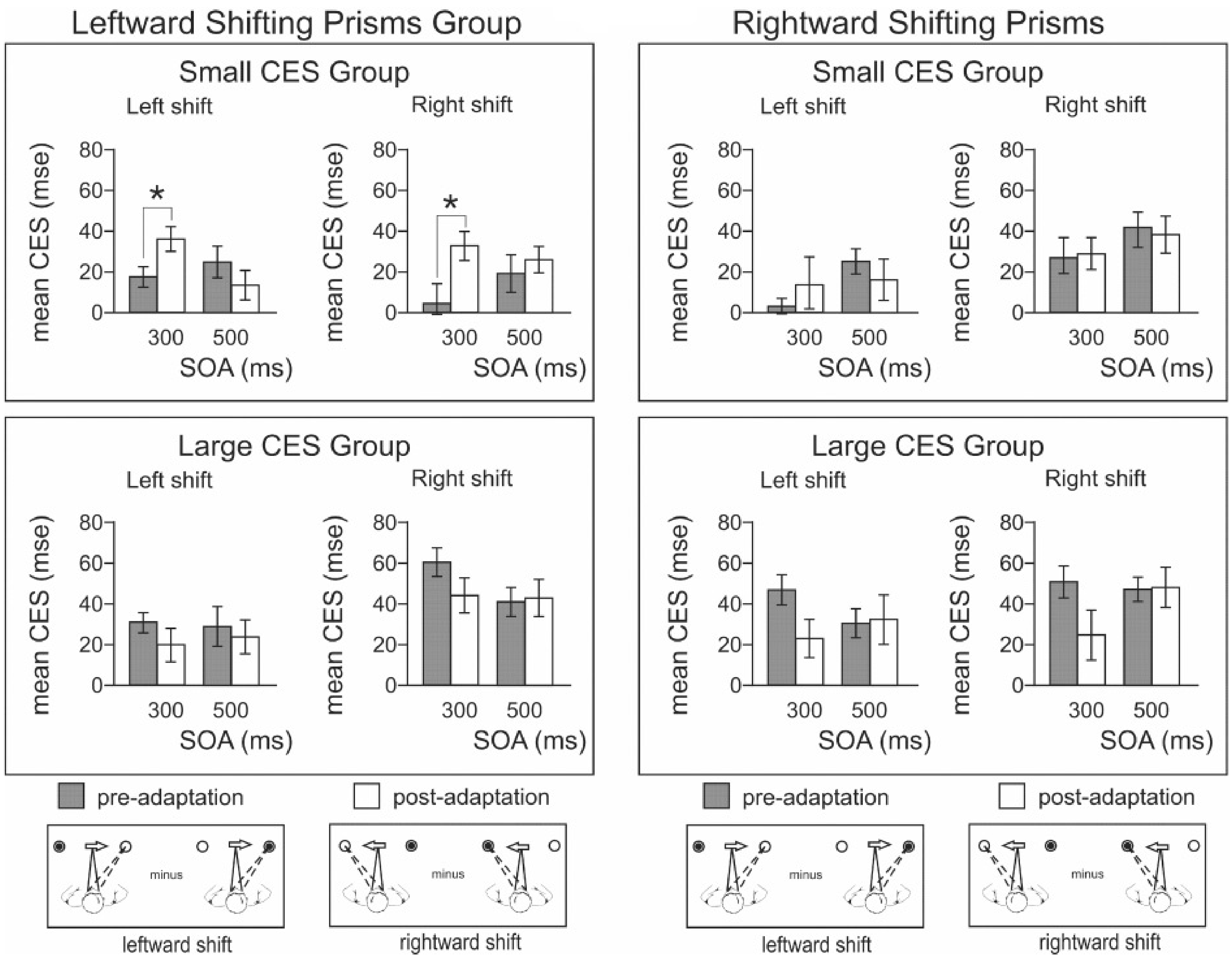

Fig. 4. Data from the leftward (left panels) and rightward (right panels) shifting prism groups for voluntary orienting. Data from the small cue effect size (CES) groups are presented in the top two panels, whereas data from the large CES groups are presented in the bottom two panels. Within each group, CES data are presented separately for leftward and rightward attentional shifts. All data are in milliseconds, and error bars represent between-subject variance. An asterisk indicates a statistically significant difference. Gray bars represent pre-adaptation CES data, and open bars represent post-adaptation CES data. At the bottom of the figure is a schematic representing the calculation made for leftward and rightward attentional shifts. SOA = stimulus onset asynchrony.

Table 6. Mean response times and standard deviations (in brackets) for voluntary orienting for the sham prism group as a function of target side, cue validity, stimulus onset asynchrony (SOA), and session (pre- *vs.* post-prism)[a]

	Left target				Right target			
	Valid		Invalid		Valid		Invalid	
SOA	300	500	300	500	300	500	300	500
				Pre-prism				
Large CES group	293(20)	277(19)	335(15)	314(28)	294(12)	286(14)	337(39)	340(18)
Small CES group	279(15)	272(19)	293(16)	304(24)	282(18)	278(21)	302(28)	297(25)
Whole group	284(17)	272(19)	310(20)	305(25)	285(15)	278(17)	315(35)	314(26)
				Post-prism				
Large CES group	275(17)	267(12)	311(23)	300(39)	279(10)	275(27)	314(30)	313(29)
Small CES group	276(9)	265(15)	281(30)	286(31)	273(14)	265(22)	292(26)	291(38)
Whole group	271(15)	263(15)	295(27)	288(34)	273(12)	267(23)	299(27)	298(32)

[a] The standard deviations reported reflect the between-subject variability.
Note. CES = cue-effect size.

we still know relatively little about the cognitive mechanisms underlying PA. One hypothesis is that PA may influence mechanisms involved in visual attention. What the current results show is that, in healthy individuals, PA influences the way in which covert attention is oriented (or reoriented) across the visual field. For reflexive orienting, PA produced *direction-specific* effects in covert orienting. More specifically, after adaptation to leftward shifting prisms, participants in the large CES group were *faster* at disengaging or reorienting attention away from an invalid cue in the right visual field. The results in the rightward shifting prism group mirrored these effects, with participants in the large CES group now being *faster* to disengage or reorient attention away from an invalid cue in the left visual field. Importantly, the effect of PA was only evident at the earliest (50-ms) SOA. Participants in the sham prism group showed no significant effects of PA adding strong support to the notion that the observed effects in the left and right prism groups were specific to PA and are not simply reflective of a practice effect.

Together these results suggest that PA made reflexive attention "less sticky" on the side of space opposite the prismatic shift. That is, for a reflexive orienting task of the kind used here, faster disengagement from a noninformative cue can be seen as advantageous to the participant. Interestingly, the current results parallel those of Posner and colleagues (1984) in patients with parietal injury with the opposite effects on RT. Specifically, after right parietal injury, patients were *slower* to reorient attention away from an invalid cue in the right visual field and vice versa for patients with left parietal injury. This finding may suggest that left prisms affect the right parietal cortex, whereas right prisms affect the left parietal cortex. The current results also compliment the findings of a recent study by Berberovic and colleagues (2004) in which rightward PA reduced the rightward bias in temporal order judgments in patients with neglect, suggesting that prisms may influence the orienting of visual attention.

The results for voluntary orienting suggest that, for individuals with a small CES before PA, leftward PA induced more efficient voluntary orienting. To pick up on the metaphor, leftward prisms made attention "more sticky" for both leftward and rightward attentional shifts in those individuals whose CES was small before adaptation. This increase in the CES for left and right attentional shifts arose as a result of slower RTs for invalid trials coupled with faster RTs for valid trials post-adaptation (Table 4). These changes in RT can be seen as advantageous to the participant whose pre-adaptation RT advantage for valid trials was small to begin with. That is, it seems that prisms have altered the way in which these individuals attend to the cued location perhaps by speeding up their response to that location on the one hand (faster RTs to valid trials) and making them more reluctant to disengage attention from that location on the other hand (slower RTs to invalid trials). Alternatively, for participants with a large CES before PA, rightward shifting prisms led to a slight decrease in the efficiency of voluntary covert attention such that there was a *decrease* in CES post-adaptation at the 300-ms SOA. This effect was not significant when left and right shifts of attention when analyzed separately, with the corresponding small effect size calculations. The smaller effect size and lack of significance, when analyzed for each direction of shift, may suggest that this effect of PA was less reliable than the effect observed for leftward shifting prisms. Finally, there were no significant changes in CES after sham adaptation, which again lends strong support to the notion that the effects observed post-PA for voluntary orienting were due specifically to the effects of the prisms.

Two questions that remain are why PA had nondirectional effects in voluntary orienting, and, why left and right prisms produced contrasting effects on CES? As suggested earlier, left prisms may be affecting the right parietal cortex, whereas right prisms may be affecting the left parietal cortex. This could also explain the apparent contrasting findings for voluntary orienting. Specifically, previous research suggests that, in healthy individuals, the right parietal cortex is dominant for voluntary shifts of spatial attention in both left and right space (Corbetta et al., 1993; Mesulam, 1999). Thus, if left prisms influence the right parietal cortex, one might expect an *increase* in the efficiency of voluntary attention for both left and right shifts. In contrast, if right prisms influence the left parietal cortex, this may serve to interfere with functioning within the right parietal cortex, which may lead to a decreased CES for left and right shifts of attention. This theory is necessarily speculative, and further research is needed to validate it.

A recent study by Morris and colleagues (2004) failed to observe any effects of PA on visual attention using a visual search task, which undoubtedly involves voluntary attention. While this result is in direct contrast to the current findings, it may be the case that prisms exert differential influence on processes involved in visual search *versus* cued target detection. Directing covert attention within a fairly uncomplicated environment such as the one used here in which there are only two possible target locations is a very different task when compared with a typical visual search task containing multiple targets and distracters that may reflect more closely the demands of "real world" environments.

The current study demonstrates a possible cognitive mechanism by which PA may work, however, it remains unclear as to the extent to which this mechanism could be exploited for real-world rehabilitation purposes. At least one recent study (Jacquin-Courtois et al., in press) has demonstrated that a single session of PA can have beneficial effects on wheelchair navigation in a patient with neglect in a hospital ward for up to 4 days post-adaptation. Further research is obviously needed before any firm conclusions regarding PA and rehabilitation can be made. Toward this end, Rossetti and colleagues are currently carrying out a large-scale long-term rehabilitation study using PA in patients with neglect, which examines more directly the effects PA on activities of daily living (Y. Rossetti, personal communication, November 25, 2005). To reiterate, our current findings do not suggest that *covert attention* is rehabilitated in neglect but that prism adaptation may operate—however effectively—by altering the way in which covert attention is deployed.

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