Article

Driving With Hemianopia VI: Peripheral Prisms and Perceptual-Motor Training Improve Detection in a Driving Simulator

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Purpose: Drivers with homonymous hemianopia (HH) were previously found to have impaired detection of blind-side hazards, yet in many jurisdictions they may obtain a license. We evaluated whether oblique 57Δ peripheral prisms (p-prisms) and perceptual-motor training improved blind-side detection rates.

Methods: Patients with HH ($n = 11$) wore p-prisms for 2 weeks and then received perceptual-motor training (six visits) detecting and touching stimuli in the prism-expanded vision. In a driving simulator, patients drove and pressed the horn upon detection of pedestrians who ran toward the roadway (26 from each side): (1) without p-prisms at baseline; (2) with p-prisms after 2 weeks acclimation but before training; (3) with p-prisms after training; and (4) 3 months later.

Results: P-prisms improved blind-side detection from 42% to 56%, which further improved after training to 72% (all $P < 0.001$). Blind-side timely responses (adequate time to have stopped) improved from 31% without to 44% with p-prisms ($P < 0.001$) and further improved with training to 55% ($P = 0.02$). At the 3-month follow-up, improvements from training were maintained for detection (65%; $P = 0.02$) but not timely responses ($P = 0.725$). There was wide between-subject variability in baseline detection performance and response to p-prisms. There were no negative effects of p-prisms on vehicle control or seeing-side performance.

Conclusions: P-prisms improved detection with no negative effects, and training may provide additional benefit.

Translational Relevance: In jurisdictions where people with HH are legally driving, these data aid in clinical decision making by providing evidence that p-prisms improve performance without negative effects.

Introduction

Complete homonymous hemianopia (HH), the loss of one-half of the visual field on the same side in each eye from stroke or other neurologic pathology affecting the primary visual pathway, impairs detection of blind-side hazards.[1–4] Peripheral prisms[5] (p-prisms) are a promising treatment that expand the visual field on the side of the vision loss (blind side) up to 40° on standard perimetry.[6] Field expansion is achieved by optically inducing exotropia with high-power rigid (57Δ) (polymethyl methacrylate) Fresnel prisms, typically placed base-out over the eye on the side of the HH, but they may be fitted over either eye with the base toward the blind field. Rather than inducing optical exotropia over the entire field, peripheral prisms are limited to the peripheral (superior and inferior) lens (Fig. 1) to avoid central double vision. Because they span both sides of the pupil, p-prisms expand the visual field not only in the primary gaze position but also when gazing to the seeing side,[7] and to some extent when scanning to the blind side,[6] unlike other prism designs.[7] P-prisms have now been evaluated in four open-label clinical studies[5,8–10] and a randomized controlled clinical trial,[11] with positive results suggesting improved detection of blind-side obstacles when walking.

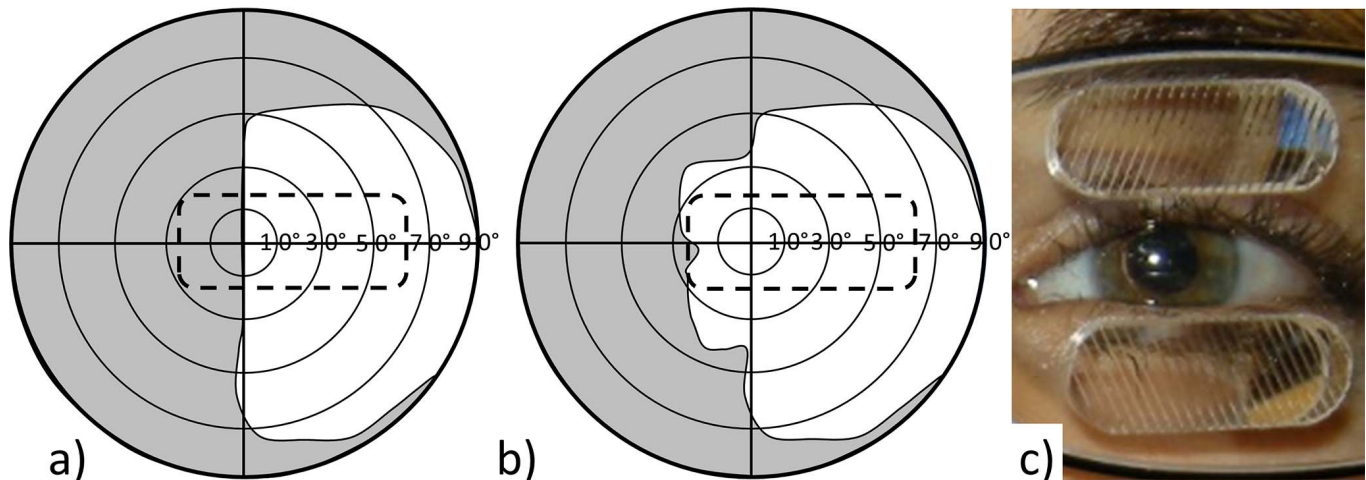The oblique p-prism design, in which the prism

Figure 1. (a) The binocular visual field of a patient with left HH as measured by Goldmann perimetry with V4e stimulus. The *dashed rounded rectangle* represents the field of view through a typical car windshield[12] when driving on the right side of the road. (b) The binocular field of the same patient wearing oblique 57Δ p-prisms (base-apex tilt ∼25°). (c) The oblique design in the permanent p-prism fitted unilaterally over the left eye as for the patient in 1b.

bases are oriented obliquely (out and down in the upper segment and out and up in the lower segment),[13,14] provides expansion of the paracentral field in areas falling within the region of the windshield (Fig. 1) and may, therefore, improve blind-side detection when driving. However, because p-prisms are usually fitted unilaterally, it is also possible that the prism image might be partially suppressed due to binocular rivalry or might not be salient enough to be useful for hazard detection when driving.[15–17] In a pilot on-road study,[18] patients with HH drove once with real (40Δ) and once with sham (5Δ) oblique p-prisms along busy city streets. Responses to potential hazards, scored by a masked rater, were better with the real than the sham prisms.[18] This prior study was important for demonstration of ecological validity; however, there was no control over when or where hazards appeared. Thus, a study where these factors were controlled was needed.

In this current study we addressed this gap in the literature by evaluating the effects of 57Δ oblique p-prisms on detection of pedestrian hazards in the controlled, repeatable environment of a driving simulator using a paradigm sensitive to detection deficits of HH patients.[2] Additionally, we examined the effects of computerized perceptual-motor training on pedestrian detection while driving. In the training, patients attempted to touch checkerboard stimuli appearing peripherally in the p-prism-expanded field (see Houston et al.[19] for details). Although this training was designed to adapt the patient to the

prism shift, not to enhance detection (a large suprathreshold stimulus was used), improvements in both localization and detection were found.[19] In this paper we present results from a cohort of 11 out of 13 patients who participated in the perceptual-motor training and who also completed an extended evaluation in our driving simulator. Specifically, we evaluated whether the prisms and training improved detection performance in the simulator.

The overall aim of this pilot study was to gather preliminary data on the efficacy of the oblique 57Δ p-prism glasses to improve blind-side detection as a basis for a future clinical trial. Our primary hypotheses were that blind-side detection performance with oblique 57Δ p-prisms would be better than detection performance without prisms (with only habitual scanning) and that further improvement would be measureable after perceptual-motor training. To determine whether improvements were maintained in the longer term, we also evaluated detection performance 3 months after training.

In addition, we tested a secondary hypothesis that greater improvements in detection performance would occur for pedestrian hazards approaching from a larger eccentricity than from a smaller eccentricity. When a hazard approaches on a collision course in real-world driving and other mobility situations, it stays at a constant visual angle.[20] Our simulator paradigm replicates this real-world phenomenon, having smaller (∼4°) and larger (∼14°) eccentricity pedestrian hazards moving toward the roadway on a collision course with the patient's vehicle. In prior

studies of HH patients without p-prism glasses using the same paradigm, detection rates on the affected side were more impaired for pedestrian hazards at larger eccentricities (~14°) than at smaller (~4°) eccentricities,[1,2] suggesting that patients were often not scanning sufficiently far into the affected hemifield. As these larger-eccentricity hazards are less likely to be detected by scanning but are well within the visual field expansion range of the p-prism glasses, we expected greater improvements in detection performance with the p-prisms at the larger eccentricity.

A third consideration in this study was the potential negative impact of p-prisms on driving. P-prisms cause portions of the visual field to be shifted toward the seeing side, which may cause problems with lane position and steering stability. For example, p-prisms for left HH (LHH) shift images from the blind left field rightward, which may cause patients to take a more rightward lane position or exhibit larger variability in their steering. The perceptual-motor training aimed to improve perceived direction of the prism-shifted images and might, therefore, counteract any negative p-prism-induced vehicle handling problems. The previous on-road pilot study reported no negative effects of the p-prisms on vehicle handling;[18] however, lane position and variability were based on observer ratings rather than quantitative positional data, which can be more easily recorded in a driving simulator. It is also possible that increased attentional demand is needed to monitor the prism vision or to compensate for p-prism-induced vehicle control issues, which could negatively impact detection performance on the seeing side. We therefore also evaluated seeing-side detection rates and reaction times.

Methods

The study used a within-subjects design where blind side detection performance with p-prisms and training was compared to performance without p-prisms (habitual scanning only). The primary funding mechanism allowed only an open-label design, specifically prohibiting a randomized controlled clinical trial. The study was conducted in accordance with the tenets of the Declaration of Helsinki. Informed consent was obtained from the participants after explanation of the nature and possible consequences of the study. The protocol was approved by the institutional review board at the Massachusetts Eye and Ear Infirmary and the U.S. Army Medical Research and Material Command Office of Research Protections, Human Research Protection Office.

Participants

Inclusion criteria were complete HH,[8] prior driving experience, >3 months since HH onset, no hemispatial neglect on Schenkenberg's line bisection test[21] or Bells test,[22] best-corrected visual acuity 20/40 or better in each eye, no strabismus (when wearing spectacles), ability to walk or self-ambulate wheelchair, no severe vertigo or vestibular dysfunction, no history of seizures in the prior 3 months, and willingness to wear p-prisms and attend numerous study visits. We excluded patients if they had never driven but did not exclude based on time since driving cessation with the rationale that many patients with HH interested in driver rehabilitation have not driven for many years. Those with greater than mild cognitive impairment were excluded, defined as Mini-Mental Status Examination (MMSE) score ≤20.

All patients enrolled in the pilot study of the perceptual-motor training (reported in Houston et al.[19]) were invited to participate in the driving simulator study. Fifteen were enrolled, 11 completed the study, and four withdrew: three due to simulator sickness and one citing difficulty attending multiple visits.

Prism Glasses and Training Methods

All participants received permanent 57Δ oblique p-prism glasses fitted using methods described in detail elsewhere.[11] They wore the p-prism glasses in their habitual environment for 2 weeks to acclimate to the glasses and then attended six 1-hour visits for perceptual-motor training. Self-reported wear times were recorded at each visit. To promote adaptation to the prism shift, training involved reaching and touching (on a wide touch-screen monitor, horizontal field of view 80°) peripheral suprathreshold checkerboard stimuli presented over videos of driving scenes while fixating a central target, progressing through five levels of increasing difficulty. In level 1, checkerboard stimuli were presented within the prism vision only, while patients were coached to slowly bring their prism-side hand into the prism view to touch the stimulus (no discrimination between the prism and regular view was required); level 2 presented stimuli to either side of the screen, requiring discrimination between the prism-shifted view and regular view; level 3 required increasing response

speed; level 4 increased the attentional load of the central task; and level 5 attempted to train perceptual adaptation by requiring a verbal response indicating the relative location of the stimuli to a central fixation point. For further details, see Houston et al.[19] Although the training was performed with fixed gaze, participants were instructed to move their eyes when using the p-prism glasses in everyday life and to look to the blind side through the prism-free portion of the lens to identify objects after detection through the prisms.

Driving Simulator Sessions

Patients completed four sessions in the driving simulator: one with no p-prisms (NP); one with p-prisms after 2 weeks acclimation but before training (PBT); and again with p-prisms immediately after the training (PAT) and 3 months after training (P3M). During the intervals between assessments, patients were advised to continue to the wear the p-prisms for mobility activities (they were not driving but may have used the p-prisms as passengers).

At each session (~3 hours long), patients performed five drives—three city (30 mph) and two rural highway (60 mph)—in a simulator (LE-1500; FAAC Corp., Ann Arbor, MI), as previously described.[1,2] In brief, the simulator had five flat 42-inch monitors with all except the center monitor oriented vertically, with native resolution of 1366 × 768 pixels (LG Electronics, Seoul, South Korea). They surrounded the driver's seat, providing a 225° horizontal field of view. The patients fully controlled vehicle steering and speed and were asked to press the horn upon detection of any pedestrians. There were other vehicles on the road as well as numerous intersections with traffic lights and yield and stop signs in city drives. Across the five drives, there were 52 pedestrians, 26 each from the right and left, at eccentricities of ~4° or ~14°, who walked or ran toward the roadway on a collision course, maintaining a constant visual angle with the vehicle (assuming a constant driving speed at the speed limit).[23]

The pedestrian at the smaller eccentricity represented a hazard approaching from the next lane on the left or the right sidewalk beside the participant's lane, while the larger eccentricity represented a hazard approaching at a faster speed from a greater distance. In city drives, pedestrians at the smaller ~4° eccentricity moved at 3 to 4 mph, while those at the larger ~14° eccentricity moved at 7 to 8 mph. On highways, pedestrians moved faster than in the city, at approximately 7 to 8 mph and 14 to 15 mph for ~4°

and ~14° eccentricities respectively, similar to running and cycling speeds. Pedestrians stopped before entering the participant's lane, so there was no collision unless the patients drove out of their lane, and thus patients were mostly unaware of detection failures. Participants were instructed to obey all the normal rules of the road and to try to maintain the posted speed limit. Data were recorded at 30 Hz, including the location and status of all programmed objects and the driver's car in the virtual world.

Prior to data collection, two practice drives each for the city and highway environments were conducted. The first lasted for ~10 minutes, with the goal of acclimation to vehicle control. The second was identical to a data collection drive and introduced the patient to the pedestrian-detection task. Comfort was monitored using a 10-point scale administered after each drive (from 1 = poor to 10 = great); data collection was halted if the self-rating was 6 out of 10 or less and resumed only once comfort returned to normal. Participants were also asked to rate their driving performance/safety on a 10-point scale (from 1 = unsafe to 10 = safest) at the end of each drive.

Methods to Evaluate Detection Performance

The response to each pedestrian event was classified as either timely, where detection occurred with sufficient time to brake and avoid a collision if the pedestrian had continued into the travel lane, or a potential collision, which included missed pedestrians and late detection responses where there would not have been sufficient time to avoid a collision. Time to collision was calculated for each event, taking into account the speed of the vehicle and distance to the potential collision point at the time of the horn press. A typical dry-pavement 5-m/s^2 braking deceleration rate[24] was used, assuming that braking started at the time of the horn press.

The primary outcome measures were detection rates (the proportion of all pedestrian events when the patient responded to the pedestrian by pressing the horn) and timely response rates (the proportion of all pedestrian events that were timely). Reaction times (from pedestrian appearance to the horn press) were also calculated as a secondary measure and are provided in Supplementary Materials.

Methods to Evaluate Vehicle Control

Lane position and steering stability were evaluated on straight road segments[25] without any events such as pedestrian hazards that could have affected

steering (e.g., when reaching to press the horn or steering to make an avoidance maneuver). Lane position was quantified in terms of the lateral offset between the center of the virtual vehicle and the center of the driving lane, with negative values representing leftward offsets and positive values representing rightward offsets.[25] For each straight segment (two per drive), the lateral offset was computed as the mean of all recorded offsets, and steering stability was quantified as the standard deviation (variability) of these offsets. Because simulator data were recorded at 30 Hz, a straight segment 200-m long driven at 30 mph (13.4 m/s) would have 447 samples from which the mean and standard deviations were computed.

Methods to Evaluate Masking of Participants

As detailed above, participants were largely unaware of their blind side detection failures because pedestrians stopped before entering the driving lane. We were therefore able to mask patients to their blind-side detection performance at each session. They were not given feedback about detection performance until the very end of the study. We evaluated the efficacy of the masking by comparing participants' self-ratings of driving performance/safety to their actual blind-side detection performance.

Statistical Methods

Within-subjects comparisons of detection performance and vehicle control were made at four assessment time points: NP (habitual scanning only), PBT, PAT, and P3M. For the primary analysis, mixed-effects logistic regression was used with either detection or timely response as the dependent variable and assessment (NP, PBT, PAT, P3M) as the main independent factor. In prior driving simulator studies of HH patients using this pedestrian-detection paradigm,[1,2] lower detection rates were correlated with older age and pedestrians appearing at the larger eccentricity; therefore, age and eccentricity (small/large) were included as covariates. Interaction terms between assessment and eccentricity were not included as sample size was limited. To address our secondary hypothesis, the analysis was repeated for small and large-eccentricity pedestrian appearances separately (including assessment as the main independent factor and age as the covariate). To evaluate the effects of prisms and training on lane position, mixed-effects multiple-linear regressions were performed with mean lateral lane offset and variability of lateral

lane offset as the dependent variables and assessment as the independent variable. For lateral lane offset, side of field loss was included as a covariate because prior driving simulator[25] and on-road[26] studies have found opposite lane offsets in drivers with right HH (RHH) and LHH. Correlations between objective measures of detection performance and subjective ratings of driving safety were evaluated using Spearman's ρ.

Complete data were available for 9 of the 11 subjects; the remaining two each missed one visit (S2 missed visit 2, and S9 missed visit 4). All statistical analyses were performed with statistical software (Stata/IC 14; StataCorp, College Station, TX); $P \leq 0.05$ was taken to indicate statistical significance.

Results

Sample Characteristics

Characteristics of each of the 11 participants are detailed in the Table. They were predominately male (91%) with a wide age range (18– 86 years, median 49) and relatively long-standing HH (1–20 years, median 6). About half had LHH. Two participants (S2 and S6) were currently driving despite not meeting state minimum visual field requirements, but reported cessation at our recommendation. For those not driving, the median time since they last drove was 2 years (interquartile range [IQR] 1–9). Driving was the primary vision rehabilitation goal for 9 out of the 11 patients. Median p-prism wear times (hours per day) were 3 during acclimation before training, 2.5 at the end of training, and 1.5 at the 3-month visit (three patients had discontinued p-prism use by 3 months, one patient moved and could not be contacted). The long-term continuation rate (70%) was better than that in the prior randomized controlled clinical trial of the p-prism glasses (41%).[11]

Individual Differences in Blind-Side Detection Performance

As illustrated in Figure 2, there was wide between-subject variability in blind-side detection rates and timely response rates, both without and with p-prism glasses. For example, detection rates ranged from 15% to 81% with NP and from 27% to 96% with PAT, while timely response rates ranged from 11% to 73% with NP and 23% to 92% with PAT.

There was also wide between-subject variability in the amount of improvement with p-prisms and

Table. Patient Characteristics

Patient Number	Age	HH	Gender	Lesion[a]	Duration, y	Cause	MMSE[b]	Continued p-prisms at 3 mo	Last Drove, y
S1	32	Right	M	Left fronto-temporal	6	Aneurysm	23	Yes	2
S2	18	Left	M	occipital/PCA	1	Aneurysm	x[c]	Yes	0
S3	86	Right	F	Left occipital and temporal	6	Ischemic	26	No	2
S4	49	Right	M	Left parietal, occipital, temporal	16	Infectious	21	Yes	10
S5	67	Right	M	Left PCA	4	Ischemic	24	Yes	1
S6	74	Left	M	Right temporal and occipital	5	Ischemic	30	No	0
S7	49	Left	M	Right anterior temporal	20	Lobectomy	29	Yes	29
S8	50	Left	M	Right occipital, left thalamic	18	Ischemic	25	No	9
S9	24	Left	M	Right parieto-occipital	5	Aneurysm	27	x[c]	2
S10	40	Left	M	Left temporal, parietal ICH	6	Aneurysm	27	Yes	1
S11	81	Right	M	Left PCA	3	Ischemic	24	Yes	0.5
Median	49				6		26		2

PCA, posterior cerebral artery distribution; ICH, intracerebral hemorrhage.
[a] Lesion location obtained from review of radiology notes.
[b] MMSE score is out of 30.
[c] x indicates missing data.

training. As illustrated in Figure 2, six patients seemed to show improvement with prisms and training, two patients had relatively good performance even with NP and thus had little room for improvement, and three patients had no clear improvement with p-prisms or training.

Blind-Side Detection Rate

Blind side detection rate without p-prisms (NP) was 42%, improved significantly with p-prisms to 56% even before training (PBT) ($P < 0.001$), and further improved after training (PAT) to 72% ($P < 0.001$; Fig. 3 top left). At the 3 month follow-up (P3M), the effect of p-prisms and training was maintained 65% (169/260); detection was not significantly worse than PAT ($P = 0.12$) and was still significantly better than PBT ($P = 0.02$). As expected, increasing age was associated with lower detection rates ($P < 0.001$). There was no effect of side of HH ($P = 0.992$) or duration of HH ($P = 0.790$).

Consistent with our secondary hypothesis concerning pedestrian eccentricity, blind-side detection rates were significantly lower for large-eccentricity than for small-eccentricity pedestrians (overall 47% vs. 71%, $P < 0.001$). At the large eccentricity, there was an improvement with p-prisms even before training (NP versus PBT, $P < 0.001$) but not at the small eccentricity ($P = 0.20$, Fig. 3 top right). Training
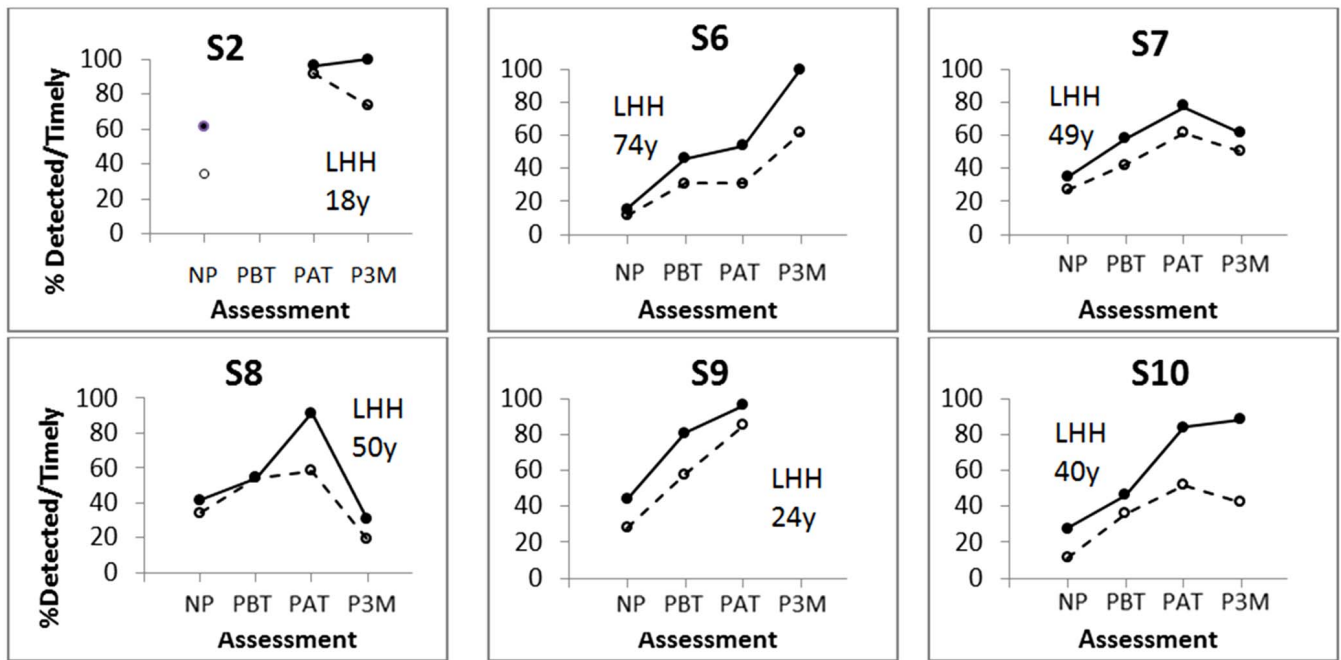
further improved detection at both the large and small eccentricities (PBT versus PAT, $P = 0.012$ and $P = 0.004$, respectively). Improvements from training were maintained at 3 months for small ($P = 0.05$) but not large ($P = 0.207$) eccentricities.
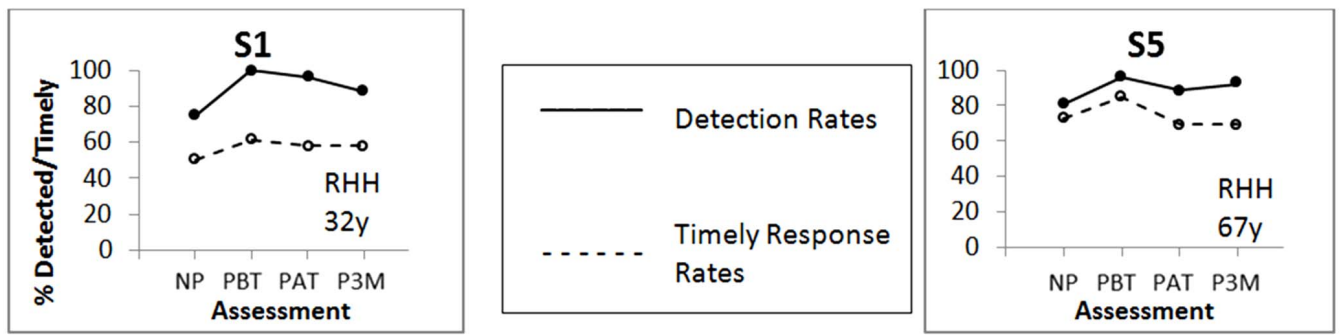
Blind-Side Timely Response Rate

Blind-side timely response rate without p-prisms was only 31%, improved significantly with p-prisms to 44% (NP versus PBT $P < 0.001$), and further improved with training to 55% (PBT versus PAT, $P < 0.02$; Fig. 3). At the 3-month follow-up, the additional effect of training on timely response rate was lost, dropping to 43%, significantly worse than post training (P3M versus PAT, $P = 0.006$) but not significantly different from pretraining (P3M versus PBT, $P = 0.726$). Three-month timely response rates were still significantly better than baseline without p-prisms (P3M versus NP, $P = 0.001$). As expected, timely response rates decreased significantly with increasing age ($P < 0.001$). There was no effect of side of HH ($P = 0.758$) or duration of HH ($P = 0.974$).

Similar to detection rate results and consistent with our secondary hypotheses concerning pedestrian eccentricities, blind-side timely response rate was significantly lower at large than at small eccentricities (overall 31% vs. 55%, $P < 0.001$). At the large eccentricity, p-prisms improved timely response rate
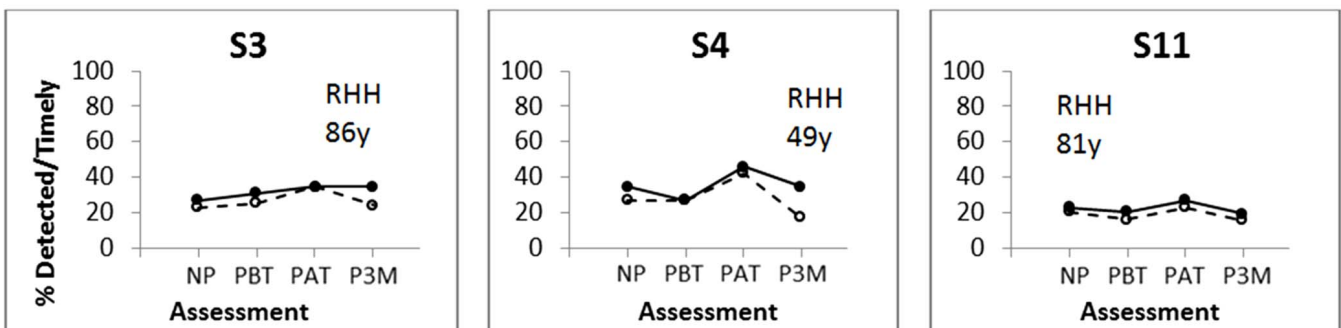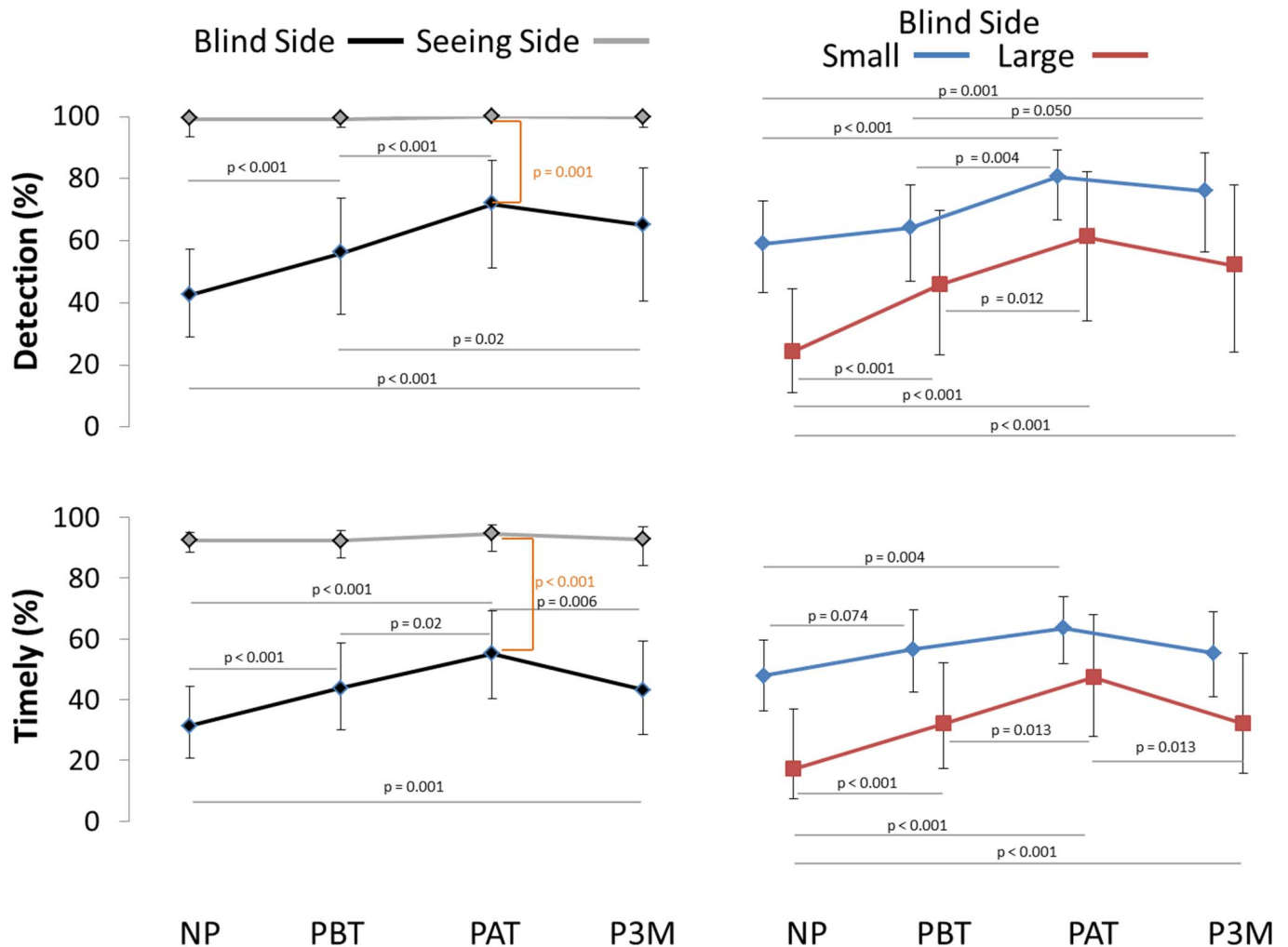
Figure 2. Individual patient plots for blind-side detection rates (*solid black line* and *data points*) and timely response rates (*dashed*, *open data points*) by assessment, grouped by the extent to which performance improved with p-prisms and training. Assessments: NP, no p-prisms; PBT, with p-prisms before training; PAT, with p-prisms after training; and P3M, with p-prisms 3 months after training. Patient S2 missed the PBT assessment. Patient S9 missed the P3M assessment.

Figure 3. Pedestrian-detection (*upper plots*) and timely response rates (*lower plots*) (mean and 95% confidence intervals [CIs]) by assessment for the group of 11 patients. Plots on the *left* show data for the blind side (*black line*) and the seeing side (*gray line*) collapsed across small and large eccentricities. Plots to the *right* show data for the blind side only for small (*blue line*) and large (*red line*) eccentricities. Significant differences are indicated with connector and corresponding *P*-value. Comparisons without a connector or *P*-value were not significant.

even before training (NP vs. PBT, $P < 0.001$), while the effect at the small eccentricity before training was only marginal (NP vs. PBT, $P = 0.074$; Fig. 3). There was no additional effect of training at the small eccentricity (PBT vs. PAT, $P = 0.306$), but there was an improvement at the small eccentricity from the combined effect of p-prisms and training (NP vs. PAT, $P = 0.004$). However, timely response rate at the 3-month visit was not significantly different from baseline without p-prisms ($P = 0.166$). On the other hand, at the large eccentricity there was an additional

improvement with training (PBT vs. PAT, $P = 0.013$), which was lost at 3 months (PAT vs. P3M, $P = 0.013$; PBT vs. P3M, $P = 0.987$); however, timely response rate at the large eccentricity at 3 months was still better than at baseline without p-prisms (NP vs. P3M, $P < 0.001$).

Seeing-Side Detection Performance

In contrast to blind-side detection performance, there was no significant effect of assessment on
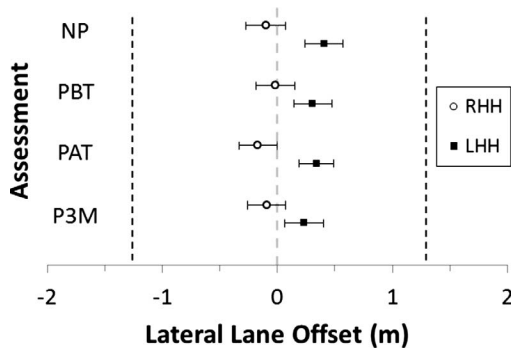
Figure 4. Lateral lane offset (mean and 95% CIs) by assessment for patients with RHH and LHH. There were no significant differences in lateral lane offset between assessments so the p-prisms did not have detrimental effects on vehicle control. With or without p-prisms, LHH patients had a small rightward mean lane offset (33 cm), whereas RHH patients had a small leftward mean offset (10 cm). The *dashed black lines* represent the lane offset at which the vehicle tires would first be out of lane whereas the extent of the x-axis is the lane width (4.0 m). With the small mean offsets, the vehicle was nowhere near the lane boundaries.

seeing-side performance (Fig. 3). Over all four sessions, there were only five detection failures out of 1077 total pedestrian appearances on the seeing side (99.9% detection rate), and timely response rates were 93%. There were no significant changes in timely response rates over the four assessments ($P = 0.514$).

Although blind-side performance with p-prisms was best at the posttraining assessment, it was still significantly worse than seeing-side performance. This was true for both detection rate ($P = 0.005$) and timely response rate ($P < 0.001$).

Masking to Performance

Patients were masked by withholding results of their detection performance until the end of the study in order to limit any potential effects of learning across assessments. Masking was evaluated by comparing subjective self-rated performance to objective actual performance. In general, most patients highly rated their driving safety (median safety rating 8.4, IQR 7.6–9), which was not correlated with the actual proportion of blind-side detection failures, suggesting effective masking (Spearman's $\rho = 0.13$, $P = 0.43$, for data pooled across the four assessments). Lack of subjective-objective correlation suggests that despite priming via the seeing side (there were the same number of pedestrians on blind and seeing sides), patients did not recognize that seemingly fewer appearances on their blind side represented detection failures.

Lane Position and Steering Stability

There was no effect of assessment on either the mean lateral lane offset ($P = 0.340$) or the variability of the lateral lane offset ($P = 0.461$), suggesting that neither the p-prisms nor the training had any effects on steering. However, as reported previously,[25] LHH was associated with a more rightward average lane position compared to RHH ($P < 0.001$, Fig. 4). The average offset of LHH patients was 33 cm to the right of the lane center compared to the RHH patients with an average offset of 10 cm to the left of the lane center.

Discussion

The primary findings of this study were that the oblique p-prisms improved detection and timely response rates on the blind side in patients with complete HH and that our perceptual-motor training protocol further enhanced detection performance. There were no negative effects of p-prisms on vehicle handling or seeing-side detection, consistent with the prior on-road study.[18]

When driving without p-prisms, patients were presumably attempting to employ compensatory scanning, yet the majority of participants demonstrated substantial blind-side performance deficits. Mean blind-side detection rate was only 42% (ranging from 15% to 81%), while blind-side timely response rate was only 31% (ranging from 11% to 73%). The p-prisms significantly improved both detection rates and timely response rates after only a 2-week period of using the prism glasses; this improvement occurred without any training other than usual clinical instruction in the use of the p-prisms. Furthermore, the improvement was maintained at the 3-month follow-up. These results are consistent with the reports of improved responses to potential hazards with real p-prisms in the prior on-road study[18] where no perceptual-motor training was provided.

Perceptual-motor training for the p-prisms further improved detection and timely response performance when driving despite the fact that it was not specifically designed to do so (the main goal of training was to improve perceived direction of prism-shifted images).[19] This is consistent with improvements in detection for the stimuli on the training task itself.[19] Enhanced detection from perceptual-motor training may be due to better awareness or understanding of the prism vision or better positioning of the head to decrease the vertical retinal eccentricity of

the prism image (patients were coached on this during training). Improvements in the training effect might be possible by specifically training detection, perhaps by reducing training stimulus contrast or size. For the goal of driving, training in the driving simulator or using a desktop version of the pedestrian-detection paradigm could be considered.

The improvement in detection rates and timely response rates with p-prisms found at the pretraining assessment was sustained at the 3-month follow-up, but the additional beneficial effect of the perceptual-motor training on detection rates (measured at the posttraining assessment) had faded by 3 months. The reason for loss of training effect at 3 months could be related to the fact that patients were not permitted to drive in the 3 months after training (people with HH do not meet the visual field extent requirements for driving in Massachusetts). Perhaps they would not have lost the training effect had they been driving with the p-prisms. A multicenter trial that includes study sites in jurisdictions where HH patients are allowed to drive could help answer this question. If training effects still dissipate, maintenance training may be a solution.

As hypothesized, the effect of p-prisms was greater for pedestrians at the larger (~14°) eccentricity (Fig. 3). Detection of the pedestrians at the smaller (~4°) eccentricity would have required only a small magnitude scan to the blind side (about 4°), which may explain why there was less measurable effect (approached but did not reach statistical significance). By comparison, the larger-eccentricity pedestrians were less likely to be detected by habitual scanning (needed about a 14° scan) but were within the field expansion area of the prisms, and thus detection rates improved to a greater extent. This was an important finding because the large-eccentricity pedestrians represent a visual situation identical to that when a higher-speed hazard (e.g., bicyclist) is approaching the driver on a collision course.

Consistent with a number of prior studies,[1–4] we found a wide range in blind-side detection performance at baseline without p-prisms. In this study we also found a wide range in the extent to which detection improved with the p-prisms (see the individual data plots for each patient in Fig. 2). Two patients had relatively good blind-side detection performance without prisms (>75% detection rates) and did not show much improvement with prisms, while six showed improvement and three showed no improvement. The study was not designed to examine which factors might predict blind-side detection performance or aid in selection of optimal candidates for p-prisms.

However, in agreement with prior studies,[1–3] older patients had lower detection rates and lower timely response rates than did younger patients. Five of the six who showed improvement with p-prisms were in the younger 18- to 50-year age range, while two of the three who showed no improvement were >80 years of age. Of interest, all patients who showed improvement had LHH, while all patients who showed no improvement had RHH, but the sample size was too limited to draw conclusions about the effect of side of field loss on outcomes. Our sample was primarily male, which is not expected to be a factor in response to p-prisms or training and should not limit generalizability of the study findings.

Whether or not the prisms were still being used at 3 months might have accounted for individual differences in the maintenance of the training effect at 3 months; however, there were no clear trends in the data to suggest that was the case. Performance of one of the dropouts was much lower at 3 months (S8), but the other was much better (S6). S3 showed poor performance at all visits.

Our study was, to our knowledge, the first to measure the effects of field-expanding prisms and the additional effect of training on blind-side detection during driving. The results of our study are specific to the 57Δ oblique p-prism design and should not be generalized to other hemianopic prism designs. A prior study by Szlyk et al.[27] applied a different field-expanding prism design (18.5Δ, i.e., 10° monocular round sector prism) with extensive training using a variety of procedures. Unlike our study, the independent effects of the training were not measured, there were no comparisons of performance on the blind versus the seeing side, and the effects on detection when driving were not measured. The Szlyk et al.[27] results suggest that performance was actually worse with the round sector prism and training than without (see Supplementary Materials for our rationale behind this interpretation). Decreased performance might have been predicted considering the central double vision caused by looking into the round sector prism. This problem is avoided in the p-prism design by having a prism-free central portion (Fig. 1c).

Public safety is a major concern when granting even limited licensure to visually impaired patients. In states where patients with hemianopia meet the visual standards and are already driving, our results are promising, suggesting p-prisms improve performance for some patients without negative effects. Whether or

not the improvement from p-prisms reduces risk to an acceptable level is a policy decision for governing bodies.

Another safety concern might be any adverse effects of the image shift from the p-prisms on lane position and vehicle handling; however, no additional lane offset resulted from p-prism use, and there was no increase in lane position variability. Similar to the prior driving simulator study by Bowers et al.,[25] patients in the present study with LHH assumed a slightly more rightward lane position (about 33 cm, even without p-prisms) compared to patients with RHH (10 cm), but this offset was not related to or changed by the p-prisms or training. This can be interpreted to mean there was no negative effect of p-prisms on vehicle handling, and thus training adaptation to the shift does not appear to be necessary for driving. Possible reasons why HH patients shift slightly away from the blind side even without p-prisms (relative to the normally sighted who maintain a central position on straight road segments[25]) have been proposed previously.[28] Theories include a compensatory behavior to position away from the unseen area, particularly in the presence of oncoming traffic (safety margin hypothesis)[25] or as a result of a spatial misperception.[29] The leftward shift of participants with RHH (even without p-prisms) might be considered a safety concern when driving on the right as it would put them in danger of crossing the lane boundary into the path of oncoming traffic. However, those participants should see oncoming traffic on that side, and the shift was relatively small (10 cm to the left of lane center on average) and did not bring them anywhere near the edge of the lane. In the driving simulator, the tires would first cross the lane boundary when the center of the vehicle was offset by 130 cm from lane center (see Fig. 4).

The smaller sample size of this study may limit generalizability but included a wide range of ages and balanced representation of RHH and LHH. Sample size was not an issue in terms of statistical power. There were numerous presentations of pedestrian hazards at each assessment, and we were able to measure statistically significant effects of both the prisms and the training. It could be questioned whether improved detection was simply due to repetition of the driving simulator pedestrian-detection task (an order or learning effect), rather than effects of the prisms and training. However, in a prior study, participants with HH driving without p-prisms showed no significant improvements in blind-side pedestrian-detection rates or response times between two driving simulator sessions, 1 week apart.[1] In the current study, the minimum time between driving simulator visits was 2 weeks; therefore, it seems reasonable that the effects we measured represent treatment effects rather than learning or order effects. The lack of correlation between patients' subjective safety rating data and their detection rates provides additional support to this conclusion, suggesting patients were effectively masked to their actual performance and so had no stimulus to learn to improve. It is interesting that despite priming via the seeing side (there were the same number of pedestrians on blind and seeing sides), patients did not recognize they experienced fewer pedestrians on their blind side, representing the detection failures. Inability to properly self-assess in HH represents a public safety issue.

Since the simulator sessions were 3 hours in duration, fatigue may have affected performance in the later portions of each session; however, this effect would be expected in each of the sessions and therefore would not influence the between-session comparisons. Long driving times and resulting fatigue could be seen as adding real-world validity to the data.

In conclusion, this study further confirms that detection of blind-side hazards is impaired in HH patients with the goal of return to driving and lends support to the hypothesis that p-prisms improve blind-side detection of roadside hazards, thereby improving the safety of drivers with HH. Perceptual-motor training appears to further improve detection and timely responses, but maintenance training may be required to retain the benefits. It is also important to emphasize that while p-prisms appear to have improved performance, there continued to be impairment on the blind side relative to the seeing side. Furthermore, there was wide between-subject variability in performance both without and with p-prisms, supporting the need for individualized assessment. Still, p-prisms appear to improve safety by reducing the risk of untimely detections, and although use of p-prisms for driving cannot be endorsed as a complete resolution of impairment, the results of this pilot study are very encouraging and justify the next step—a randomized, sham-controlled trial with a larger sample size, possibly with specific training to increase detection.

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Supplement

Report of Reaction Times

Statistical Analysis

A log transform was performed to normalize a right-skewed distribution of the reaction time data. A mixed-effects multiple linear regression model was then conducted with log reaction time as the dependent variable, assessment as the main independent factor, and age and eccentricity (small/large) included as covariates (as in the analysis of detection rates). For simplicity, results are reported using reaction times rather than log reaction times.

Results

Overall blind side mean reaction time without p-prisms was 2.8 s, which improved (decreased) with p-prisms to 2.5 s ($p = 0.001$; Figure S1, left panel). There was no additional effect of training on reaction times with a mean of 2.5 s at the post-training assessment ($p = 0.21$); however, the reaction times were still faster than at baseline ($p = 0.003$). Mean reaction time at 3 months was 2.7 s and was no longer faster than at baseline ($p = 0.207$), and was slower than pre-training ($p = 0.034$). Reaction times were significantly faster for pedestrians appearing at small than large eccentricities (overall, 2.4 s versus 2.9 s; $p < 0.0001$), but unlike detection rates, there was no effect of age on reaction times ($p = 0.293$).

Prisms improved reaction times at the large eccentricity even before training ($p = 0.008$), while the effect at the small eccentricity was only marginal ($p = 0.058$, Figure S1, right panel). For the large eccentricity, there was no additional effect of training on reaction times ($p = 0.269$), but at 3 months reaction times were still faster than at baseline ($p = 0.043$). For the small eccentricity, there was no effect of training. Reaction times at both the post-training and 3-month visits did not differ from baseline ($p = 0.378$ and $p = 0.998$, respectively).

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For the seeing side, over all 4 sessions mean reaction time was 1.2 s. There was a small, but statistically significant, improvement in seeing side reaction times over the 4 assessments, with faster reaction times post-training (1.3 s) and at three months (1.3 s) than at the first assessment (1.5 s, p = 0.015). Although blind side reaction time with prisms was best at the post-training assessment, it was still significantly worse than seeing-side performance (p < 0.0001).
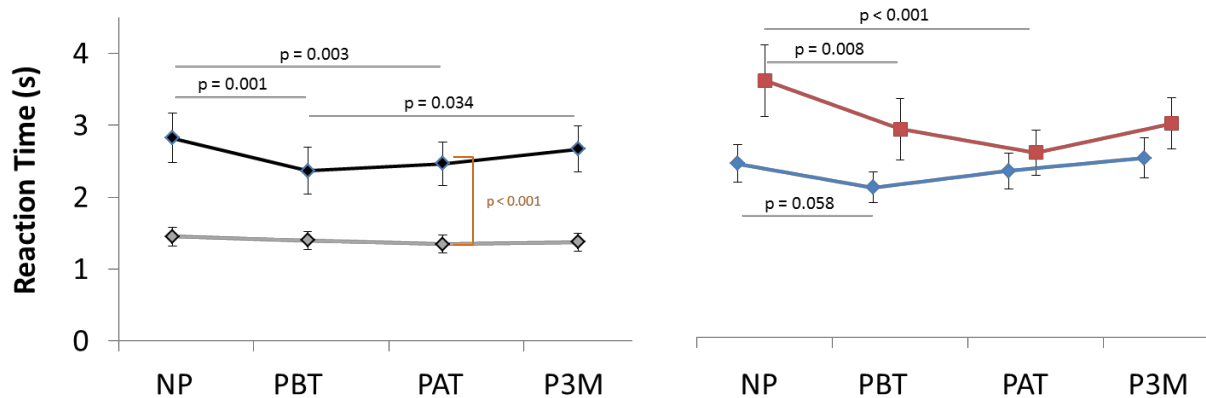

Figure S1: Reaction times (mean and 95% CIs) by assessment for the group of 11 patients. Plot on the left shows data for the blind side (black line) and the seeing side (grey line) collapsed across small and large eccentricities. Plot to the right shows data for the blind side only for small (blue line) and large (red line) eccentricities.   Significant differences are indicated with connector and corresponding p-value. Comparisons without a connector or p-value were not-significant. NP = No p-prisms, PBT = with p-prisms before training, PAT = with p-prisms after training, P3M = with p-prisms 3 months after training.

Additional discussion

Statistical rationale for our interpretation of results of Szlyk et. al 2005[1]:

No statistical analyses were reported in the 2005 manuscript by Szlyk et. al, but percentages of improved tasks were provided. Improvement was defined as an increase in assessment score

with prisms greater than the mean of the difference between two baseline assessments without prisms. The 95% CI of the mean change score would have been a more traditional threshold for improvement because it accounts for the spread/variability of the data/measurements.[2] Using the mean change score criterion, no change in performance would be predicted to yield 50% of tasks (with prism) above and 50% below the mean of the baseline assessments, yet there were only 13-36% of tasks above the threshold (as shown in their Figure 1[1]), suggesting that the round sector prism and the training procedure may have actually worsened performance.

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