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Article

A Pilot Study of Perceptual-Motor Training for Peripheral Prisms

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Purpose: Peripheral prisms (p-prisms) shift peripheral portions of the visual field of one eye, providing visual field expansion for patients with hemianopia. However, patients rarely show adaption to the shift, incorrectly localizing objects viewed within the p-prisms. A pilot evaluation of a novel computerized perceptual-motor training program aiming to promote p-prism adaption was conducted.

Methods: Thirteen patients with hemianopia fitted with 57Δ oblique p-prisms completed the training protocol. They attended six 1-hour visits reaching and touching peripheral checkerboard stimuli presented over videos of driving scenes while fixating a central target. Performance was measured at each visit and after 3 months.

Results: There was a significant reduction in touch error ($P = 0.01$) for p-prism zone stimuli from pretraining median of 16.6° (IQR 12.1°–19.6°) to 2.7° (IQR 1.0°–8.5°) at the end of training. P-prism zone reaction times did not change significantly with training ($P > 0.05$). P-prism zone detection improved significantly ($P = 0.01$) from a pretraining median 70% (IQR 50%–88%) to 95% at the end of training (IQR 73%–98%). Three months after training improvements had regressed but performance was still better than pretraining.

Conclusions: Improved pointing accuracy for stimuli detected in prism-expanded vision of patients with hemianopia wearing 57Δ oblique p-prisms is possible and training appears to further improve detection.

Translational Relevance: This is the first use of this novel software to train adaptation of visual direction in patients with hemianopia wearing peripheral prisms.

Introduction

Peripheral prism glasses (p-prisms; also known as EP-glasses or the Peli Lens) provide up to 40° of visual field expansion for patients with homonymous hemianopia (HH), measurable with standard perimetry (Fig. 1).[1–4] The unilateral fitting allows the prism eye to have areas of the seeing hemifield substituted with the prism-shifted views while the fellow eye continues to see the portions of the field obscured by the prisms due to the optical apical scotomas,[5] resulting in true field expansion under binocular viewing conditions. P-prisms have now been evaluated in four open-label clinical studies,[1,6–8] a randomized controlled clinical trial,[9] and a pilot on-road study[10] with positive results suggesting improved detection of blind side obstacles when walking and driving.

Although p-prisms improve detection, objects on the blind side are optically shifted onto the seeing side (Fig. 2a). When asked to point at objects seen through the prisms, patients almost always point toward the prism image making a pointing error equivalent to the prism power.[6] In real-world mobility this may result in difficulty interpreting the expanded vision, unnecessary avoidance maneuvers, and perhaps rejection of the device despite improved detection. It was expected that after a month or two of wear, patients would, at minimum, show motor-proprioceptive adaptation (exhibit quick and accurate pointing at objects seen via the p-prisms), and perhaps report visual-percep-
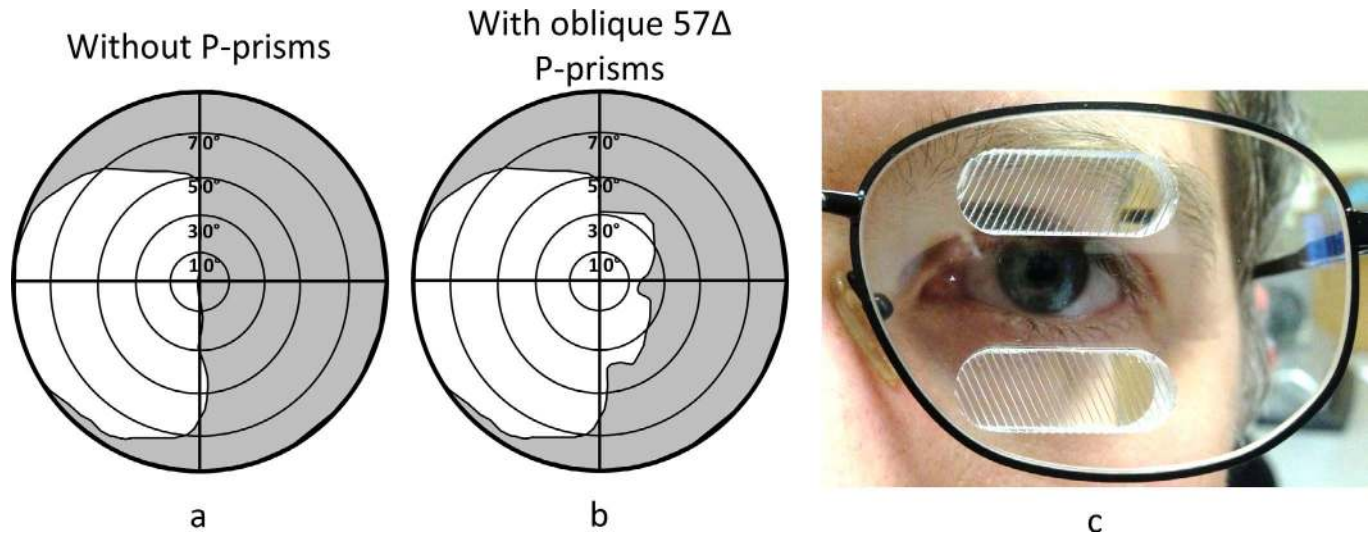
Figure 1. (a) The binocular visual field of a patient with left HH as measured by Goldmann perimetry with V4e stimulus. (b) The binocular field of the same patient wearing oblique 57Δ p-prisms. (c) The oblique design in the permanent p-prism fitted unilaterally over the left eye as for the patient in 1b.

tual adaptation (i.e., report seeing objects in their correct direction),[6] as had been reported decades earlier for optically similar split-field prisms.[11,12] However, patients wearing p-prisms in an extended-wear trial failed to show accurate pointing.[6]

Adaptation should result in faster more appropriate responses to hazards and more comfortable vision. We therefore developed and evaluated a computerized perceptual-motor training regimen and testing paradigms that aimed to promote adaptation. The training involved repetitive reaching for stimuli seen through the p-prisms, similar to traditional prism adaptation paradigms (see Kornheiser[13] for a review), and was based on prior research showing that adaptation to prisms was faster and more complete when combined with a reaching task.[14,15] The overall aims of the study were to (1) develop a perceptual motor training protocol that was feasible for patients with HH, and (2) gather preliminary data in a pilot study on the efficacy of the training to improve localization as a basis for a future clinical trial. We hypothesized that the majority of patients would be able to complete the training protocol and show significant improvements in touch accuracy.

Methods

This pilot study was designed to develop the training regimen and gather preliminary data. It was not intended to be a clinical trial evaluating the efficacy of the training. Hence, patients were not randomized to training or placebo (all patients received the training), sham prism glasses were not used, and there was no masking of the experimenter or patient. This design was mandated by the primary funding agency.

Participants

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 (USAMRMC), Human Research Protection Office (HRPO).

Participants were recruited from ophthalmology, optometry, and physical medicine practices within the Greater Boston area and from a database search at Massachusetts Eye and Ear Infirmary for patients with a diagnosis of homonymous field defect. Inclusion criteria were: complete HH defined ≤ 5° of residual vision on the hemianopic side of the vertical meridian within 20° above and below fixation measured with a Goldmann V4e[6]; at least 14 years of age; greater than 3 months since HH vision loss, Mini-Mental Status Examination (MMSE) greater than or equal to 24[16]; no hemispatial neglect on Schenkenberg Line Bisection Test[17] and Bells test[18]; best corrected visual acuity 20/50 or better in each eye; no strabismus; ability to walk or self-ambulate

Figure 2. (a) Point of view of a driver with normal vision entering a driveway with a hazard approaching from the left (pedestrian in a red jacket). The *cross* signifies the point of fixation. (b) Illustration of the same view as seen by a driver with left HH. In complete left HH, anything left of the point of fixation (*cross*), which includes the pedestrian, would not be seen. The HH field is shaded here for illustration purposes only; patients with dense HH do not describe seeing a black or shaded area in their vision. (c) Illustration of the left HH driver's view when wearing oblique 57Δ p-prisms fitted conventionally for left HH (unilaterally on the left lens). The areas within the *solid white lines* represent the physical locations of the prism segments. The *dashed lines* outline the areas that are imaged by the oblique p-prisms. The portion of the blind left field containing the pedestrian is visible only to the left (p-prism) eye. The right eye has no p-prisms and so sees the regular view (pedestrian not visible to right eye). This results in binocular confusion in the area of the p-prism image (illustrated as transparency), but no binocular scotomas due to the prisms, and no diplopia. The pedestrian is visible partially in both segments and may be detected, but his location is expected to be misinterpreted as being to the right of its veridical position. If the patient is asked to point at the pedestrian without looking over, they should point 20° to 25° to the right (and perhaps either up or down). (d) Illustration of the presumed result of perceptual adaptation to p-prisms: the pedestrian is perceived in the veridical position/direction left of the fixation (*cross*). The slight contrast reduction in (d) in the prism vision left of fixation depicts the light scattering effect of the Fresnel prisms.

Table 1. Patient Characteristics (*n* = 13)

	Median	IQR
Age, y	50	49–74
Male, *n* (%)	10 (77)	NA
Left HH, *n* (%)	8 (62)	NA
Time since vision loss, y	6	5–7
MMSE score (max 30)	27	24–29

wheelchair; no severe vertigo or vestibular dysfunction; and no history of seizures in the prior 3 months.

A total of 16 patients were enrolled (July 2011 to November 2013) of which three withdrew before the start of training citing declining health (*n* = 1) and too many visits (*n* = 2). Characteristics of those who completed training (*n* = 13) are given in Table 1. Etiologies of visual loss included stroke (*n* = 7), aneurysm (*n* = 3), anterior temporal lobectomy (*n* = 2), a cerebral infection (*n* = 1). The patients reported moderate difficulty with mobility and detecting objects to the affected side when walking (overall self-perceived difficulty with mobility ranged from a little to extreme on a 5-point scale). None had previously used p-prism glasses.

Prism Glasses and Acclimation

All participants received permanent 57Δ oblique p-prisms glasses fitted using methods described in detail elsewhere.[9] After the glasses were dispensed patients were given usual clinical instructions in how to use the p-prisms[9] including: reaching to touch the examiner's finger within the prism vision, advice to look between the prisms to avoid central diplopia, a demonstration of central diplopia when looking into the p-prisms and how to adjust the head to alleviate this, and a guided walk that included proper head positioning on stairs. To acclimate to the p-prisms, patients wore them in their typical environment for 2 weeks prior to the start of the in-lab training sessions. The median reported daily wear time during this period was 3 hours (interquartile range (IQR), 2.8–4.8).

Training Set-Up

The training station was composed of a 70 × 40 cm Surface Acoustic Wave LCD monitor touch screen (NEC, Tokyo, Japan), computer with Windows operating system (Microsoft, Redmond, WA) fixation monitoring camera, operator monitor, chinrest/head-rest assembly, and adjustable height table and chair (Fig. 3). During the training patients fixated a cross at
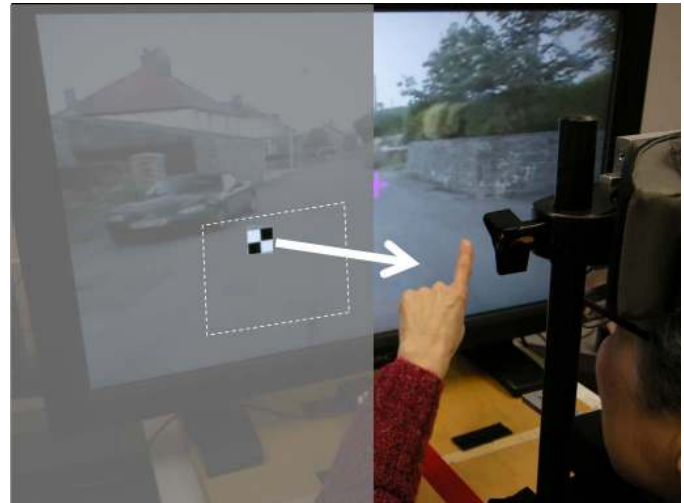

Figure 3. Participant training station showing a person with left HH performing a pretraining trial. The checkerboard stimulus was presented over a video scene in the blind left hemifield (illustrated by *shading*) within an oblique prism (*lower segment*) expansion area (outlined by the *dashed rectangle*). The prism image of the checkerboard is optically shifted toward the seeing hemifield by the p-prisms so that it appears to the patient as though on the right side of the screen, at the lower position pointed to by the *arrow head* (note: patient's hand is shown in midreach, eventually ending at the position of the *tip of the arrowhead*). The prism image results in an incorrect patient response (touching of the apparent position). The participant is unaware of their error since the view of their finger (seen by the nonprism eye) is in the same direction as the prism image of the target. Even once they reach the screen and have visual feedback of their finger and the target, they are still unaware of their error because the smooth touch screen provides no tactile feedback. They continue to believe they are touching the correct location unless auditory feedback is given.

the center of the screen while targets were briefly presented in peripheral vision. The touch screen and software measured time from target onset to first touch and touch position (x, y). The patient's head was held at a comfortable distance for reaching out to touch the screen, usually approximately 45 cm from the screen (but closer or farther away, as needed). The actual eye-to-screen distance was entered into the software, which calculated and adjusted visual angles. Targets (peripheral stimuli that the patient should touch) were 30-mm square checkerboards (3.82°, 0.26 cpd, ~20/900), equivalent to the height of a 6-foot pedestrian 90 feet away, presented from 5 to 0.2 seconds, depending on the training level. Screen backgrounds were most often videos taken from the point of view of a car driver (extracted from driver training videos from the UK Hazard Perception Test[19] (Driving Test Success Hazard Perception: Imagitech Ltd., Swansea, UK) and reversed horizon-

Table 2. Perceptual-Motor Training Levels (see supplementary materials for details)

Level	Description	Goal	Pass Criteria
1	Targets on prism side only	Adapt the prism side arm to the displacement (slow reaches)	$\leq 4°$ touch error
2	Targets on prism and seeing sides, long durations	Learn to discriminate prism and seeing side targets	Maintain $\leq 4°$ touch error
3	Improve reaction time by reducing stimulus duration	Eliminate strategies (arm sweeping) and increase speed	Maintain $\leq 4°$ error and reduce prism zone response time to $\leq 2\times$ seeing side
4	4.1 Stop-go task 4.2 Movie watching 4.3 Hazard detection	Maintain performance under increasing attentional demand and improve detection in natural scenes	Maintain $\leq 4°$ touch error Maintain $\leq 4°$ touch error Improve detection of hazards within natural driving scenes to 80% correct localization
5	Perceptual Training: Verbalize correct target location. Use components of the background scene to code target location in far space	Perceptual adaptation	Verbalize correct target location ($\geq$80% accuracy) with $\leq 4°$ touch error

tally to present driving on the right side of the road). Plain gray or natural image photographs of walking or road scenes could also be selected.

Fixation stimuli were either a 15-mm fixation cross or a video file in a central display window used to increase cognitive load while making the session more enjoyable (see movie watching task, Table 2). Fixation was monitored with a table-mounted webcam and probed by presenting catch trials in nonseeing areas. Additionally, a second investigator visually monitored gaze and provided reminders to keep fixation on the central cross.

Mapping the Visual Field and Zone Placement

The training software was also used to measure the central 90°H × 42°V of the visual field (Fig. 4). First, the visual field was mapped kinetically, using the 30-mm checkerboard target, without and then with the p-prisms (Goldmann perimetry was performed at study intake). Next, zones (rectangular regions in which targets would be presented) were manually positioned, using the operator screen, within the areas of field expansion. One zone was positioned within each of the upper and lower prism expansion areas, and a "catch zone" was placed outside the expansion areas in the blind hemifield where no detection was

expected (Fig. 4). Upper, lower, and outer (temporal) borders of the prism zones were set using kinetic presentation (nonseeing to seeing) by asking the patient when the target appeared. The inner border (next to the seeing hemifield) was determined by presenting the target to the newly defined prism zone, moving it toward the midline, and having the patient report if they ever saw two targets. Targets close to the middle of the screen (near the border of the field loss) may be seen in two different directions depending on the patient's head position and glasses adjustment; one by the prism eye and the other by the nonprism eye, resulting in peripheral diplopia.[3] This could cause erratic responses during training; adjusting the inner prism zone border further into the blind field prevented this.

Once the prism zones were mapped and sized, they were confirmed with static presentations to the four corners of each zone. Next, three seeing-side zones were manually positioned within areas corresponding to the prism zones for a total of six zones where targets were presented during training. Zones were verified at the start of each visit, and as needed during training. Zone locations could change due to head movements which shift the position of the prism relative to the eyes and the fixation target. If changes in location or size were discovered, every effort was
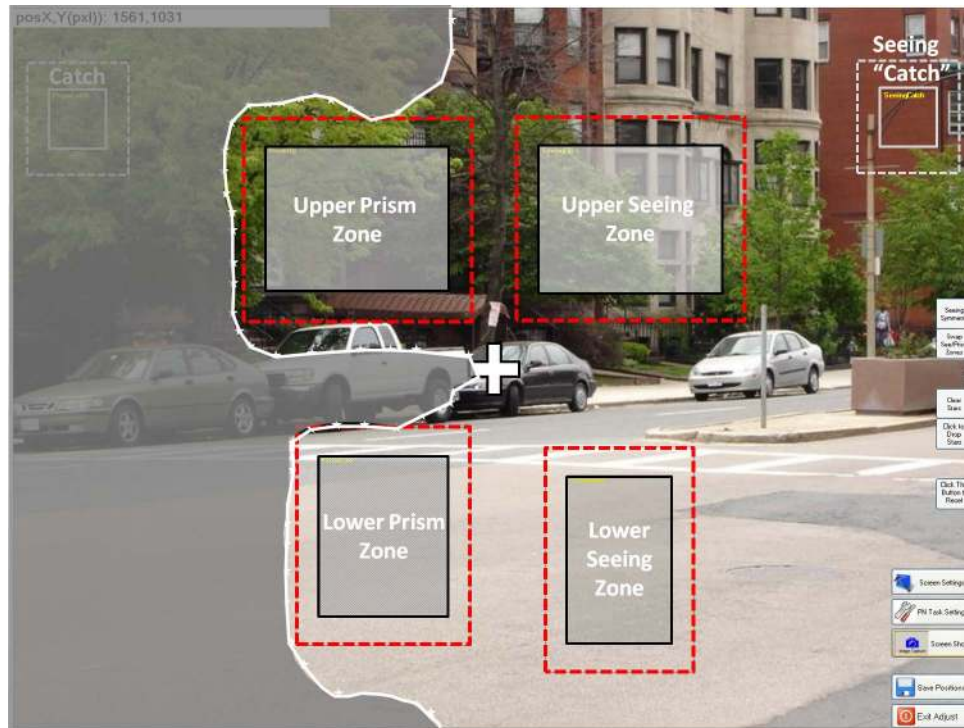
Figure 4. Photo illustration of the operator screen (37 × 28 cm) showing zone placement for a patient with left HH wearing oblique p-prisms. Using kinetic perimetry, the operator marked the border of the field on the prism side (*white line*), while the patient fixated the *white cross*, and then drew the borders of the prism zones (*dashed rectangles*). During training, targets were only presented within the *shaded areas* of the zones, leaving a buffer (area between the *dashed red lines* and *solid black lines* of each zone). The catch zone was set in an area of the blind hemifield where detection was not expected (*upper left*). There were also three seeing side zones corresponding to each prism zone.

made to readjust the glasses or chinrest first, only changing the zone locations as a last alternative.

Training Methods

Patients fixated the cross at the center of the touch screen and touched the 30-mm checkerboard targets appearing in the prism and corresponding seeing zones. They were taught to reach for prism-side targets with the prism-side hand, and seeing-side targets with the seeing-side hand. This method was found to be physically easier for patients and also ensured that the fixation cross was not obscured by the hand when reaching to touch the screen.

Before training, the patients typically touched the apparent location, approximately 20° to the right of the actual target for left HH (and opposite for right HH; Fig. 3).[4] This was on the opposite side of the screen to where the target had actually appeared. The primary goal was then to train the patient to quickly touch the real position of the target when it appeared in the prism without looking over. This was contrary to the way in which p-prisms are used in everyday life

(patients are taught to look to the blind side to identify objects after detection through the prisms[7]). The importance of maintaining central fixation during the training was therefore explained and reinforced throughout.

The experimental training protocol consisted of six, approximately 1-hour visits over the course of 3 weeks (usually 2 visits per week) progressing through five levels of increasing difficulty (Table 2). See supplementary materials for detailed descriptions of each training level. During the training, audio feedback from the software and verbal feedback from the investigator was given to indicate if touches were correct or incorrect. The criterion for a correct touch was determined in a preliminary experiment where the median touch error for normally sighted participants was 1.6° (IQR 1.4°–1.9°) of horizontal error for short stimulus durations. Therefore, an accurate touch was conservatively defined as touch error not greater than 4° from the center of the target. This level of accuracy was found to be feasible during early pilot testing with HH patients. Without feedback the patients were not aware of

errors as it looked as though they were touching the correct location, and there was no tactile feedback of the error. See videos of training in Supplement III. The audio feedback given by the software was composed of three different sounds for (1) a correct touch ($\leq 4°$ touch error), (2) a same side miss ($> 4°$ touch error, but on the correct side of the screen), and (3) a wrong side miss (reached for the prism image on the opposite side of the screen). The meaning of the audio feedback was explained to the patients. Descriptive statistics of performance were output at the end of each training session on the operator's screen, and a simplified version on the patient screen with success rates for target accuracy and an animated character providing feedback such as "good job" or "almost there," and so on. In order to progress to the next level of training patients had to meet minimum performance criteria (summarized in Table 2 and in Supplement I.

Performance Task and Outcome Measures

Outcomes were measured using a "performance task," which was administered without any feedback at the beginning (pre-session performance task) and midway (mid-session performance task) through each training visit. To evaluate retention of training, the performance task was administered again approximately 3 months after the end of training. During development of the training, it was apparent that patients were fatigued by the end of a visit; therefore, a midvisit performance measure was more representative of within-visit learning than an end-of-visit measure. The performance task used 10 presentations in each zone and two in each catch zone. The stimulus remained on the screen for 1500 ms and the time between presentations varied from 1000 to 1950 ms. Importantly, there was no audio feedback other than a beep indicating the screen had been touched. Patients were kept naïve to their performance on the task. There were only 11 false positives out of 300 prism catch trials (3.7%) for all performance tasks, confirming dense complete HH and reliable fixation (also see video of gaze tracking during training in Supplement III.

Horizontal touch error (the horizontal angular distance from the center of the touch to the center of the target) was the primary outcome measure. Training success was defined as median horizontal accuracy $\leq 4°$ on the visit six pre-session performance task. Detection rates and reaction times were secondary measures.

Statistical Analyses

Preliminary analyses found no differences in touch error, reaction times or detection rates between the upper and lower zones on each side; therefore, data for the upper and lower prism zones were combined, and data for the upper and lower seeing zones were combined.

The primary analysis of training results involved a nonparametric ANOVA (Friedman test) of the distribution of responses for the primary and secondary outcome measures across the six visits. Data were analyzed separately for the pre-session and mid-session performance tasks. When the Friedman was significant, post-hoc pairwise comparisons (Wilcoxon rank sum test) were performed in a step-wise manner for each visit compared with pretraining (visit one pre-session task) to determine at what point in training improvements reached significance. Performance tasks from the 3-month follow-up were compared with those at visits one and six. All statistical analyses were performed with SPSS 11.5 2002 (IBM, Armonk, NY); $\alpha \leq 0.05$ was taken to indicate statistical significance with correction for multiple comparisons where appropriate. Because the sample sizes in each group were relatively small, we also report marginal significances, where $0.05 < \alpha \leq 0.10$.

Results

Pretraining Performance

At the visit one pre-session task (pretraining; immediately prior to the first training session), most participants did not localize targets accurately on the prism side with a median horizontal touch error of 16.6° (IQR 12.1°–19.6°), significantly greater than median seeing-side touch error 0.8° (IQR 0.7°–1.6°), Wilcoxon, $P = 0.002$. Only two patients (1 and 9) had a median prism-side touch error that approached or was within the 4° touch error considered accurate (Fig. 5) suggesting they might have adapted to the prisms without training. These two patients (aged 32 and 50 years, respectively) did not wear the prisms for more hours per day during acclimation than the other patients; there was no relationship between reported wear time and accuracy (low touch error) for prism detected targets pre-training (Spearman's rho = −0.08, $P = 0.82$).

Pretraining prism-side detection rates were median 70% (IQR 50%–88%), significantly lower than seeing-side detection rates (100% [IQR 95%–100%], Wilcox-
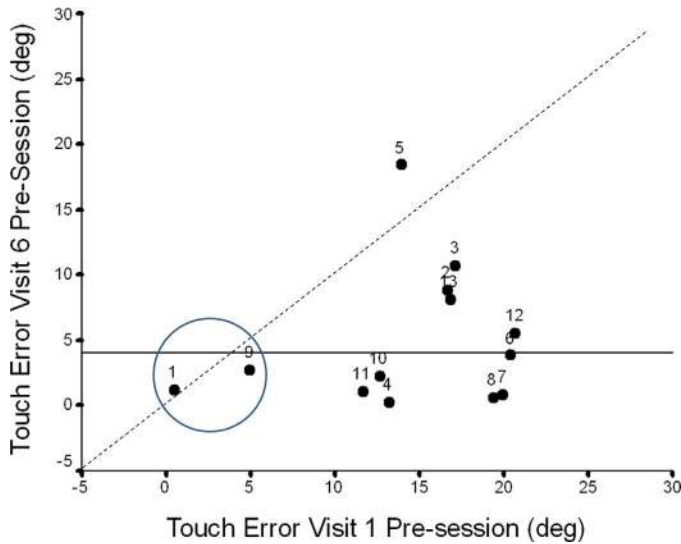
Figure 5. Horizontal touch error for targets presented in prism vision for the visit one pre-session task (pretraining) and the visit six pre-session task at the final training visit. Pretraining, most patients showed error consistent in magnitude and direction with the p-prism deviation (only horizontal error is plotted here), pointing to the apparent target location (data points clustered on the *right side* of the plot, not circled). Two patients showed fairly good accuracy pretraining (*circled*). At visit six most patients showed improved accuracy (points below *dashed diagonal line*). Eight met the 4° success criterion (points on or below *solid horizontal line*). Only patient 5 showed no improvement.

Figure 6. Number of patients passing each training level (L1–L5; Table 2) by visit. Before moving on to the next level the prior level had to be completed. At visit six, 10 of 13 (77%) had passed all training levels. The *blank box* at visit one represents the seven patients who did not manage to complete the first level of training at that visit.

on, $P = 0.001$). However, despite the inaccurate touches, reaction times to prism-side targets were relatively quick, 1.4 seconds (IQR 1.3–1.5 seconds), only 0.2 seconds slower than seeing side reaction times, 1.2 seconds (IQR 1.0–1.3 seconds), that small different was statistically significant Wilcoxon, $P = 0.001$, $n = 13$.

Progress Through Training

Patients progressed at their own pace through training with 10/13 (77%) passing all training levels (1–5) by the end of visit six (Fig. 6). Training plots showing touch accuracy and response time performance across training for each of the 13 patients are available in Supplement II, Figure 1. Group results are summarized in the next section.

Compliance was excellent with training and patients attended all training sessions required. Two patients (1 and 11) with good performance had their training terminated early as it seemed unlikely they would derive any benefit from further sessions. Patient 1 completed levels one through four and met all the training goals by visit four, and also demonstrated excellent maintenance of performance
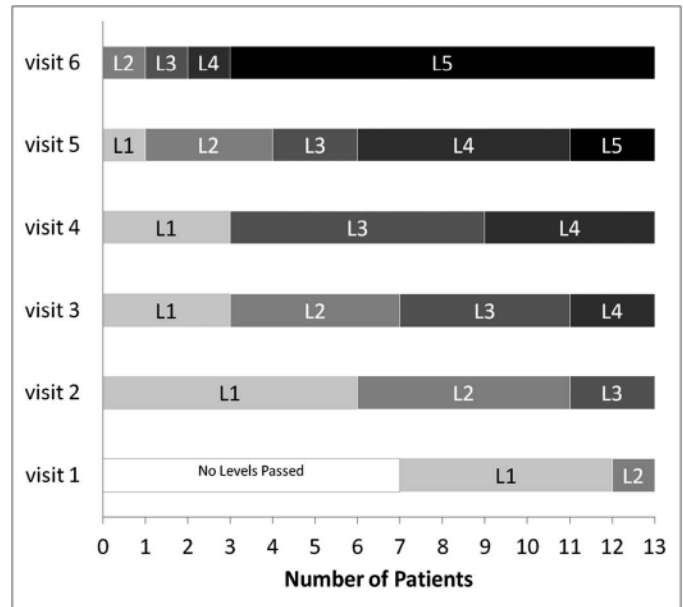
between sessions three and four (see Supplement II, Fig. 1, individual training plots). Level five had not been developed at the time patient one completed training. Patient 11 similarly finished early, requiring only five visits to complete all levels (see Supplement II, Fig. 1).

## Effect of Training on Performance Measure Tests

The pre-session performance task and the mid-session performance task were analyzed separately. The pre-session task data related to the retention of training from one session to the next, while the mid-session task provided a measure of the training effect within each session. For patients 1 and 11 who terminated early, the scores from their final pre- and postsession tasks were carried forward and entered as data points for subsequent "missed" visits (mid-session visit four through six for patient 1, and visit six for patient 11). The only other missing data points were from three mid-session tasks (one each for patients 2, 7, and 11) because of fatigue and time constraints. In each case, the score from the prior mid-session task was used in the analysis. Thus, data were only missing from 10 of 156 performance tests
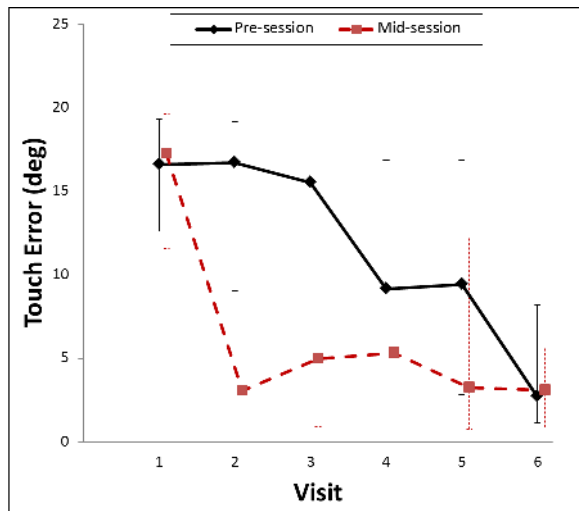
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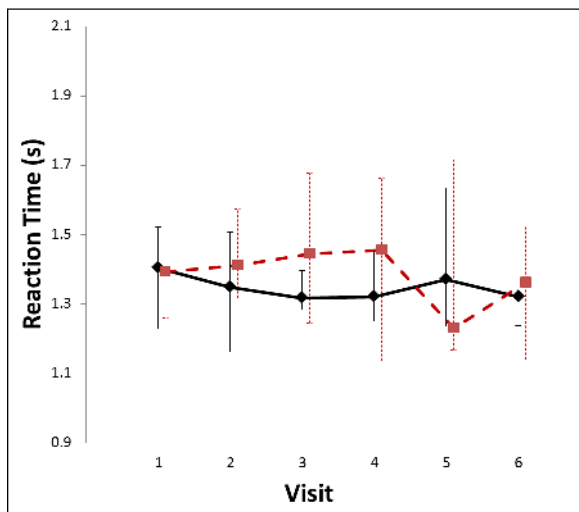
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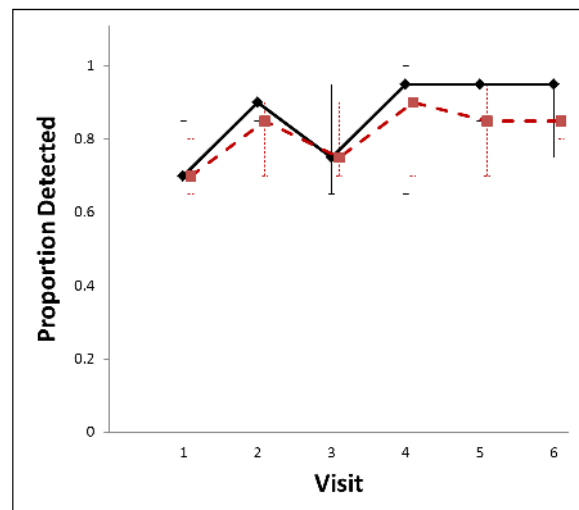
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(6%), with 7 of the 10 missing data points being related to the early termination in successful (accurate) patients.

Prism-Side Training Effects

For targets presented in prism vision, there were significant improvements in touch error for both the pre-session task (Friedman, $P = 0.01$, $n = 13$) and the mid-session task (Friedman, $P = 0.001$, $n = 13$; Fig. 7a). For the pre-session task, improvements reached significance by visit six (Wilcoxon for visit six vs. visit 1, $P = 0.004$, Bonferroni correction for five comparisons $P < 0.01$). Mid-session task improvements reached significance by visit two (Wilcoxon for visit 2 vs. visit one, $P = 0.003$) and were sustained through the end of training (all $P < 0.01$, Bonferroni correction for five comparisons $P \leq 0.01$). This improvement in accuracy was consistent with the goals of level two (Table 2), which the majority of patients (7/13) passed prior to the visit two mid-session task performance measure (Fig. 6, visit 2 bar). At the last training visit (visit 6), there was only a small difference in accuracy between the prism and seeing side, but this difference was significant for the pre-session task only (pre-session median 2.7° prism side compared with 1.1° on the seeing side, Wilcoxon, $P = 0.007$; mid-session task median 3.1° prism side compared with 1.0° on the seeing side, Wilcoxon, $P = 0.09$).

For reaction times, changes across training visits were not significant for either the pre-session or mid-session tasks (Friedman, both $P > 0.10$; Fig. 7b). For the mid-session task, reaction times tended to worsen over visits two, three, and four; this may represent the patient slowing down to begin accurate reaching. This

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Figure 7. Changes on the performance task across the six training visits for (a) median horizontal touch error, (b) median reaction time, and (c) detection rates for prism zone data for all 13 patients. The pre-session task (*solid lines*), administered at the beginning of each visit, represents between-visit retention of training effects and the mid-session task (*dashed lines*) represents within-visit training effects. *Black solid error bars* represent the IQR (25%–75%) for the pre-session task whereas *red dashed error bars* are the IQR for the mid-session task. In (a), improvements in touch error were significant by visit two for the mid-session task and by visit six for the pre-session task. (b) Reaction times did not show any significant changes. (c) Pre-session task detection improved significantly by visit four and was maintained, but there was no mid-session task improvement in detection. Mid-session data points are slightly offset to make *error bars* more visible.
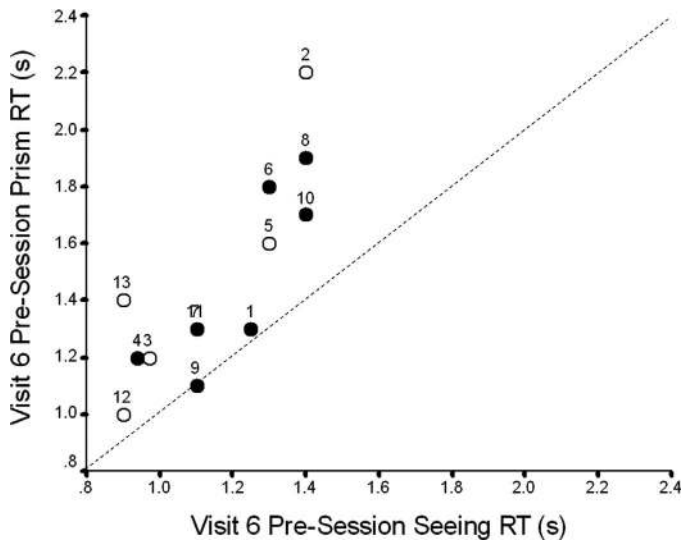
Figure 8. Median reaction times from the visit six pre-session task for the prism and seeing sides were highly correlated (Spearman's rho = 0.85, $P < 0.001$). Patients 1 and 9 had prism-side reaction times equivalent to seeing-side reaction times (on the *diagonal dashed line*). *Solid* and *open data points* denote successful and less successful cases (in terms of accuracy), respectively.

pattern can be more distinctly seen in individual training plots (see Supplement II, Fig. 1, patient 6 visit 4 mid-session task and patient 7 visit three mid-session task). At the last training visit (visit six), prism zone reaction times remained only slightly but significantly worse than seeing side (pre-session median 1.3 seconds on prism side versus 1.1 seconds on seeing side, $P = 0.002$; mid-session task median 1.4 seconds on prism side versus 1.1 seconds on seeing side, $P = 0.002$) and were highly correlated (Fig. 8); patients with longer seeing-side reaction times had longer prism-side reaction times (pre-session task Spearman's rho = 0.85, $P < 0.001$; mid-session task Spearman's rho = 0.77, $P = 0.002$).

There were significant improvements in detection rates with training for the pre-session task (Friedman, $P = 0.01$, $n = 13$), but only marginal improvements in the mid-session task (Friedman, $P = 0.11$, $n = 13$; Fig. 7c). Improvements in the pre-session task reached significance by visit four (visit four vs. visit one, Wilcoxon, $P = 0.01$) and were maintained through the end of training $P \leq 0.01$. However, at visit six, prism-side detection remained significantly lower than seeing side (pre-session median of 95% on prism side versus 100% on seeing side; Wilcoxon, $P = 0.007$; mid-session task median of 85% on prism side versus 100% on seeing side; Wilcoxon, $P = 0.002$).

Seeing-Side Training Effects

There was no effect of training on seeing-side touch error, seeing-side reaction times, or seeing-side mid-session task detection rates (Friedman, all $P > 0.10$, $n = 13$). There was, however, a significant improvement in seeing-side pre-session task detection with several detection failures at visit one (median, 100%, range, 75%–100%) but no detection failures for all other visits, perhaps representing a learning effect (Friedman, $P = 0.02$, $n = 13$).

Training Success

Training success was defined as a median visit six pre-session task prism zone touch error $\leq 4°$. There were eight patients who met this criterion, one who was borderline (patient 12 with median touch error of 5.5°), three who showed some improvement (patients 2, 3, and 13 with median touch error of 8.9°, 10.8°, and 8.1°, respectively), and one who showed no improvement (patient 5 with median touch error 18.4°; Fig. 5). Patients 9 and 1 had accurate reaching with equivalent prism- and seeing-side reaction times, and other successful patients were approaching this level of performance (Fig. 8). Figure 9 summarizes the changes in touch error, response times, and detection rates over the course of training for the eight successful patients compared with the five less successful patients (defined as visit 6a touch error > 4°). The successful patients had more rapid improvements in accuracy and also had higher detection rates across all visits. There were no differences between the two groups in reaction times.

Retention of Training at 3 Month Follow-up

Twelve of 13 patients completed the 3-month follow-up. For touch error (prism side), the group median at 3 months was 8.5° (IQR 6.0°–17.2°), which was marginally worse than the 3.3° (IQR 1.0°–8.7°) at visit six, pre-session task (Wilcoxon, $P = 0.08$, $n = 12$), and also marginally better than the pretraining 16.7° (IQR 12.7°–19.8°) at visit one, pre-session (Wilcoxon, $P = 0.06$, $n = 12$). However, at the 3-month assessment, only two patients (1 and 12) fell at or within the 4° considered as training success. For detection, the group median at the 3-month post-training assessment was 75%, which was significantly worse than the 95% at the visit six pre-session task (Wilcoxon, $P = 0.05$, $n = 12$), but still marginally better than the 65% on the visit one pre-session task (Wilcoxon, $P = 0.07$, $n = 12$). Prism zone reaction times were not significantly different at the 3-month
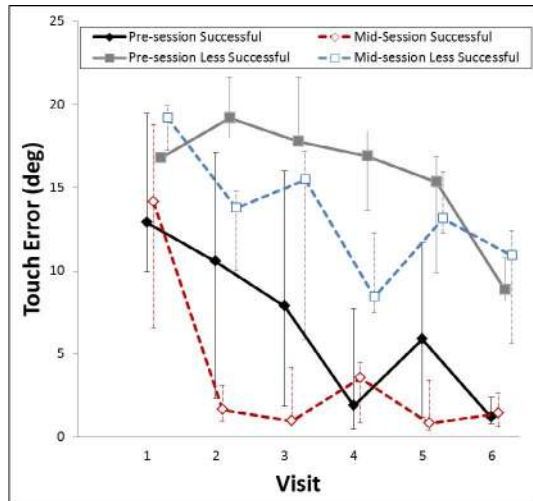
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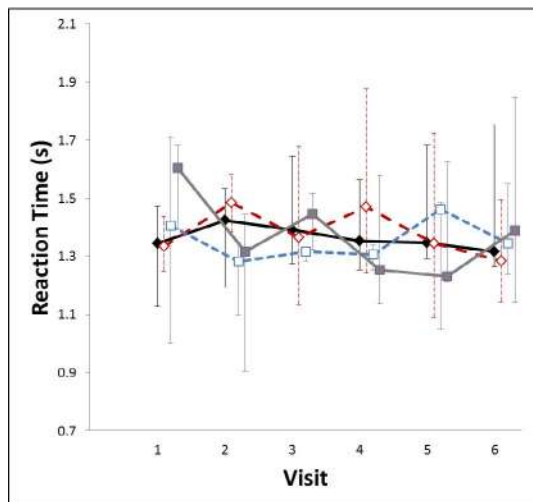
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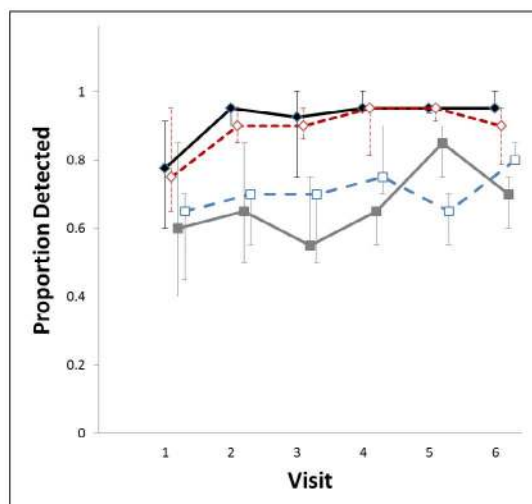
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assessment from pretraining ($P = 0.27$) or the visit six pre-session task ($P = 0.75$), $n = 12$.

Discussion

We conducted a pilot study of perceptual-motor training to promote adaptation to prismatic field expansion in patients with long-standing, complete HH wearing high-power (57Δ), unilaterally-fitted, p-prisms. Prior to training after 2 weeks of general p-prism wear, all participants except two incorrectly touched the apparent location of the prism image rather than the true location. This finding is consistent with the prior study,[6] confirming the need for training. Although failure to adapt with general wear may seem contrary to prior reports with optically similar spilt-prisms,[11,12] there were several important methodological differences. In split-prism studies, wear times were much longer (all waking hours), split-prisms were less than half the power of p-prisms, the junction between the split-prisms was in central vision rather than peripheral, and participants in split-prism studies did not have a history of neurological pathology. P-prism wear times in our study were not correlated with pretraining touch errors; however, wear times were self-reported and not verified. Furthermore, we did not document wear times between the last training session and the 3-month assessment so the relationship between wear times and touch error at 3 months could not be evaluated. Limited wear time may still prove to be an important factor limiting adaptation and improved methods of measuring wear time would be beneficial in future p-prism studies.

Consistent with our primary hypothesis, most patients (13 of 16 that originally enrolled) were able to complete the training protocol with the majority meeting the criteria for training success (8/13).

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Figure 9. Changes on the performance task across the 6 training visits for successful and less successful patients: (a) median touch error, (b) median reaction time, and (c) detection rates for the prism zone. Data are shown for patients who met the training success criterion ($n = 8$) and those who did not ($n = 5$) for the pre-session task (*solid lines*) at the beginning of each visit, and the mid-session task (*dashed lines*) at the mid-way point of each visit. (a) Changes in touch error were only significant for the group of successful patients. (b) For reaction times, there were no differences between successful and less successful patients. (c) For detection, successful patients tended to have better rates. *Error bars* represent the IQR (25%–75%). Data points are slightly offset to *make error* bars more visible.

Improvements in accuracy were, as a group, statistically significant. It was feasible to conduct training with gaze fixed on a central fixation cross; a concern at the outset of the study. This allowed visual field expansion areas to be precisely mapped assuring the target was only seen in the prism when that was the intention. This is not how the p-prisms are intended to be used in everyday life, but may be critical in achieving visuomotor adaptation to the p-prisms.

Improved accuracy was measured after only two training visits for the mid-session task; however, in order to have effects sustained between visits, our data suggests four to six visits are needed (Fig. 7a). By comparison, there were no significant changes in prism-side reaction times across the six visits (Fig. 7b). In fact, prism-side reaction times were only approximately 0.2 seconds longer than seeing-side at both the beginning and end of training, leaving little room for improvement. A longer duration of training could be investigated in future studies for the potential to enhance the completeness of adaptation and any sustained effects.

Improvements in touch error with training may merely represent a strategic technique such as side pointing (aiming further to the side to where they knew the target was located). It is also possible localized motor-proprioceptive adaptation of the prism-side arm or adaptation in visual (e.g., spatiotopic) coordinates occurred. This study was not designed to determine the mechanism of improved accuracy (visual, motor-proprioceptive, or strategic), but the mechanism is important to consider as it relates to generalization of training effects to everyday tasks.[20–22] For example, while it is possible proprioceptive-motor adaptation of the trained (prism-side) arm is useful when making a quick movement led by that arm, a visual adaptation or strategic correction is more likely to generalize to other tasks such as obstacle avoidance.[23,24] In an extension of this study, which will be reported in future manuscripts, we examined effects of the training on virtual and real-world mobility behaviors including, detection of pedestrians in a driving simulator (Bowers AR et al. *IOVS*. 2014;55:ARVO E-Abstract 2155), collision judgments in a walking simulator,[25] and gaze behaviors during outdoor walking (Tomasi M, et al. *IOVS*. 2013;54:ARVO E-Abstract 2758).

A secondary finding of this study was preliminary evidence that training improves detection of stimuli in the prism-expanded vision. This might represent improved attention to the prism vision, improved ability to interpret/use the information from the prism vision, or better positioning of the head by the patient to bring the prism image closer to the line of sight. We specifically trained the patient to move the prism segment closer to the line of sight by adjusting the chin in and out (Table 2 level 4.3) in order to image the prism vision on a lower eccentricity/higher resolution retinal area, which might have led to improved detection. Improved detection might have benefit for everyday tasks such as walking or driving. These results should be interpreted with caution as the effect might also have arisen from improved positioning of the patient or placement of training zones by the experimenter.

Improvements in both touch error and detection present at the end of training had substantially faded by 3 months. If benefits of training indeed generalize to realistic mobility tasks, in-office maintenance training or simple, home-based training exercises would need to be explored.

Our study was not designed to identify potential predictors of training success, such as age, cognitive status, side of field loss, or brain lesion location. Furthermore, the results cannot be generalized to the overall population of people with HH. Our sample was relatively young with moderately longstanding HH (median, 6 years; Table 1) and without neglect on the Schenkenberg line bisection and Bells tests; it is possible that older populations of HH patients would not show as much improvement. This was not a clinical trial and was not sham-controlled, so the magnitude of any placebo-effect could not be determined. Additional studies would be needed prior to recommendation for clinical implementation.

In summary, we fulfilled the aims of this pilot study. All of the participants who started the training completed it, with good compliance. All but two demonstrated improvements in touch accuracy by the end of training, and 8 of 13 met the criterion for training success. Training also appeared to improve detection. It is possible that accurate reaching/localization and improved detection might only be measured on the training task; future papers will address the effects of the training on mobility in real and simulated tasks.

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