Improvement in Vernier Acuity in Adults With Amblyopia
Practice Makes Better

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Purpose. To determine the nature and limits of visual improvement through repetitive practice in human adults with naturally occurring amblyopia.

Methods. A key measure the authors used was a psychophysical estimate of Vernier acuity; persons with amblyopia have marked deficits in Vernier acuity that are highly correlated with their loss of Snellen acuity. The experiment consisted of three phases: pretraining measurements of Vernier acuity and a second task (either line-detection thresholds or Snellen acuity) in each eye with the lines at two orientations; a training phase in which observers repetitively trained on the Vernier task at a specific line orientation until each had completed 4000 to 5000 trials; and posttraining measurements (identical to those in the first phase). Two groups of amblyopic observers were tested: novice observers (n = 6), who had no experience in making psychophysical judgments with their amblyopic eyes, and experienced observers (n = 5), who had previous experience in making Vernier judgments with their amblyopic eyes (with the lines at a different orientation) using the signal-detection methodology.

Results. The authors found that strong and significant improvement in Vernier acuity occurs in the trained orientation in all observers. Learning was generally strongest at the trained orientation but may partially have been transferred to other orientations (n = 4). Significant learning was transferred partially to the other eye (at the trained orientation) in two observers with anisometropic amblyopia. Improvement in Vernier acuity did not transfer to an untrained detection task. In two observers, the improvement in Vernier acuity was accompanied by a commensurate improvement in Snellen acuity.

Conclusions. Some adults with amblyopia retain a significant degree of neural plasticity. Although several observers (primarily novices) showed evidence of generalized learning, several amblyopic patients showed evidence for improvement that was orientation and task specific. In this latter group of observers, the improvement appeared to reflect alterations that were, at least in part, in early neural processes that were orientation specific and were localized beyond the site of convergence of the two eyes. Invest Ophthalmol Vis Sci. 1997;38:1493–1510.

Amblyopia is a developmental disorder of spatial vision that develops only when strabismus, anisometropia, or form deprivation (caused by cataract or high, uncorrected ametropia, for example) are present during a period of neural plasticity early in life. Amblyopia is characterized by reductions in visual acuity, contrast sensitivity, and positional acuity. Although amblyopia can often be reversed when treated early, treatment is generally not undertaken in older children and adults (but see Discussion).

In adults with normal vision, practice can improve performance in a variety of visual tasks. The perceptual learning that follows practice is considered to be a form of neural plasticity. Many recently reported findings suggest that this neural plasticity may be observed in adults, and that the improvement in performance that follows practice may be quite specific. For example, in adults with normal foveal vision, learning is specific to the learned orientation, spatial frequency, and direction of motion. This stimulus
specificity has often been taken as evidence that perceptual learning occurs at a relatively low level.

Strong learning effects also occur in the retinal periphery, and this learning appears to be location-specific. For example, Fiorentini and Berardi\(^8\) found no transfer when they trained observers in contrast sensitivity in the superior field and tested their performance in the inferior visual field. Similar location specificity has been obtained for other tasks.\(^12-15\) The recently reported findings of Schoups et al\(^14\) suggest that learning to discriminate among orientations in peripheral vision is topographically precise. Learning at one location did not transfer to an adjacent location at the same eccentricity (on an isoeccentric arc, but see Beard et al\(^16\)). Moreover, in the results of Schoups et al,\(^14\) learning at one orientation did not transfer to other orientations. Interestingly, in their results, transfer between eyes was almost complete. Similarly, Beard et al\(^15\) found substantial interocular transfer of learning but only when the visual pathway leads to the corresponding location in the trained hemisphere. These results are consistent with the interpretation that, at least in part, improvement after practice represents neural fine-tuning at a relatively low level of visual processing.\(^17,18\) If perceptual learning reflects neural fine-tuning of processes in V1 for example, then learning would be expected to be task-specific and orientation-specific. If perceptual learning occurs in binocular neurons, then learning would also be expected to show significant interocular transfer (as it apparently does for some, but not in all tasks). Taken together, these results provide strong evidence for plasticity in the adult visual nervous system at a relatively early stage of processing. However, we note also that higher level (cognitive) processes sometimes may play a role in effects obtained in practice. For example, in their results Beard et al\(^19\) found that there was significant transfer of practice from a Vernier task to a resolution task and vice-versa in peripheral vision. This transfer could reflect that the two tasks share early (front-end) processes; however, it is also possible that it reflects the observers’ learning to allocate their attention to the peripheral task,\(^19\) because shifting attention from fovea to periphery may require practice.

The purpose of the current study was to investigate whether similar neural plasticity exists in the visual system of adults with naturally occurring amblyopia, related to anisometropia or strabismus. Specifically, in the current study we were interested in knowing whether adults with amblyopia demonstrate perceptual learning of Vernier acuity, and whether this learning, if it occurs, reflects alterations in early neural processes. We studied Vernier acuity because persons with amblyopia have marked deficits in Vernier acuity that are strongly correlated with their Snellen acuity. Results reported in a recent study\(^20\) suggest that in a large group of observers with “normal” vision, those with the worst initial performance showed the strongest effects of practice. Because persons with amblyopia have elevated Vernier thresholds, these results predict large learning effects in amblyopic eyes. To assess the relative contributions of neural factors to any learning effects, we evaluated the orientation specificity, task specificity and interocular specificity of learning. A brief report of part of this work appears elsewhere.\(^21,22\)

**METHODS**

**Stimuli**

The stimuli in our experiments consisted of short, dark line segments presented on a background with a mean luminance of 100 cd/m\(^2\). When testing the preferred eyes, each line segment was 4 minutes of arc long and 0.9 minutes of arc wide, at the viewing distance of 4 m. For the amblyopic eyes, the viewing distance was decreased (in proportion to the observer’s visual acuity), so the angular dimensions of the stimuli were proportionally larger. The Vernier stimulus consisted of two abutting, dark lines, with a Vernier offset between the two lines. The Weber contrast of the lines was 80%, between 4 and 10 times the line-contrast-detection threshold for both the nonamblyopic and the amblyopic eyes. The line-detection stimulus was one of these Vernier lines, whose contrast was varied to measure the line-contrast-detection threshold. In all experiments, the stimuli were presented for 1 second, with an abrupt onset and offset, on a Tektronix (Beaverton, OR) 608 oscilloscope screen with a P31 phosphor, by a Neuroscientific VENUS stimulus generator (Neuroscientific Corp., Farmingdale, NY), and were viewed through a circular aperture.

**Procedure**

To obtain criterion-free measurements of performance, all thresholds were measured using a self-paced, signal-detection rating-scale method of constant stimuli.\(^23,24\) For the Vernier task, during each trial one of five stimulus offsets (aligned, 1 step up, 1 step down, 2 steps up, or 2 steps down) was randomly presented to the observer. The magnitude of the steps was chosen on the basis of a small number of preliminary trials, so that the offsets bracketed the threshold (the threshold offset was generally between step 1 and step 2). After each trial, the observer rated the perceived direction and magnitude of the offset by giving integers from −2 to +2 and then received feedback regarding the actual direction and magnitude of the offset on the trial. For the Vernier task, each actual run consisted of 125 trials, preceded by about 10 prac-
practice trials. To obtain a criterion-free estimate of the Vernier threshold, we used a maximum-likelihood fit to the ratings-scale data to estimate the $d'$ values (indicating the detectability of the offset) for each stimulus position tested during a run and interpolated to a $d'$ value of 1 (84% correct), using a linear transducer function. Our thresholds represent the precision for discriminating the direction of the offset, and represent the offset required to discriminate the direction of offset, specified at a $d'$ equal to 1.

Preliminary runs were provided (for each eye), to familiarize the observer with the procedure and to establish the appropriate steps for use in the actual trials. Preliminary runs consisted of two or three blocks of 50 trials per block, and were (except for the number of trials) identical to the actual runs. Based on the results of the preliminary runs, we chose a step size that bracketed the threshold (i.e., the offset yielding $d'$ = 1, fell between step 1 and step 2). During the actual experiment, if performance improved, the step size was decreased according to a $d'$ criterion. Specifically, the step size was reduced (to bracket the threshold) if $d'$ for the small offset exceeded 1.6 in three consecutive runs.

Thresholds for detecting the individual line segments were measured using the same self-paced, rating-scale method of constant stimuli.25 Observers rated the contrast of the line on a scale of 0 to 4. Detection thresholds were specified at a $d'$ value of 1 (equivalent to 84% correct). For the detection task, each run consisted of 100 trials, preceded by approximately 10 practice trials.

For the novice observers (defined later) Snellen acuity was measured using Davidson–Eskridge charts.25 These are highly “crowded” charts, and acuities were estimated from the psychometric functions relating the percentage of correct performances to the size of letters, using probit analysis.26

Observers

We tested two groups of amblyopic observers. One group consisted of six novice observers who had no prior experience in making psychophysical judgments. Because we were interested in perceptual learning, as opposed to simply learning the psychophysical technique or learning a strategy for making psychophysical observations with an amblyopic eye, we also tested a group of five observers with previous experience in making Vernier and detection judgments using our signal-detection rating-scale methods. The most experienced observers, RH, RJ, and BJ had several years’ (and hundreds of thousands of trials) experience as observers using these methods; KW and FG had less previous experience (FG had approximately 5000 trials divided evenly between the two eyes). One potential problem with testing highly experienced observers is that, through many trials with feedback, they may have already improved to their limit. Therefore, we trained our previously experienced observers with oblique Vernier lines, knowing that all their previous experiments had been with horizontal or vertical targets. We have previously noted that observers with normal vision, who have extensive experience in making Vernier judgments with horizontal and vertical targets, show considerable learning with oblique targets.25 Our observers were all adults between the ages of 19 and 53 years with amblyopia related to strabismus, anisometropia, or both. Their visual characteristics are given in Table 1. The research followed the tenets of the Declaration of Helsinki, informed consent was obtained after the nature and possible consequences of the study were explained, and the research was approved by the University of Houston’s institutional human experimentation committee.

Experimental Strategy

Our experiment consisted of three phases: pretraining measurements of Vernier acuity in both eyes for at least two orientations of the lines. For some observers we also made pretraining and posttraining measurements for a second task (line detection or Snellen acuity); a training phase in which observers repetitively trained on the Vernier task at a specific orientation until each had completed 4000 to 5000 trials; posttraining measurements, which were the same as the pretraining measurements. For the pretraining and posttraining measurements, the order of testing was counterbalanced for all eyes and conditions. A subset ($n = 7$) of the observers, underwent a subsequent training phase at a second orientation (e.g., 90° for the novices, 45 or 135° for the experienced observers [Table 2], followed by another round of posttraining measurements. One observer (RH) repeated this sequence, at four angles of orientation (45°, 135°, 90°, and 0°). All testing was monocular, with the untested eye occluded with a black patch.

RESULTS

Improvement Throughout Training

Figures 1, 2, and 3 show representative data from the training sessions. Consider Figure 1, which shows the Vernier threshold data for two anisometropic novice observers. The observers were trained with a Vernier task of a specific orientation (0°)—the filled circles represent the pretraining and posttraining data for this condition (that is, the trained condition). For all training days, each datum represents the threshold on the basis of 125 trials. Rather than connect the data points, we fit each data set within a daily session with
a linear function. By fitting the data in this way “local” trends can be more easily seen. The local trends are interesting, because they highlight the large, individual differences in how learning occurs. For example, observer EW shows significant learning during the first few sessions; however, most of her subsequent learning takes place between sessions, and she actually shows worsening during the later sessions, whereas her thresholds decrease between sessions. Similar trends can be seen in the data recorded on other observers (LM, DS, and KW, for example). Simple regression analysis on the overall data showed that each observer’s Vernier threshold improved significantly (10 of the 11 at <0.0001 P) at the trained orientation. The significance of each F statistic (the probability values) for these overall analyses (probability values) is shown in Table 2 for each observer.

To look more closely at where and how learning occurred, we used a segmented regression analysis (see Appendix for details). The results are shown by the heavy dotted lines and the numbers in each figure. For example, consider the data of EW. According to the segmented regression analysis, blocks 1 through 7 showed significant improvement in performance ($P = 0.021$), followed by a significant step improvement in performance (denoted by “jmp”). From block 8 to 16, performance improved slightly but not significantly ($P = 0.27$); and from blocks 17 through 44, performance improved steadily and significantly ($P = 0.012$). Each panel shows the learning trends indicated by our analysis; it is clear that the magnitude, time-scale and style of learning is highly individualistic. Despite the individual differences in learning styles, the segmented regression analysis reveals significant improvement in the course of learning in all 11 observers.

To summarize the improvements, Vernier thresholds for each session ($\approx 1000$ trials) were normalized by the pretraining threshold, and averaged to include results in all five practiced observers (Fig. 4, left panel) and those in all six novice observers (Fig. 4, right panel). The error bars are ± 1 SE. The lines are exponential fits to the data. Despite the substantial individual differences in learning, the trends revealed in the group data are quite clear. For the experienced observers, thresholds become asymptotic at about half of the pretrained value after approximately five or six sessions (5000 to 6000 trials). As might be expected, the novice observers show stronger learning effects that are less than 40% of their initial values after 10 sessions and may not yet have reached their asymptotic level by the end of all of the practice trials.
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In summary, all 11 of our observers showed significant overall improvement after practicing Vernier acuity at one orientation. Here, we examine the effects of training at a new orientation, and the specificity of the improvement.

Subsequent Training

After completion of the initial training and posttesting, seven observers underwent a subsequent round of training with the lines set at a new orientation (the methods and procedure were identical to those in the initial training). Figures 5 and 6 show the training data recorded for five of the seven observers (three novice observers, Fig. 5; two experienced observers, Fig. 6) who underwent a subsequent round of practice at a different orientation. The regression analyses of these subsequent rounds of practice (and several others that are not shown) are included in Table 2. For experienced observers BJ and FG, the second round of learning also resulted in significant improvement of performance ($P < 0.0001$), and it is interesting to note that they maintained the level of improvement achieved after the initial training; for RH (Table 2) none of the subsequent rounds resulted in significant improvement. For novice observers KC and JB, subsequent training at an orientation of $90^\circ$ improved performance significantly. Similarly, EW, who completed only about 20 blocks, roughly 2500 trials, at $45^\circ$, showed a significant improvement with the new orientation (Table 2). However, DS showed no significant improvement with the new orientation.

Transfer of Training

We assessed transfer of learning using the pretraining and posttraining data (see Experimental Strategy) collected in both eyes with different orientations and in different tasks. Specifically, after training in only one task (Vernier) at a single orientation, we compared the pretraining and posttraining performances. Figure 7 summarizes the results of the initial training by plotting, in histogram form, the percentage of improvement from pretraining to posttraining for each observer. The left column shows results recorded in the experienced observers, the right column those recorded in the novice observers.

Orientation. The top panels show the improvement in the trained (amblyopic) eye at the trained orientation, and at an untrained orientation. As expected, on the basis of data measuring performance on training days, all 11 observers showed improvement during the trained orientation (Table 2). The mean improvement was 44% for experienced and 59% for novice observers; however, there were substantial interindividual differences. The two most experienced observers (RH and RJ) showed only about a 25% improvement, whereas several novice observers showed improvements greater than 70%.

Improvement was generally most notable at the trained orientation, with improvement at the untrained orientation considerably reduced—to 12% for the experienced and 27% for the novice observers. Eight of the observers showed substantial and significant improvement ($P = 0.01$, or better) at the trained orientation, with little or no significant improvement in the untrained orientation—suggesting orientation-specific learning (Table 3). Conversely, one of the novice observers (JB) showed significant transfer to

\[\text{In the experienced observers, we made measurements at several orientations. These data are presented elsewhere (Levi and Polat21). For simplicity, here we report the results at a neighboring orientation (90°) with which the observers had not had previous psychophysical experience.}\]
FIGURE 2. Vernier thresholds plotted as a function of consecutive blocks of 125 trials per block for four novice observers, two with strabismus, and two with strabismus and anisometropia. Filled circles represent the pretraining and posttraining data for the trained condition. The solid line segments show the linear regression line fit to the data of each daily session. The heavy dotted lines and numbers (P values) in each panel show the results of segmented regression analyses (see Results and Appendix).

the untrained orientation, and three other observers (KC, LM, and FG) showed weaker improvement (P < 0.05 > 0.01) at the untrained orientation, suggesting some generalized learning, too. Our finding of strong improvement at the trained orientation, and weaker improvement at the untrained orientations suggests that both cognitive and neural factors can contribute to the improvement.

Eye. There is substantial transfer to the untrained eye at the trained orientation (middle panels). In this condition, the mean improvement in the untrained eye was 33% in the experienced observers, and 24% in the novices. At the untrained orientation the mean improvement was considerably smaller (11% and 12%, respectively). Thus, our results show partial transfer of learning to the untrained (nonamblyopic) eye. This is most notable in the two observers (FG and BJ) with anisometropic amblyopia, for whom data showed strong and significant transfer (P = 0.01, or better) at the trained orientation, and little or no transfer at the untrained orientation (Table 3). Overall, the transfer (that is, improvement in the untrained eye compared with improvement in the trained eye) averaged approximately 60% of the direct learning effect in the trained orientation. Thus, we believe that our results reflect, at least in some observers, neural learning beyond the site of binocular convergence, rather than a generalized learning. Supporting this opinion is the argument that in some observers the transfer is significant in the trained orientation and not in the untrained orientation.

Detection. In contrast with the marked improvement in the (trained) Vernier task, there is little improvement in a line-detection task (data of the experienced observers are shown in the lower left panel of Fig. 7, and the results in all five observers are summa-
FIGURE 3. Vernier thresholds plotted as a function of consecutive blocks of 125 trials per block, for four experienced observers tested with oblique lines, three with anisometropia, and one with strabismus. Filled circles represent the pretraining and posttraining data for the trained condition. The solid line segments show the linear regression line fit to the data of each daily session. The heavy dotted lines and numbers ($P$ values) in each panel show the results of segmented regression analyses (see Results and Appendix).

**TABLE 2. Simple Regression Analysis* of Training Days**

<table>
<thead>
<tr>
<th>Observer</th>
<th>Type</th>
<th>Orientation</th>
<th>P</th>
<th>Orientation</th>
<th>P</th>
<th>Orientation</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experienced</td>
<td>1</td>
<td>135</td>
<td>&lt;0.0001†</td>
<td>45</td>
<td>&lt;0.0001†</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>BJ</td>
<td>Aniso</td>
<td>135</td>
<td>&lt;0.0001†</td>
<td>45</td>
<td>&lt;0.0001†</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>FG</td>
<td>Aniso</td>
<td>45</td>
<td>&lt;0.0001†</td>
<td>135</td>
<td>&lt;0.0001†</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>KW</td>
<td>Strab</td>
<td>135</td>
<td>&lt;0.0001†</td>
<td>45</td>
<td>0.006†</td>
<td>135</td>
<td>0.94</td>
</tr>
<tr>
<td>RJ</td>
<td>Aniso</td>
<td>135</td>
<td>&lt;0.0001†</td>
<td>135</td>
<td>0.94</td>
<td>90</td>
<td>0.84</td>
</tr>
<tr>
<td>RH</td>
<td>Strab</td>
<td>45</td>
<td>0.006†</td>
<td>135</td>
<td>0.94</td>
<td>90</td>
<td>0.84</td>
</tr>
<tr>
<td>Novices</td>
<td>2</td>
<td>0</td>
<td>&lt;0.0001†</td>
<td>45†</td>
<td>&lt;0.0005†</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
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<td>Aniso</td>
<td>0</td>
<td>&lt;0.0001†</td>
<td>45†</td>
<td>&lt;0.0005†</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>DS</td>
<td>Both</td>
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<td>&lt;0.0001†</td>
<td>90</td>
<td>0.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM</td>
<td>Strab</td>
<td>0</td>
<td>&lt;0.0001†</td>
<td>90</td>
<td>0.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JV</td>
<td>Both</td>
<td>0</td>
<td>&lt;0.0001†</td>
<td>90</td>
<td>0.27</td>
<td></td>
<td></td>
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<tr>
<td>JB</td>
<td>Strab</td>
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<td>90</td>
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<td></td>
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</tr>
<tr>
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<td>&lt;0.0001†</td>
<td>90</td>
<td>0.27</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Regression analyses were performed on the data across training sessions. The significance of each F statistic ($P$ values) is given for each observer and condition.
† Significant $P$ values.
‡ Only 2250 learning trials completed.
Experienced Observers  Inexperienced Observers

Sessions Pre 6  Sessions  Post

FIGURE 4. Vernier thresholds for each session (≈1000 trials) were normalized by the pretraining threshold, and averaged for all five practiced observers (left) and all six novice observers (right). The error bars are ±1 SE. The lines are exponential fits to the data.

rized in Table 3). The mean improvement in detection thresholds is 7% in the trained orientation, and 9% in the untrained orientations (neither of which is significant). None of the five observers showed significant improvement in the untrained task at either the trained or untrained orientation (Table 3). Thus, in persons with amblyopia, training in a Vernier acuity task does not transfer to the detection task. It has been postulated that the amblyopic deficit in Vernier acuity reflects noise (or undersampling) at a stage in the visual pathway, beyond the site that limits detection.23’24 If this view is correct, it is tempting to speculate that the learning evident in our observers takes place at this later stage. Statistical analysis of the trends described is provided in Table 3 in the form of P values based upon paired student’s t-tests.

Snellen Acuity. Interestingly, at least some persons with amblyopia do show transfer of learning to a different task—Snellen acuity. Recall that we made pretraining and posttraining measurements of Snellen acuity in the six novice observers. Two of the six novice observers, EW and KC, showed improvements in Snellen acuity that were comparable to improvements in their Vernier acuity. For EW—Snellen acuity had improved from 20/80 to 20/22; KC improved from an initial acuity of slightly worse than 20/40 to 20/20 (Fig. 8). This improvement in Snellen acuity is consistent with the close connection between Vernier acuity and Snellen acuity noted earlier.

DISCUSSION

Perceptual Learning in Amblyopia

Our 11 observers showed substantial perceptual learning of Vernier acuity. The approximately 50% overall average improvement in Vernier acuity in the trained orientation is similar to the average improvement in peripheral orientation discrimination recently reported by Schoups et al14; however, it is considerably larger than the approximately 20% average improvement in peripheral Vernier thresholds reported by Beard et al,15 and larger than that reported in data from many previous studies of normal central vision. It should also be noted that all of our observers showed significant effects of practice, whereas, in Beard et al,15 as in results of many other studies of learning, some observers failed to show significant learning. In data collected in a previous study of Vernier acuity using similar methods and stimuli, Saarinen and Levi18 found that in four normal observers, Vernier acuity improved 34%, on average, but with large individual differences: One observer showed no significant improvement (≈ −2.5%), whereas one observer showed a more than 60% improvement. It should be kept in mind that in the current study, unlike in many other learning studies, five observers had substantial previous experience with Vernier acuity and our rating-scale task. Although all five showed significant improvement in Vernier...
acuity, the percentage was generally less than that obtained in the novice observers. Our experienced observers, like normal observers, show substantial improvement in Vernier acuity with oblique stimuli. For example, McKee and Westheimer's observers showed ~2% to 70% improvement in normal foveal oblique Vernier acuity; however, in persons with amblyopia, perceptual learning is not limited to the oblique meridian. All of the novices showed substantial improvement in horizontal Vernier thresholds. Interestingly, after the training, EW's horizontal Vernier thresholds had improved from 0.64 ± 0.05 minutes to 0.26 ± 0.03 minutes, comparable to the postraining thresholds in her preferred eye (0.26 ± 0.02 minutes). Similarly, thresholds in KC's amblyopic eye improved to 0.24 ± 0.01 minutes, comparable to the postraining thresholds in his preferred eye (0.25 ± 0.04 minutes).

Our results and analysis also point out the large individual differences in learning styles. Observers showed individual differences in the magnitude, time course, and style of learning. Neither the physiological nor the biochemical basis for neural plasticity is fully understood; however, there appear to be at least two processes at work: The first is a slow process that involves neural modification and requires consolida-

### Why Does Training Improve Performance?

There have been many attempts to explain why training or practice results in lower thresholds in normal foveal vision; a full discussion is beyond the scope of this report. One point of view is that perceptual learning reflects alterations of neural response early in the visual pathway, where neurons are sensitive to local features. An alternative point of view is that improvement in performance is based on high-level (or cognitive) processes. Recent evidence suggests that the learning to discriminate among orientations that is retinally local may be modulated by attention, and thus may involve higher-order visual mechanisms. As previously noted, this result does not necessarily imply that learning occurs at a high level, but it might be viewed as attention's gating the information flow, possibly at an early level. Relevant to results of the current experiments, Saarinen and Levi found that perceptual learning in Vernier acuity was accompanied by a narrowing of the orientation-tuning of Vernier acuity, as revealed by masking experiments, which will be discussed further.

To draw reasonable conclusions about the mechanisms of learning in our amblyopic observers, it is important to consider several plausible (but less interesting) possibilities, specifically, fixational eye movements, accommodation, and learning general strategies for viewing with an amblyopic eye.

Many persons with amblyopia have inaccurate or unsteady fixation; thus improvement after practice could result from an observer's learning to fixate more accurately. Although improved fixation could result
from forced use of the amblyopic eye, we believe that this cannot fully explain our results, for two reasons. First, Vernier acuity is robust to retinal image motion of less than about 4 °/sec\(^6\) — considerably faster than the fixational movements of amblyopic eyes.\(^5\) Second, more accurate fixation would be expected to improve performance at all orientations, whereas steadier fixation would be likely to improve performance most for vertical stimuli (the drift is primarily horizontal and would therefore smear vertical contours). However, in many of our observers the improvement was selective for orientation, being strongest at the trained orientation (which was either oblique or horizontal). Only one observer (a novice) showed significant improvement at the untrained orientation (Table 3). Moreover, improvement in fixation would also be expected to improve performance in the detection task; however, we found little evidence of significant transfer of learning to the untrained detection task (Table 3).

Another possible explanation of improvement after practice is that our observers learned better control of accommodation with their amblyopic eye. This explanation also seems not to account fully for the results, because Vernier acuity is relatively robust to the effects of blur.\(^7\) In addition, if the effect of training could be explained by accommodative improvement, then improvement should occur equally in all orientations and in both tasks, not just in the trained
FIGURE 7. A summary of the results of the initial training by plotting, in histogram form, the percentage of improvement from pretraining to posttraining for each observer. The left column shows results from the experienced observers, the right column from the novice observers. (top panels) The improvement in the trained (amblyopic) eye at the trained orientation and at an untrained orientation. Improvement was generally most marked at the trained orientation, with less improvement at the untrained orientation. (middle panels) Histograms show the improvement in the untrained (nonamblyopic) eye. The horizontal line segments represent the improvement in Vernier acuity in the trained eye at the trained orientation (top panel). There is considerable transfer of training to the untrained eye at the trained orientation (mean improvement is 33% for the experienced observers, 24% for the novices). At the untrained orientation, the mean improvement is considerably smaller (11% and 12% for experienced and novice observers, respectively). (lower left panel) The histograms show there is little improvement in performing a line-detection task (data of the experienced observers are shown, and the results of all five observers are summarized in Table 3). The mean improvements in detection thresholds are 7% in the trained orientation and 9% in the untrained orientations. Neither was statistically significant (Table 3). (lower right panel) Transfer of learning to Snellen acuity. Note that two novice observers (EW and KC) showed substantial improvements in Snellen acuity that were comparable to their improvements in Vernier acuity. In both panels, the horizontal line segments represent the improvement in Vernier acuity in the trained eye at the trained orientation (top panel).

orientation and task. Although some of the improvement evident in the novice observers was undoubtedly the result of learning more accurate fixation or accommodation or other general strategies for viewing with an amblyopic eye, recall that five of our observers had previous experience (from a few thousand to hundreds of thousands of trials) in making Vernier judgments with their amblyopic eyes. In these observers fixation and accommodation would be expected to be stable, as would their cognitive strategy, yet each showed a significant improvement in performance at the new orientation. Moreover, the absence of transfer of learning to the detection task makes it difficult to explain fully the training effects by some generalized cognitive change that happens gradually or by learning to focus and fixate with an unpracticed eye. Thus, we argue that at least some of the improvement in performance reflects the effects of genuine neural plasticity.

Specificity of Perceptual Learning
We explored the specificity of visual learning in an attempt to pinpoint possible mechanisms for the plasticity. The experimental strategy was to test whether

### TABLE 3. Matched-Pair One-Sample t-Test Analysis of Pre vs Post Learning Data (P)

<table>
<thead>
<tr>
<th>Observer</th>
<th>Trained Task (Vernier)</th>
<th>Untrained Task (detection)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trained Eye</td>
<td>Untrained Eye</td>
</tr>
<tr>
<td></td>
<td>Trained Orientation</td>
<td>Untrained Orientation</td>
</tr>
<tr>
<td>Experienced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FG</td>
<td>0.0049*</td>
<td>0.016†</td>
</tr>
<tr>
<td>BJ</td>
<td>0.0001*</td>
<td>0.44</td>
</tr>
<tr>
<td>KW</td>
<td>0.0038*</td>
<td>0.38</td>
</tr>
<tr>
<td>RH</td>
<td>0.08</td>
<td>0.29</td>
</tr>
<tr>
<td>RJ</td>
<td>0.373</td>
<td>0.26</td>
</tr>
<tr>
<td>Novices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td>0.0033*</td>
<td>0.22</td>
</tr>
<tr>
<td>JB</td>
<td>0.092</td>
<td>0.001</td>
</tr>
<tr>
<td>JV</td>
<td>0.0053*</td>
<td>0.18</td>
</tr>
<tr>
<td>KC</td>
<td>0.0005*</td>
<td>0.024†</td>
</tr>
<tr>
<td>LM</td>
<td>0.01*</td>
<td>0.033†</td>
</tr>
<tr>
<td>EW</td>
<td>0.0005*</td>
<td>0.27</td>
</tr>
</tbody>
</table>

* Significant P (P = 0.01 or better).
† P > 0.01 and < 0.05.
Orientation Specificity. Our results suggest that learning was strongest at the trained orientation (Fig. 3, Table 3); however, in contrast with the results of Schoups et al., we found some improvement at the untrained orientations. If the improvement with practice reflected the fine-tuning of orientation-specific neurons in V1, then improvement should be restricted to the trained orientation. However, if the improvement reflects either cognitive learning, or the learning of strategies for making perceptual judgments with an amblyopic eye (including how to fixate or accommodate), then performance would be expected to improve uniformly at all orientations. Clearly, this is not the case. Our finding of strong improvement at the trained orientation and weak improvement at the untrained orientation suggests that both cognitive and neural factors can contribute to the improvement. However, it is also important to recognize the large differences among persons. For example, EW, JV, DS, BJ, and KW showed substantial improvement at the trained orientation, with little or no improvement in the untrained orientation. Conversely, some observers (KC, JB, LM, and FG) showed considerable transfer of learning to the untrained orientation, suggesting some generalized learning as well.

Task Specificity. As a second test of the specificity of learning, we examined the specificity of improvement in the untrained detection task after extensive practice on the Vernier task. Our results suggest that perceptual learning in amblyopia is task specific. None of our observers showed significant improvement in the untrained task at the trained orientation (Table 3). Interestingly, in normal peripheral vision there is partial transfer of learning from one task (Vernier or resolution) to the other. The amblyopic deficit is more notable in Vernier acuity than in line detection, and it has been postulated that the deficit in position coding reflects noise (or undersampling) at a stage in the visual pathway beyond the site that limits detection. If this view is correct, it is tempting to speculate that the learning evident in our observers takes place at this later stage.

One of the most interesting aspects of our results is the finding that, in two of the novices with amblyopia, training in Vernier acuity appears to transfer to Snellen acuity. The improvement in EW's and KC's Snellen acuity is rather encouraging and is consistent with the close connection between Vernier acuity and Snellen acuity noted earlier. We have also noted steady improvement in several of our highly experienced observers—most notably in the one with strabismic amblyopia (RH), and in the one with anisometropic am-
blyopia (RJ). When he was first recruited as an observer in 1987, RH's Snellen acuity was 20/175. His acuity had improved to 20/68 when retested in 1989, and to 20/59 in 1990. At the most recent testing (May 1996, after completion of the learning experiments), his acuity was 20/34. We attribute this approximately fivefold improvement in acuity to his participation in psychophysical experiments (mostly involving position acuity tasks) using his amblyopic eye on average, 5 to 6 hours each week. Not quite so dramatically, RJ, who participated in experiments using his amblyopic eye for only ~1 to 2 hours a week, showed an approximate twofold improvement in acuity from 20/80 in 1987 to 20/57 in 1991, and most recently 20/43 in 1996.

Eye Specificity. Our results show partial transfer of learning to the untrained (nonamblyopic) eye. The transfer averaged approximately 60% of the direct learning effect in the trained orientation. Transfer to the other eye has been reported in results of previous studies of observers with normal vision and foveal orientation or peripheral viewing. Beard et al.15 and Ball and Sekuler16 found a transfer of learning to the untrained eye when the visual pathway led to the trained hemisphere (but no transfer of learning when the path was led to the untrained hemisphere).

The interpretation of binocular transfer is not always straightforward. No transfer suggests that learning occurs in monocular pathways. Complete interocular transfer could be interpreted as reflecting either cognitive (nonspecific) learning, or learning in binocular pathways (if the improvement in performance is specific). In peripheral vision, transfer to the trained hemisphere or to both hemispheres can distinguish between these possibilities. However, in foveal experiments, this strategy cannot be used. We believe that our results reflect, at least in some observers, neural learning beyond the site of binocular convergence. The main argument to support this contention is that the transfer is significant for the trained orientation and not for the untrained orientations (in particular, in anisometropic observers FG and BJ). If this conjecture is correct, it is surprising, because persons with amblyopia are generally considered to have a reduced complement of binocular neurons. However, there is evidence to suggest that despite a paucity of excitatory binocular connections, some persons with amblyopia maintain some binocular interactions.38–40

In summary, we found evidence for both general learning (particularly in the novice observers) and specific learning. We note that some observers, particularly the novices, showed more transfer of learning (for example, to the untrained orientation) than is typically reported in experiments of this type in normal observers. We believe that this transfer reflects generalized learning effects, which probably occurred in the early stages of learning (perhaps in the first few sessions). For several of our observers, the improvement in performance was both orientation and task dependent. The task and orientation specificity are both strong arguments for learning in orientation-tuned neurons, possibly owing to fine-tuning (or calibration) of the mechanisms mediating the task.17,18

Interocular transfer of learning provides evidence for the view that learning occurs at or beyond the primary visual cortex where binocular interactions have been reported, perhaps at or beyond area V1.41 Finally, we note the point made forcefully by Mollon and Danilova,42 that an absence of transfer does not necessarily imply that the site of learning is early. The learning may be central, and the specificity may lie in what is learned. For example, the narrowing of orientation tuning reported by Saarinen and Levi18 may reflect that the observer learns to rely on the signals from a more sensitive (and more narrowly tuned) subset of all the neurons that respond to the stimulus. In this view, perceptual learning in persons with amblyopia may reflect a form of "calibration" of visual space with the amblyopic eye.

Cortical Plasticity in Adults With Amblyopia

The current results suggest that some adults with amblyopia retain at least some cortical plasticity. Repetitive training leads to substantial improvement in Vernier acuity that is task and orientation specific. This result is consistent with recent evidence of a remarkable degree of plasticity in the visual cortex of adult cats with experimentally induced retinal lesions43,44; however, it is surprising, because the physiological effects of strabismus or lid suture on the cortex are generally thought to be irreversible after some critical period (typically 3 to 4 months in cats and monkeys).45,46

Although it is often stated that persons with amblyopia cannot be treated beyond a certain age,4 a review of the literature suggests otherwise. For example, Kupfer47 reported marked improvement in acuity, in seven adults with strabismic amblyopia (age range, 18 to 22 years). All seven showed improvements ranging from 71% (20/70 to 20/20) to a dramatic improvement from seeing hand-only movements, to 20/25 after 4 weeks. It is important to note that all patients had relatively late onset (age 2 years or older), were highly motivated, and that Kupfer's treatment was aggressive. The patients were hospitalized for 4 weeks, during which time their preferred eyes were continuously patched and given fixation training. However, the very fact that adults with amblyopia can improve suggests that there is no clear upper age limit for recovery of acuity, at least in strabismic amblyopia with an onset older than age 2 or so. Since Kupfer's findings, there have been many reports of improvement in acuity of older persons with amblyopia.48,49
Our results raise some interesting questions about the treatment of amblyopia. The “standard” treatment for amblyopia consists of patching the preferred eye. Although results in anatomic and physiological studies suggest that early reverse occlusion operates to reverse the physiological dominance of the deprived eye, the mechanisms of improvement in acuity in older children (and adults) is not yet known, although it is clear that treatment is frequently effective in improving visual acuity and other visual capacities. Could the improvements evidenced in clinical treatment of amblyopia represent effects that are similar to the plasticity that we have documented here? The specificity of perceptual learning evidenced in the current results poses some difficulties. If the improvement after practice were solely limited to the trained stimulus, condition, and task, the type of plasticity documented here would have limited (if any) therapeutic value for amblyopia, because amblyopia is defined primarily on the basis of reduced Snellen acuity. However, the Vernier acuity of amblyopic persons is highly correlated with their Snellen acuity (see Levi), suggesting that the same mechanisms might limit both tasks; and two of our observers, both novices, after practicing Vernier acuity, showed commensurate improvements in Snellen acuity. Note that, similar to clinical treatment of amblyopia, during the experimental sessions the preferred eyes of our observers were patched while they performed the Vernier task (see Methods section). Brief periods of occlusion have been shown to result in improvements in young children with amblyopia. Moreover, during the experiments, our observers were engaged in making fine visual discriminations using their amblyopic eyes, and it is often claimed that “active” learning is more effective than passive learning. Finally, it is important to emphasize that in our experiments, observers were provided repeated exposure to the same stimuli, and were given explicit feedback regarding the direction and magnitude of the Vernier offset. To the extent that poor positional acuity in amblyopia results from improper calibration of visual space, we speculate that this feedback may have been helpful in developing a useful calibration of visual space with the amblyopic eye.

Permanence of Perceptual Learning

In adults with normal vision, perceptual learning effects are often reported to be long lasting. The longevity of these effects is clearly of special interest in persons with amblyopia, where it is well known that the effects of treatment often regress. One of our observers who showed significant learning (KC) returned approximately 10 months after the conclusion of the study. Figure 10A shows his Vernier acuity for horizontal lines during the original training period (open symbols), and after a 10-month hiatus (solid symbols). Clearly, his performance after the hiatus was not as good as when he finished the initial training but was considerably better than his initial performance. In other words, he retained about 40% of his improvement. More important, note the rapid improvement in performance to a level equal to or slightly better than that achieved initially. Similarly, his Snellen acuity (Fig. 10B) regressed throughout the 10 months to just slightly better than his baseline level; but, like his Vernier acuity, it showed marked improvement after about 1 week of practicing Vernier acuity.

Summary

The major findings of the current study are that repetitive practice leads to significant and substantial improvements in Vernier acuity in the amblyopic eyes of adults with naturally occurring amblyopia. In at least some of our observers, the improvement was orientation and task specific and shows partial transfer of learning to the untrained eye (at the trained orientation). Taken together, our results suggest that at least some of the improvement in performance in the amblyopic eyes must be a consequence of genuine neural
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learning, perhaps caused by sharpening of neural responses, that is task and orientation specific but is localized beyond the site of convergence of the two eyes.

**Key Words**

amblyopia, learning, orientation, plasticity, vernier acuity

**References**

40. Anderson P, Mitchell DE, Timney B. Residual binocu-
APPENDIX: SEGMENTED REGRESSION

Learning Data and Segmented Regression

Perceputal learning data are the record of the observer’s Vernier acuity thresholds in a series of time in-

dextes. Statistical trend analysis of the data provides a means of assessing learning efficiency. Because our data show strong nonlinear trends, we believe that the conventional linear regression model is not adequate. Instead, a model with several line segments (segmented regression) would describe the complex learning process better. For instance, we have N observations for N indexes of time: \( y_1, y_2, ..., y_N \) in which the first \( m (m < N) \) observations follow a regression line, but the rest of the observations are best fit by another line. In this situation, the slopes of the two lines may be different, or the two lines may not be connected. The statistical model for this particular segmented regression problem is as follows:

\[
\begin{align*}
\text{if } 1 \leq i < m, \quad y_i & = a_1 x_i + b_1 + \epsilon_{i,1} = 1,2,3,...,m \\
\text{if } m < i \leq N, \quad y_i & = a_2 x_i + b_2 + \epsilon_{i,m} = m + 1,...,N
\end{align*}
\]

where \( \epsilon_i \) is the error term and \( m \) is an integer \((1 < m < N)\).

The critical index \( m \) is referred to as a “turning point” or “change point” in the statistical literature. In a sequence of measurements taken in some physical process, the critical time index indicates the possible occurrence of a change—for example, in learning.

Notice that when \( a_1 = a_2 \) and \( a_1(x_{m+1} - x_m) + b_2 - b_1 = 0 \), corresponding to equal slopes and the connected condition at \( m \), the segmented regression model above is reduced to conventional linear regression.

In exploratory data analysis of perceptual learning data, the critical index \( m \) is unknown because we do not know when improvement might occur. Therefore, to apply segmented regression, first we must estimate the index \( m \) from the data, and then fit the data with the segmented regression model, using the estimated \( m \). Thus, we obtain the estimated \( a_1, b_1 \) and \( a_2, b_2 \). The final step is to select a model: We have to decide whether the data follow a true segmented model (two connected lines or two disconnected lines) or a simple linear regression model. This can be achieved through proper statistical testing. The statistics involved in estimating turning points in a sequence of observations belong to statistical change analysis, which will be described later.

Moreover, data recorded from a complicated process may reveal more complicated trends than would the two-phased segments. In such cases, a several-phased, segmented regression is more appropriate. In fact, most of the data presented in this paper are better fit with this general model than they would be with the two-phased model. Here, unknown parameters include the number and the location of the change points, which must be estimated from the data.
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Learning Process and Segmentation

To apply segmented regression to the learning data, first we must have grouping data. This corresponds to estimating the change parameters in the following way, so that if we divide the original sequence \( y_1, y_2, \ldots, y_N \) into \( r + 1 \) groups, 

\[
(y_1, \ldots, y_{m_1}), (y_{m_1+1}, \ldots, y_{m_2}), \ldots, (y_{m_r+1}, \ldots, y_N),
\]

the observations within each group are similar but different among the groups, in that the mean values of the consecutive groups are significantly different.

In our learning data, grouping the thresholds on the basis of level (mean) change indicates the different phases of the observer's performance. However, observers' performances may progress in different ways: continuously improving, worsening, or remaining relatively stable. Therefore, any model for learning data should characterize the process in three aspects: the mathematical form of slow progress, the type of substantial learning, and where the substantial learning (change) occurs.

In the current study, we use a linear function (a line) to describe local slow progress; substantial learning or change could take the form of either an abrupt change (jump), or turning (slope change), or both. The statistic involved in the grouping strategy is referred to as mean change detection, which is introduced next.

Preliminaries of Mean Change Analysis

Applications of statistical change analysis appear in a variety of fields, including quality control, econometrics, global change analysis, and medical science. Recently, change analysis has been used in the pharmaceutical industry and in vision science.\(^{54,55}\)

Mean Change-Point Problem. Suppose that the \( N \) ordered observations \( y_1, y_2, \ldots, y_N \) have distribution functions \( F_1, F_2, \ldots, F_N \) with means \( \mu_1, \ldots, \mu_N \), respectively. The basic question in the mean change-point problem is whether \( \mu_1, \ldots, \mu_N \) remain the same, or whether at least one change has occurred.

The single change-point problem is the hypothesis-testing (H) problem expressed as follows:

\[
\begin{align*}
H_0: \mu_1 = & \ldots = \mu_N \\
H_1: \mu_1 = & \ldots = \mu_m \neq \mu_{m+1} = \ldots = \mu_N
\end{align*}
\]

where \( m \) is unknown, \( 1 \leq m \leq N - 1 \).

Several procedures are available to determine the location of the change. For instance, a number of workers develop various CuSum (cumulative sum) type procedures. Encompassing much of the previous works, Parzen\(^{56}\) introduced a new approach to the change-point problem, which we will see partially in the section about the CuSum procedure. However, analysis on the several-abrupt-change-points problem is complicated and involves more advanced statistics and mathematics, which are beyond the scope of this report (see McCulloch and Tsay\(^{57}\) and Hu\(^{58}\)). Instead, we will use the sequential CuSum procedure to deal with the problem of determining several mean values in the dark in the report. The method is known as an ad hoc approach for detecting several change points. Hu\(^{58}\) demonstrated that the estimates are reasonable and comparable to those obtained from the advanced approaches under reasonable assumptions about the data. Here, we present a brief description for a CuSum procedure, and then illustrate the sequential CuSum procedure with our learning data.

CuSum Procedure. For given observations \( y_1, y_2, \ldots, y_N \), we form two processes (dynamic statistics) on the interval \([0,1]\): the density process and the CuSum process (change process)

\[
c(t) = \frac{\bar{y} - t}{\tilde{\sigma}} \quad f(s) ds
\]

respectively, where the density process \( \tilde{C}(t) \) is actually an alternative form of the standardized data with \( \tilde{c}(1) = 0 \). \( \bar{Y} \) is the sample mean and \( \tilde{\sigma} \) is the sample standard deviation as usual.

Under the null hypothesis of no change, the CuSum process \( \tilde{C}(t) \) converges in distribution to a standard Brownian Bridge stochastic process (no pattern). The term “bridge” is given by the facts that \( \tilde{C}(0) = \tilde{C}(1) = 0 \). If there is any change, some pattern will show up on the graph of the CuSum process. For instance, a simple change in the mean will produce a peak (trough) feature in the process, and it suggests a downward (upward) shift in the mean. It is true that some templates of the CuSum process plots are informative and useful when considering types of changes in the data. For example, the convex- or concave-looking and S-shaped CuSum processes present evidence of linear and quadratic trends, respectively. Thus, in the exploratory data analysis, the CuSum procedure provides a diagnosis for change in the mean.

Being rigorous in statistics, one may construct either Kolmogorov–Smirnov-type or likelihood-type statistics to test the existence of a change point, namely,

\[
KS = \max_{j=1,\ldots,N-1} |\tilde{C}(\tau_j)|.
\]

Here,

\[
\tau_j = \frac{j}{N}.
\]
The possible change point is suggested by the argument at which the statistic $KS$ takes the extreme value.

**Example 1.** The data set RJ135 (Fig. A1, [2,2]) consist of 47 observations. A peak appears at 21 on the graph of the CuSum process (Fig. A1, [3,2]). This suggests that there are two stages in RJ's learning process (improving). However, the curvature on both sides of the change point suggests a linear (not horizontal) tendency on each side. With the estimated change (21), the fitted model is formed by two connected segments whose slopes are estimated as $-0.0161$ and $-0.0044$. The significance tests leave $P$ values of 0.0005 and 0.19, respectively, and the $P$ value for the equal-slope test is 0.09. The model explains RJ's gradual learning process: He seemed to learn faster in the first 21 training blocks.

**Example 2.** In this sequential CuSum procedure, the data set DSO (Fig. A1, [2,3]) are records of 53 threshold readings. We estimate the primary change point $t = 20$ from the CuSum procedure, as described. Using this cut point, we divide the data set into two subsets: $S_1 = \{y_1, \ldots, y_{20}\}$ and $S_2 = \{y_{21}, \ldots, y_{53}\}$ and then apply the CuSum procedure to each of the two smaller sets, as though they were unrelated. Thus, the time indexes 12 and 36 are located as change points in the processes $S_1$ and $S_2$, respectively. The three estimated change points, 12, 20, and 36, suggest using the general segmented regression model to fit the data set DSO. The regression and linear hypothesis testing leave the results as follows. Slopes:

$$b_1 = -0.034 \ (P = 0.155); \quad b_2 = -0.035 \ (P = 0.426);$$
$$b_3 = -0.00066 \ (P = 0.97); \quad b_4 = 0.00061 \ (P = 0.97).$$

$P$ values for the continuity test at the three change points: 0.47, 0.23, 0.043; $P$ values for the equal-slopes tests: 0.987 ($H_0: b_1 = b_2$); 0.95 ($H_0: b_3 = b_4$)

Based on the information, we see the model agrees with $b_1 = b_2$, $b_3 = b_4 = 0$, and it is connected at 12,20 but jumps at 36. Finally, we chose the condensed segmented model with three pieces, with the lines connected at 20 and disconnected at 36. The slopes are $-0.654, 0, 0$. The CuSum process and the segmented model for data set DSO are plotted in Figure A1: (3,3) and (2,3) respectively.

The model characterizes DS's learning process: faster learning in the first 20 training blocks, then accumulating experience, but remaining at essentially the same level of performance for the next 15 blocks. Suddenly, DS achieved substantial improvement and reached a higher level of Vernier acuity (lower thresholds).

**Summary**

In summary, the statistical work on trend analysis with the segmented regression model consists of two parts: grouping sequential data based on change-points estimation and model selection. The latter is accomplished by segmented regression and the associated testing of the linear hypothesis.