



# Perceptual Learning in Parafoveal Vision

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**The present study tests the effects of practice on parafoveal vernier and resolution acuity. By measuring task specificity, transfer of training to other retinal locations in the trained eye and transfer of training to the untrained eye, we directly address whether improvement on these tasks is the result of changes in the underlying physiological processes or simply the development of new cognitive strategies. We found that: (1) significant learning can occur for both vernier and resolution acuity in many (but not all) individuals; (2) there were significant individual differences in the degree and time-course of learning; (3) learning transfers to the untrained task; and (4) learning transfers to the other eye particularly when the visual pathway leads to the trained hemisphere. These results suggest that both physiological and cognitive processes contribute to the improvement seen after repetitive practice on these visual tasks.**

Vernier acuity Learning Plasticity Hemispheric Visual mechanisms Periphery

## INTRODUCTION

Practice can improve performance on a variety of visual tasks, however little is known about what produces lower thresholds following practice. Practice-based improvement may depict the rapid synthesis of task-specific modules (Poggio, 1990; Poggio, Fahle & Edelman, 1992), a fine tuning of the neural mechanisms responsible for the task (McKee & Westheimer, 1978; Saarinen & Levi, 1995; Zohary, Celebrini, Britten & Newsome, 1994), an improvement in selective attention (Saugstad & Lie, 1964) or any combination of these factors. In this paper we explore the contributions of these factors to perceptual learning in parafoveal vision.

Several experimental methods can aid in the extraction of the relative contributions of early and late mechanisms to training-based improvement; (i) task specificity, (ii) location specificity and (iii) interocular specificity. The rationale behind the use of these methods is straightforward. First, if improvement after practice represents fine tuning of a small subset of early visual neurons, then learning should be specific to tasks mediated by the same set of visual neurons. If, on the other hand, improvement transfers to tasks mediated by different mechanisms, then some more general, possibly higher level (e.g. cognitive) process may explain the learning effects. Second, if improvement occurs in only the trained retinal location, then improvement cannot be easily explained by cognitive processes. Lastly, transfer, or lack of transfer, of training to the untrained

eye may give some pointers as to the site of training effects.

The specificity of training effects has been used to try to locate the source and determine the substrate of visual learning. Interpretations of this research suggest that practice may alter the tuning of neural mechanisms (McKee & Westheimer, 1978; Saarinen & Levi, 1995). Specificity of learning is reported for the discrimination of patterns of a similar orientation (Fiorentini & Berardi, 1981; Mayer, 1983; Poggio *et al.*, 1992; Fahle & Edelman, 1993), similar spatial frequency (Fiorentini & Berardi, 1981; Pasley, 1985) and similar direction of motion (Ball & Sekuler, 1987). In addition, learning does not appear to transfer to other retinal locations within the trained eye (Fiorentini & Berardi, 1981; Karni & Sagi, 1991; Kapadia, Gilbert & Westheimer, 1994). Fiorentini and Berardi (1981), for example, found no transfer when they trained contrast sensitivity binocularly in the superior field and tested transfer in the inferior visual field. The amount of training transfer has also been assessed between eyes. Fiorentini and Berardi (1981), Karni and Sagi (1991) and Ball and Sekuler (1987) did report some interocular transfer, whereas Poggio *et al.* (1992) reported no transfer (although their article provides no specifics of the study). Unfortunately, the results of these studies are not always conclusive. Much of this research either has a very small subject pool or has ignored the large individual differences in training data. It is still unclear if visual learning occurs at the site of selective filters responsible for the trained task or if cognitive components play a major role in lowering these thresholds.

The purpose of our experiment was three-fold. (1) To assess any change in thresholds that might occur after monocular practice on either a vernier or resolution

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acuity task. In particular, we chose to perform these experiments in the parafovea, since parafoveal learning is thought to be extensive (Saugstad & Lie, 1964; Fendick & Westheimer, 1983), perhaps because the parafovea is not used for fine spatial discriminations in everyday life. (2) To determine if training effects transfer from one task to the other. We began by obtaining baseline or pre-training vernier and resolution acuity's in all observers. We then repetitively trained observers on *either* a vernier or a resolution acuity task over a 6-day period followed by a post-training determination of both acuities. These pre- and post-training measurements quantify the amount of training transfer between the tasks. (3) To determine whether improvement transfers to other retinal locations in the trained and untrained eyes.

## METHODS

### Stimuli

Figure 1 shows a schematic of the two stimulus sets used in this experiment. Figure 1(a) shows the resolution stimulus and Fig. 1(b) the vernier stimulus. Each stimulus consisted of three bright, horizontal lines presented on a SONY Trinitron monitor and generated by an Amiga 2000. For each stimulus two of the lines were solid (distractors) and the third (the target) was either "broken" (resolution task) or "wiggly" (vernier task). The broken or wiggly line was randomly assigned to the top, middle or bottom position, and the observer's task was to judge which of the three lines was the target. This task (i.e. to choose the odd line out) was chosen to minimize both the observer's cognitive load, and any criterion effects. For both tasks, from the 3 m viewing distance, the lines were 108 min arc long, and were separated vertically by 45 min arc. The background screen was dark. Stimulus presentation time was

150 msec. The resolution target consisted of a given number of bright pixels alternated with the same number of blank pixels. The vernier stimulus consisted of five alternating offset segments each 21.5 min arc in length. By using these stimuli, the vernier and resolution acuity tasks were comparable. The three lines comprising the vernier and resolution stimuli had equal average brightness.

### Procedure

Observers viewed the display monocularly, fixating on a dim red LED. A head and chin rest maintained viewing position. The stimulus edge was located 5 deg parafoveally. The observer's task was to choose the odd line out, a spatial three-alternative forced-choice design. Resolution and vernier thresholds were estimated using a "series" staircase procedure. A "series" consisted of three trials at a fixed gap size (resolution) or offset (vernier). Preliminary data determined the initial offset value, subsequent offset levels were determined by performance on the previous trial series. The observer's task was to set one of three buttons to indicate the target position. If the responses to all three presentations within a series were correct, the vernier offset or resolution gap size was decreased by 1 pixel in the following series. Two correct responses resulted in no change, and one or no correct responses in a series resulted in the offset or gap being increased by 2 pixels. Using this tracking procedure the observer was always presented with conditions that were near their discrimination thresholds (66% correct). This staircase was used to present stimuli slightly above and below the threshold level in order to construct an entire psychometric function. Thresholds are based upon either 51 or 102 trials (i.e. 17 or 34 series—see Experimental Strategy).

We constructed psychometric functions from the data and then analyzed the number of correct responses as a function of offset (for vernier) or gap size (for resolution) using probit analysis. Initially we allowed the psychometric function slope to float. We found individual differences (between-subject differences) in the psychometric function slopes. In addition, although slopes were similar within an individual, within-subject differences in slope did exist. Because of these within-subject differences in the psychometric function steepness, we obtained average estimates of the slope for each observer. We then repeated the probit analysis for each observer by fixing the slope to the averaged slope computed for that observer. These fixed slope thresholds reduced between-block variability in the observer's thresholds. The plotted thresholds and their error bars were estimated from this second probit analysis, and are specified as the offset (vernier) or gap size (resolution) yielding 66% correct performance.

### Feedback

Previous studies of perceptual learning have yielded mixed results on the importance of trialwise feedback. Several studies found little effect of feedback (Gundy, 1961; McKee & Westheimer, 1978; Fahle & Edelman,

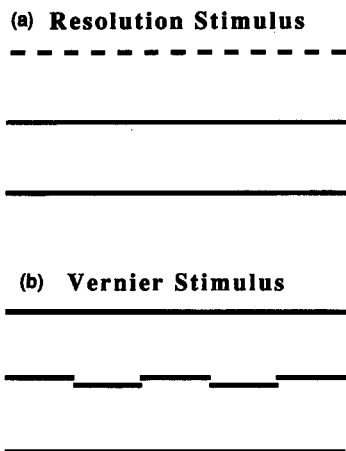


FIGURE 1. Schematic of the resolution and vernier stimuli each consisting of three bright, horizontal lines of equal average brightness. Two of the lines were solid (distractors) and the third (the target) was either "broken" (resolution task) or "wiggly" (vernier task). The broken or wiggly line was randomly assigned to the top, middle or bottom position, and the observer's task was to judge which of the three lines was the target.

1993), while other research found that feedback speeds improvement [Blackwell (cited in Green & Swets, 1966)] particularly for more difficult conditions (Ball & Sekuler, 1987). Since naive observers often find peripheral judgments difficult, we provided visual feedback (a brief light flash at the correct location) after each trial.

#### *Motivation*

Since observer motivation is important in learning studies, we attempted to maintain motivation in our observers by rewarding them with 5 cents for each correct response and deducting 1 cent for each incorrect response.

#### *Eye position*

During each session we monitored observer fixation using an ISCAN video eyetracking system. A tone sounded if the observer's eye wandered more than approx. 1 deg from the fixation point. Trials containing eye movements larger than the one deg window were discarded, and replaced by a new trial. This eyetracker was calibrated on average six times during each session. The eye movement monitoring equipment permitted relatively precise parafoveal measurements without using a potentially conflicting secondary foveal task (Ball & Sekuler, 1987; Ball, Beard, Roenker, Miller & Griggs, 1988) since it is particularly difficult to split attention between two separate spatial regions (Posner, Snyder & Davidson, 1980).

#### *Experimental strategy*

At the beginning of the experiment we assigned one training task to each observer. Ten observers were trained on the vernier task and 10 on the resolution task. Training consisted of three phases: (1) *pre-training* measures on both the vernier and resolution tasks in both eyes for both nasal and temporal retinas; (2) a *training* phase where each observer repetitively trained on either the vernier or the resolution task for 6 days, 10 repetitions of 34 series of three trials each (1020 total trials) were run each of the 6 training days; (3) *post-training* measures which were the same as the pre-training measures. Pre- and post-training required one or two sessions. On these days each block consisted of 51 trials. Two threshold measures were determined for both the vernier and resolution tasks at the nasal and temporal parafoveal retinal locations of each eye. We counterbalanced the task order for the first and second measures and determined this pre-training sequence for each observer prior to their recruitment. Each observer was trained on their assigned task in the right eye, temporal retina.

#### *Observers*

Twenty observers between the ages of 18 and 37 yr participated in eight or nine 1–2 hr sessions. They were students, faculty or staff at UH—College of Optometry and had recently had thorough eye examinations revealing no pathologies. Snellen acuities were 20/25 or better.

Eighteen of these observers had no prior experience in psychophysical experiments.

## RESULTS

### *Improvement over training days*

Figure 2 presents the threshold data for nine observers trained on the *resolution* task. Thresholds are plotted in min arc across training blocks. The first and last data points on each graph ( $\Delta$ ) represent the pre- and post-training day data for the trained condition. Over the training days each datum represents the threshold based upon 102 trials. Rather than connecting the data points, we fit each data set within a daily session with a linear function. By fitting the data in this way we feel that "local" trends can be more easily seen. Regression analyses were performed on these local trends providing information about learning within each day of training. Training day data showing a significant ( $P < 0.05$ ) threshold decrease (or threshold increase since we used a two-tailed test) are presented on a shaded background. For example, observer JA shows significant improvement within a daily session only on the 5th training day. To determine the overall training effect for each observer, we also performed regression analysis on the data across the 6 training days. The significance of each  $F$  statistic for these overall analyses (probability values) are shown in the lower left-hand corner of each individuals' panel.

In five of nine observers trained on the resolution task, thresholds improved throughout the course of practice ( $P < 0.05$ ). Since significant learning did not occur within most of the 6 daily sessions in these five observers, improvement on the resolution task was gradual over the course of training. On the other hand, observer WW did not show an overall improvement ( $P > 0.05$ ) but did show significant improvement *within* half of the training days. These results emphasize the rather considerable individual differences in initial thresholds and in the course of improvement.

Figure 3 presents the individual learning curves for nine observers trained on the vernier task. Of the five observers showing overall improvement ( $P < 0.05$ ), much of the improvement can be explained by learning within the daily sessions (shown with shaded regions). In many cases the initial daily threshold is higher than the final threshold from the session before, perhaps due to "forgetting" between sessions and rapid improvement within a session.

In summary, over half of the observers showed overall improvement after vernier and resolution acuity training, however, the nature of the learning appears to differ for the two tasks. While improvement on a resolution acuity task is gradual, improvement on a vernier acuity task more likely occurs rapidly within daily sessions.

### *Transfer of training*

To help define the nature and locus of any training effects we used a technique that takes

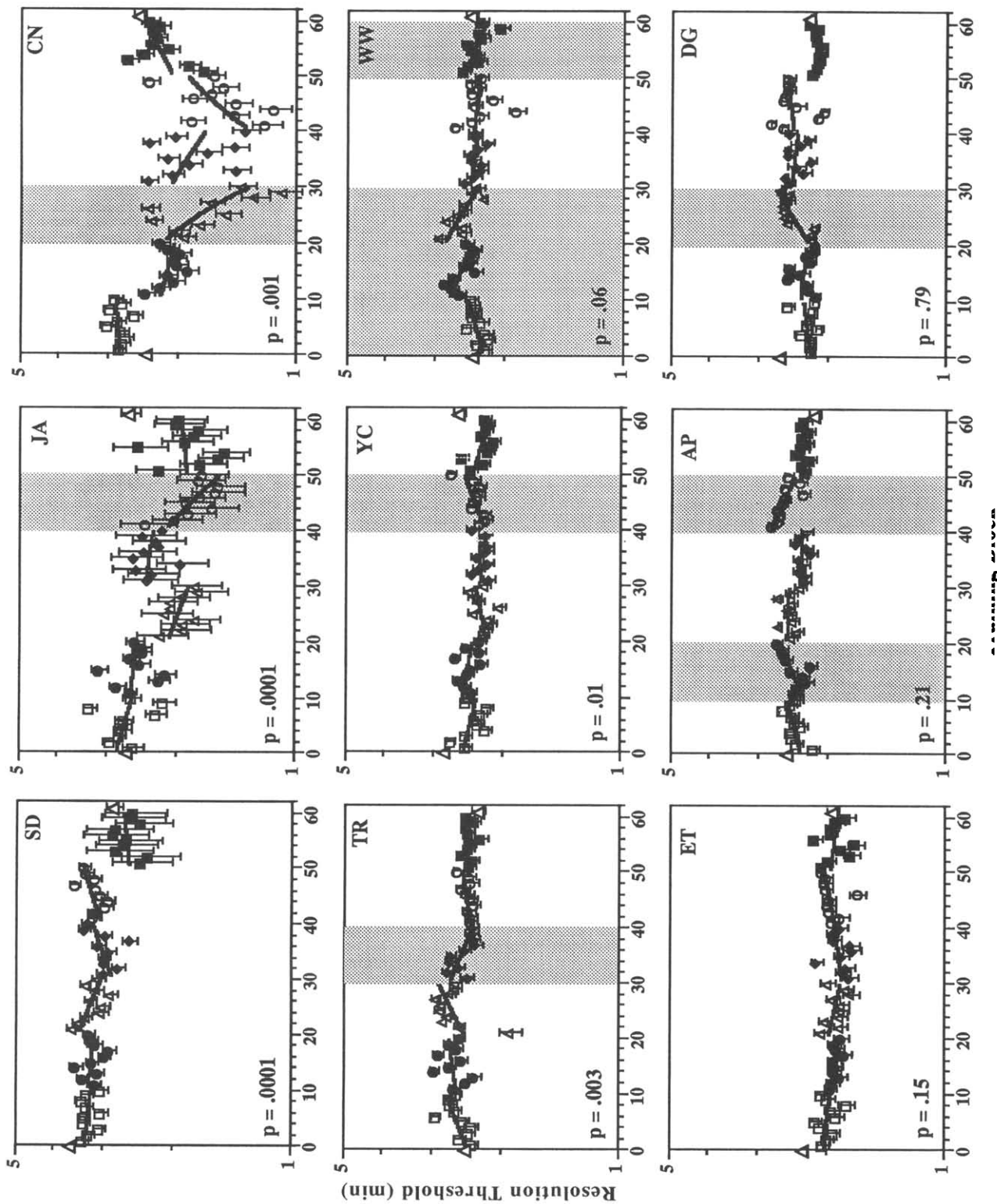


FIGURE 2. Threshold (min arc) data for nine observers trained on the resolution task. The first and last data points on each graph (Δ) represent the pre- and post-training day data for the trained condition. Each data set within a daily session have been fit with a linear function. Training day data showing a significant threshold decrease (or threshold increase since we used a two-tailed test) are presented on a shaded background. Regression analysis was also performed on the overall training over the 6 training days. The probability values from this analysis are shown in the lower left-hand corner of each individuals' panel.

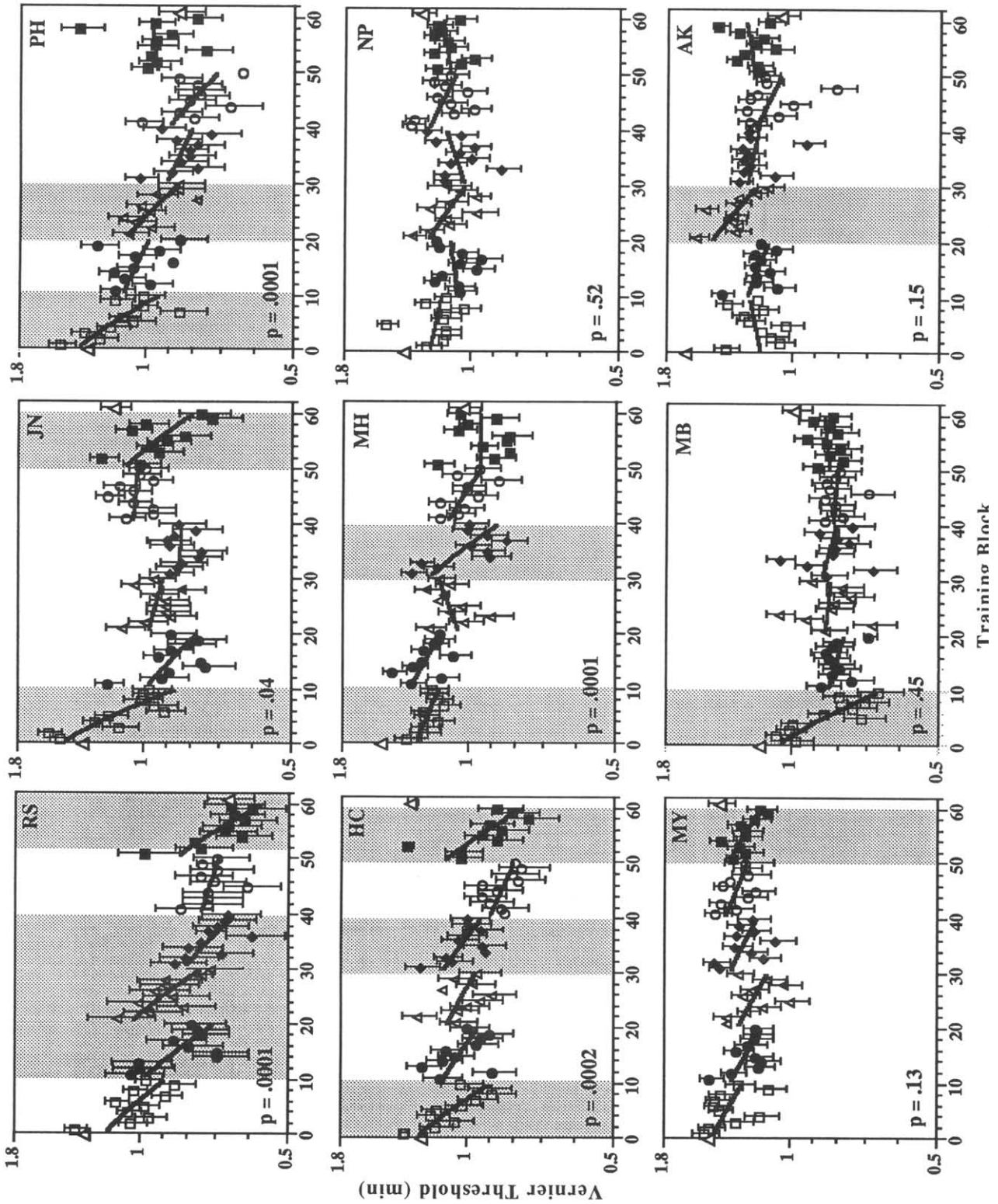


FIGURE 3. Individual learning curves for nine observers trained on the vernier task. Conventions are the same as in Fig. 2.

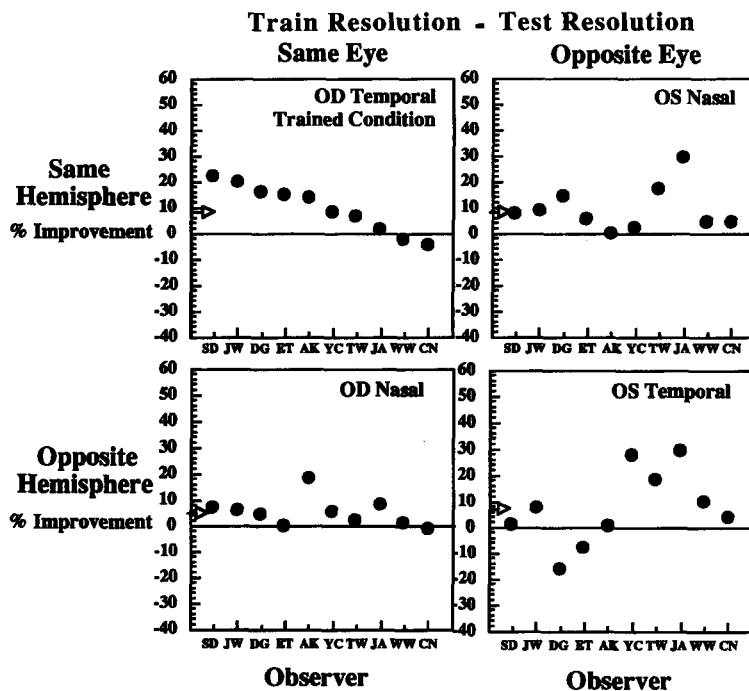


FIGURE 4. The percentage improvement, or change, from pre- to post-training for each observer trained and tested on the resolution task. The arrow on the ordinate represents the mean percent improvement for that experimental condition. The horizontal line at 0% improvement represents no change from pre- to post-training. The columns are labeled with “same” or “opposite” eye referring to whether the testing was done on the same or opposite eye to that which was trained. The rows are labeled with “same” or “opposite” hemisphere in a like manner.

advantage of the natural split in visual pathways which divides the visual world into two fields, each of which project to one brain hemisphere (see Fig. 8). We assessed transfer of learning by pre-testing at four retinal locations in both eyes and on both tasks, training at one of the locations on only one task and then post-testing performance at the original sites.

Figures 4–7 present the percentage improvement, or change, from pre- to post-training for each observer. The order of observers (shown with initials) on the abscissa is arbitrary. The arrow on the ordinate represents the mean percent improvement for that experimental condition. Figures 4 and 5 show the data for the 10 observers trained on the resolution task and Figs 6 and

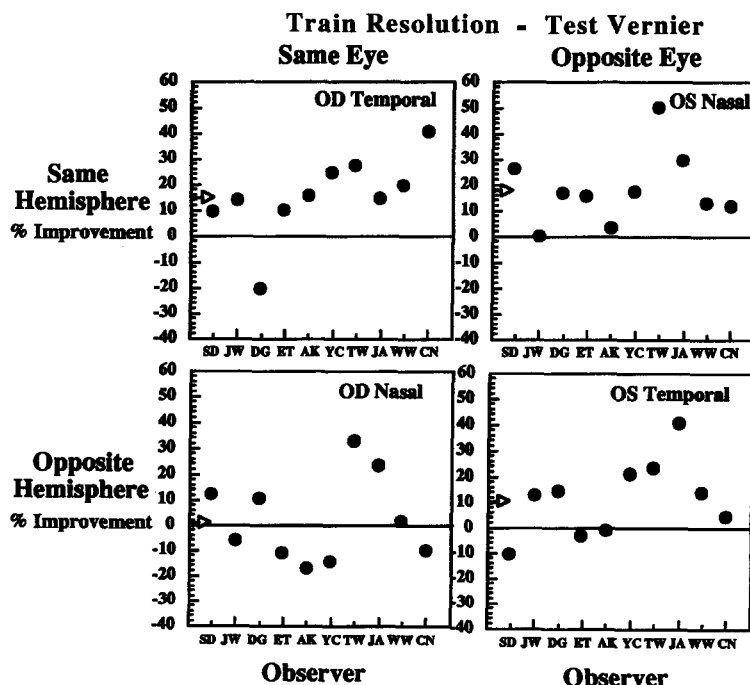


FIGURE 5. The percentage improvement, or change, from pre- to post-training for each observer trained on the resolution task and tested on the vernier task.

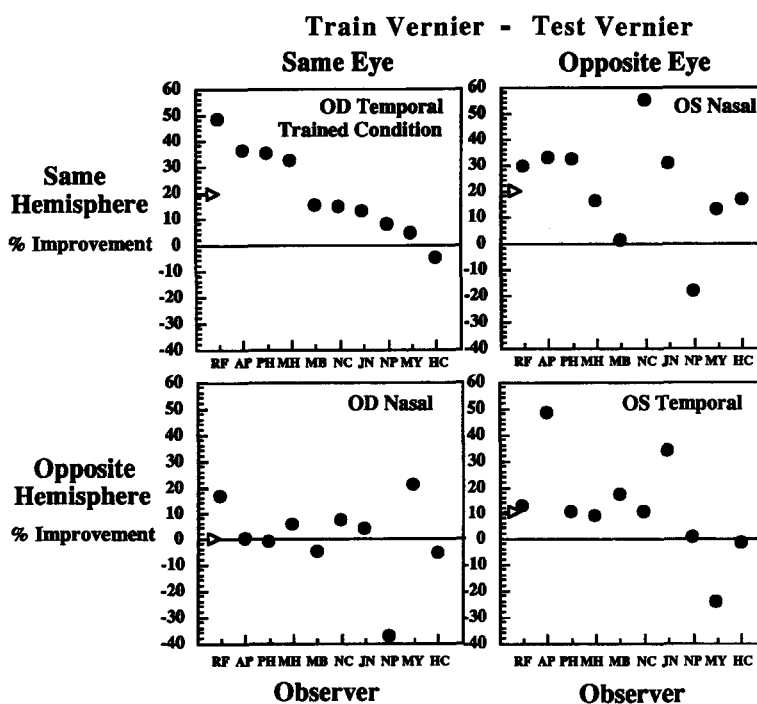


FIGURE 6. The percentage improvement, or change, from pre- to post-training for each observer trained and tested on the vernier task.

7 show the data for the observers trained on the vernier acuity task. Figures 4 and 6 show the improvement seen when the observer was tested on their trained task and Figs 5 and 7 show the amount of improvement seen for the untrained task. The horizontal line at 0% improvement represents no change from pre- to post-training. We labeled the columns with “same” or “opposite” eye referring to whether the testing was done on the same or opposite eye to that which was trained. We labeled the

rows with “same” or “opposite” hemisphere in a like manner.

Trends may be seen in the individual data and were confirmed with statistical analysis on the percent improvement scores (ANOVA). This analysis had one between groups factor (training condition) and three within groups factors (retinal location, same/opposite eye, and visual task). The analysis revealed that a similar amount of overall improvement was seen in

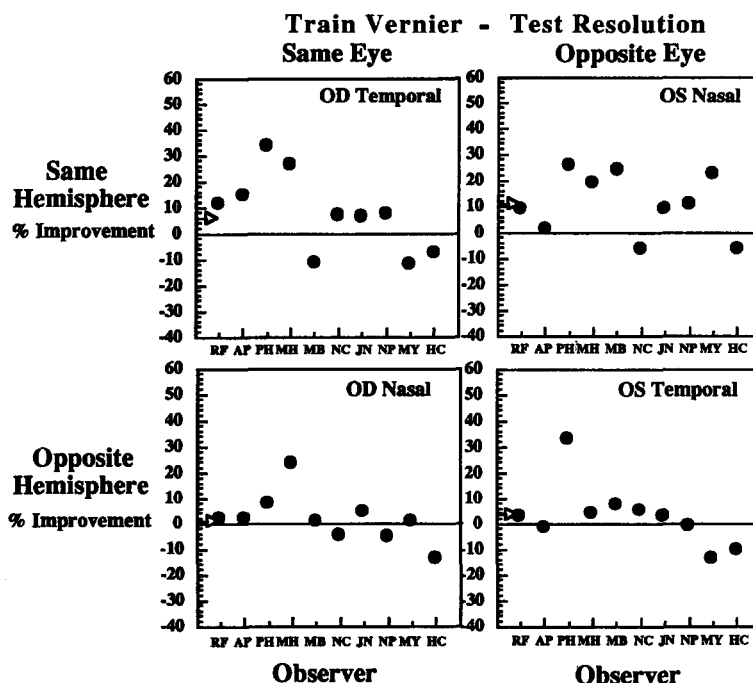


FIGURE 7. The percentage improvement, or change, from pre- to post-training for each observer trained on the vernier task and tested on the resolution task.

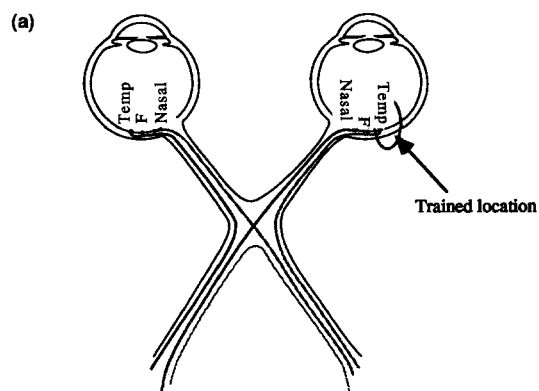
both training groups [ $F(1, 18) = 0.01, P > 0.05$ ] but that the greatest improvement was seen for the vernier task [ $F(1, 18) = 4.55, P < 0.05$ ]. The Training condition  $\times$  Visual task interaction did not reach significance [ $F(1, 18) = 0.44, P > 0.05$ ]. Therefore we conclude that there was transfer of training between tasks, supporting at least in part, a cognitive explanation (see Discussion). When the tested pathway led to the trained hemisphere (e.g. right eye temporal and left eye nasal) improvement was greater than in the untrained hemisphere as shown by the statistically significant Location  $\times$  Eye interaction [ $F(1, 18) = 39.4, P < 0.0001$ ]. Observers showed the greatest improvement on the vernier task (Figs 5 and 6), even when they trained on the resolution task. There was also significant transfer to the untrained eye for both tasks [ $F(1, 18) = 4.42, P < 0.05$ ] predominantly when the pathway led to the same hemisphere, although there was transfer to the untrained hemisphere when testing vernier acuity. The selectivity of this transfer supports a physiological or hardwired explanation for the improvement. The least amount of transfer was to the untrained location in the trained eye (OD nasal). We repeated the analysis excluding the 10 observers who did not show significant learning effects over training days (see Figs 2 and 3), with essentially identical results.

To more clearly see the transfer of training results, Fig. 8 presents a summary of the pre- and post-training days mean percentage improvement scores. Figure 8(a) presents a schematic of the four retinal positions tested and their neural pathways projecting to the left and right hemispheres of the brain. Each observer was trained on their assigned task in the right eye, temporal retina. Figure 8(b) presents the mean percent improvement scores in tabular form for each training/testing condition and their respective SEs (Tukey test).

If improvement could be explained solely on the basis of underlying front-end visual mechanism plasticity, then improvement would be expected only when testing on the trained task (i.e. train on vernier and test on vernier; train on resolution and test on resolution) at the trained location. That there is improvement for the untrained task, and in the opposite eye and hemisphere, suggests that both an early (physiological) and later (possibly cognitive\*) mechanism explanation must be proposed for improvement after training.

## DISCUSSION

We explored the specificity of visual learning in an attempt to pinpoint possible neural sites of such plasticity. The experimental strategy was to test whether improvement on vernier or resolution acuity is local, or



(b)

Retinal Location	Opposite Hemisphere		Same Hemisphere	
	OS Temporal	OD Nasal	OS Nasal	Trained Location OD Temporal
Train Vern				
Test Vern	11.39 $\pm$ 1.4 **	0.45 $\pm$ 1.3	20.57 $\pm$ 1.4 **	19.82 $\pm$ 1.3 **
Vern Res	3.05 $\pm$ 1.1	1.93 $\pm$ 1.3	11.16 $\pm$ 1.1 **	7.71 $\pm$ 1.2
Res Res	7.93 $\pm$ 1.2	5.02 $\pm$ 0.7	9.19 $\pm$ 0.9 **	9.47 $\pm$ 1.0 **
Res Vern	11.36 $\pm$ 1.2 **	1.94 $\pm$ 1.3	18.00 $\pm$ 1.2 **	15.26 $\pm$ 1.3 **
Mean	8.43 $\pm$ 1.5	2.34 $\pm$ 0.8	14.73 $\pm$ 1.1 **	13.06 $\pm$ 1.8 **

\*  $p < 0.05$

\*\*  $p < 0.01$

FIGURE 8. Schematic of the four retinal positions tested and their neural pathways projecting to the left and right hemispheres of the brain. Each observer was trained on their assigned task in the right eye, temporal retina. Shown is the average or mean percentage improvement from pre- to post-training for both vernier and resolution training and testing conditions. The improvement seen for the same eye-same hemisphere (trained condition), opposite eye-same hemisphere, opposite eye-opposite hemisphere and same eye-opposite hemisphere are shown separately.

limited to the cells or pathways excited by the training series or whether the learning is general across retinal regions. We found significant improvement in the trained neural pathway, in an untrained pathway that converged on the trained hemisphere and in an untrained pathway of the untrained eye leading to the untrained hemisphere. Very little improvement was seen in the pathways leading to the untrained hemisphere in the trained eye. We saw this effect for both the vernier and resolution acuity tasks.

### Task specificity

After extensive training on one task (either vernier or resolution acuity), we also examined the specificity of improvement for the untrained acuity task. We found partial transfer of learning from one task to the other. This is a surprising result. No other study to date has reported such transfer. However, previous research on task specificity in learning has used foveal presentation. For example, Mayer (1983) trained observers to discriminate between two grating orientations. In the untrained condition, observers were asked to discriminate orientations which were displaced from the trained position by 90 deg, thus tapping different mechanisms. In our study observers were trained 5 deg parafoveally and transfer of learning was assessed for a task resolution or a vernier.

\*It should be stressed that cognitive explanations of learning do not exclude neural components since cognition is neurally based. Therefore, our conclusion that parafoveal learning involves both physiological and cognitive components is not meant to imply that cognition is separate from neural mechanisms. We are simply pointing out that higher level mechanisms are involved in these training effects.



It could be argued that the two tasks chosen (vernier and resolution) in fact share the *same* neural machinery. If that were the case, transfer of learning would not be surprising. Vernier and resolution tasks may be processed within the same or similar front end mechanisms (i.e. retina, LGN, cortex) since all visual stimuli must pass through the optics, retina and the lateral geniculate nucleus before reaching the cortex. However, we believe it is unlikely that these shared pathways can fully account for training transfer between tasks since no transfer has been found for other tasks which would have also passed through common front end mechanisms. An example is the specificity of training found for spatial frequency (Fiorentini & Berardi, 1981) and orientation (Fiorentini & Berardi, 1981; Mayer, 1983; Poggio *et al.*, 1992; Fahle & Edelman, 1993; Fahle, Poggio & Edelman, 1992). Also, while vernier and resolution stimuli are probably both processed by spatial frequency selective mechanisms (Klein & Levi, 1985), the mechanisms mediating resolution acuity would be of a higher spatial frequency and different orientation than those used for the vernier task (Waugh, Levi & Carney, 1993; Levi & Waugh, 1994). Although vernier and resolution stimuli may pass through common pathways, they are most likely limited by different mechanisms, at least in highly practiced observers; resolution acuity may be chiefly limited by retinal factors such as the eyes optics, receptor spacing and ganglion cell pooling, while vernier acuity may be primarily limited by cortical processing (Westheimer, 1982; Waugh *et al.*, 1993). Support for this notion is seen in the decoupling of vernier and resolution acuity falloff with eccentricity (Levi, Klein & Aitsebaomo, 1985). We cannot rule out the possibility that in unpracticed observers, learning of both tasks reflects improved efficiency of using signals derived from common mechanisms (e.g. cortical filters), however, we believe that our finding of some generalization of training between tasks suggests a cognitive component to our learning effects (perhaps relating to peripheral attention as discussed further below).

#### *Eye specificity*

If learning occurred in monocular neurons, then learning would be predicted at the trained location exclusively. Similarly, if learning occurred in binocular neurons, then learning would be predicted at the trained location and in other eye at the location represented in the same hemisphere. Our results are consistent with learning in neurons sensitive to binocular inputs. Improved performance on the vernier and resolution tasks shows essentially complete transfer to the other eye (same hemisphere) suggesting that at least some of the learning occurs past the point of convergence for the two eyes. There is no significant transfer to the untrained retinal location in the trained eye [OD nasal; mean = 2.34% improvement, see column 2 in Fig. 8(b)]. Surprisingly, there appears to be some transfer to the temporal retina (projecting to the opposite hemisphere) of the untrained eye [column 1 of Fig. 8(b)], but only when testing on the vernier task.

#### *Why does training improve visual abilities?*

Improvement after training in peripheral vision could result from observers learning to quickly *shift* their fixation toward the peripheral target. Although this is a possibility, it is unlikely in our study since we limited the exposure duration to 150 msec and we monitored eye movements. Similar findings support this conclusion (Saugstadt & Lie, 1964). Conversely, Fendick and Westheimer (1983) mentioned that peripheral practice effects may be explained by an improved ability to *maintain* fixation. Improved fixational ability also does not explain our results as measured by the eye monitoring equipment. Our observers were just as able to maintain stable fixation initially as they were on the final day of the experiment.

Another possible explanation of improvement after practice is that observers are learning to better control accommodative processes. This also is not likely since vernier acuity is relatively robust to the effects of blur (Stigmar, 1971; Watt & Hess, 1987) and blur effects are negligible 5 deg in the parafovea. In addition, if this learning could be explained by accommodative improvement, then improvement should occur equally for all retinal locations, not just in the trained hemisphere.

We found considerable improvement in the trained condition. This suggests that some of these practice effects may be explained by fine tuning of the mechanisms mediating the task (McKee & Westheimer, 1978; Saarinen & Levi, 1994). But we did find some transfer to the untrained task. Saugstadt and Lie (1964) suggested that observers may be learning to direct their *attention* to the parafoveal location with training. They suggested that an observer initially attends to those objects at which they are looking, but with practice learn to shift their attention to the peripheral task. There is evidence that an observer's attention does not have to remain locked on the foveated object. Attention can be allocated to peripheral targets (Nakayama & Mackeben, 1989; Mackeben & Nakayama, 1993). Attentional factors may partially explain our findings since both vernier and resolution thresholds were measured using the same response paradigm; namely, choose the odd line out. An observer would be able to easily recognize the relation between the untrained task and the previously encountered "trained" task. In our study, repetitive exposures to the stimulus may have improved the observers ability to allocate their attention 5 deg in the periphery.

Improved attentional abilities in parafovea after training may also explain the small improvement seen in the untrained hemifield of our observers. We found an average of about 8% improvement in the untrained hemifield which did not reach statistical significance [see column 1 of Fig. 8(b)]. Recently Kapadia *et al.* (1994) reported similar findings. After significant improvement from training on a bisection task, they also failed to find significant transfer to the opposite hemifield.

### The specificity of learning

A few reports claim that learning does not transfer across retinal positions within the trained eye, but does transfer to the other eye (Fiorentini & Berardi, 1980, 1981) also in agreement with our results. We found a transfer of learning to the untrained eye. This finding is similar to that of Ball and Sekuler (1982) who trained direction discrimination thresholds for moving dots.

Evidence of interocular transfer of learning and the reduced transfer to a retinal area in the trained eye makes it difficult to fully explain the training effects in terms of processes that are not hemispherically restricted, such as some generalized cognitive change over time. Improvement through training appears to be greatest in the cerebral hemisphere that receives the training. This suggests that at least some of the learning effects involve binocular neural pathways. 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 17 (Hubel & Wiesel, 1968).

As mentioned in the Introduction, most of the training literature suggests that learning is task specific, but much of this research either ignores individual differences or has a small subject pool. One exception is a recent study by Fahle and Edelman (1993). They trained observers on two tasks; a vernier task of either horizontal or vertical orientation and subsequently trained the same observer on the same task in the other orientation. They interpreted their results as a failure to find generalization between the tasks. This conclusion is not persuasive for several reasons. First, Fahle and Edelman (1993) did not obtain essential comparative post-training scores on the first trained orientation after training on the second orientation. This post-training data would have been invaluable to show whether a mere change of task caused any initial elevation in thresholds. Second, inspection of the individual observer learning curves shows that approximately half of the observers *did* show transfer of training from one orientation to the other. A finding not mentioned in their conclusions.

### The absence of learning effects

Some training research has failed to find significant learning. We do not believe that the explanation is that observers can learn some tasks and not others (Bennett & Westheimer, 1991) since *within* a task we found some observers who learned and some who did not. Bennett and Westheimer (1991) found no training based improvement on a three point alignment task. One possibility may be due to their use of psychophysically experienced observers (Fahle & Edelman, 1993). Figure 9 shows the training data for two psychophysically experienced observers in our study, one trained on vernier and the other on resolution acuity. Neither show any overall improvement although NC shows improvement on day three and JW shows improvement on day four of training. These data appear to support the hypothesis that psychophysical experience

precludes any learning effects as suggested by Fahle and Edelman (1993), however, this does not explain why we find no overall improvement in eight of 18 observers who were psychophysically *in*experienced.

A second possibility for a failure to find improvement after practice could relate to the "challenge" of the task. Saugstad and Lie (1964) found that observers trained on a task in which initial performance was 50% correct showed improvement, whereas a second group of observers trained on the same task in which their initial performance was 90% correct did not show improvement. Similarly, Kumar and Glaser (1993) found no improvement on a vernier acuity task in which the offset size was held constant throughout the training regimen, perhaps not challenging the observer.

Another possible explanation for an absence of training effects could relate to data collection strategies. For example, Bennett and Westheimer (1991) based each threshold measure on 300 responses. Kumar and Glaser (1993) provided up to 600 practice trials before data collection even began. Our data and those of Fiorentini and Berardi (1981) suggest that improvement often occurs within the initial 200 responses. Perhaps learning effects are obscured when threshold measurements are defined by hundreds of trials.

The method used to collect the data may also determine whether learning occurs. Using a von Bekeky

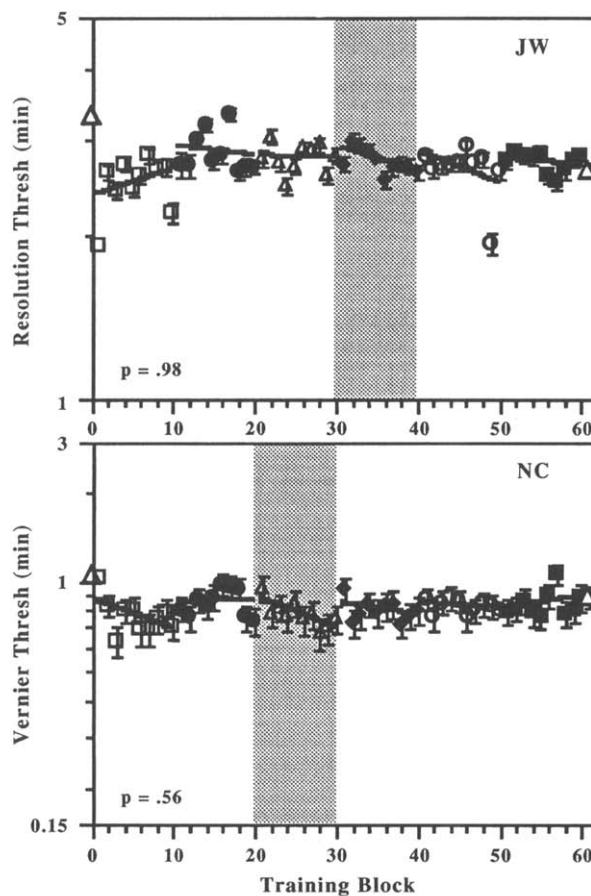


FIGURE 9. Training data for two psychophysically experienced observers in our study, one trained on vernier and the other on resolution acuity. Neither show any overall improvement.

tracking procedure, Kelly and Tomlinson (1987) found no improvement in contrast sensitivity after training. The variability of this procedure is high, and so modest improvements may not be salient. Two other factors may relate to Kelly and Tomlinson's (1987) failure to find improvement. Since they presented averaged results it is possible that improvement would have been evident if individual curves had been analyzed. In addition, observers were trained for only 15–30 min over 5 consecutive days. Perhaps more prolonged training each day would have produced significant training effects.

McKee and Westheimer (1978) suggested that there may be a limit to the amount of improvement achieved through practice. It is possible that if an observer, psychophysically experienced or not, does not show training effects, perhaps their thresholds are already as low as they can be for that individual. Every individual has different visual experiences and how these real world experiences relate to the trained procedure is not known. Because the visual system is plastic, differential practice from everyday visual tasks may underlie initial individual differences. In support of this hypothesis is the learning study of Mayer (1983) who found that practice on a certain task resulted in improvement only if the observer had initially elevated thresholds; although in the present study we did not find this tendency.

Poggio *et al.* (1992) have suggested that the brain sets up appropriate task specific modules that receive information from the retina and learn to solve a task after a brief training period. Kumar and Glaser (1993) attempted to test this model by looking at the initial few blocks of training on stereo and hyperacuity tasks. They concluded that they could find no support for the synthesis of task specific modules. However, the fact that observers possess different visual experiences, and that these experiences may determine visual thresholds, makes testing a model such as the Hyper Basis Function model (Poggio, 1990) difficult, if not impossible. This model would be hard to disprove since an observer may have had prior real-world visual experience bringing their thresholds down to the hyperacuity level before any laboratory training has begun. In the present study we chose to study learning in the parafovea partly on the basis that it is less likely that observers have real-world experience in making pattern discriminations using the parafovea. Nonetheless, we found very marked individual variation in the amount and time course of learning.

#### *Endurance of learning*

The endurance of training effects has also been investigated. Although the tasks are significantly different, Fiorentini and Berardi (1981) found total retention after several days and partial retention up to 7 months after training; Ball and Sekuler (1982) found total retention after 3–10 weeks; and Ball *et al.* (1988) found retention up to 6 months after training for adults ranging in age from 22 to 75 yr.

In our study two observers (HC and YC) were retested on the trained condition 4 months after training ended. During this 4 month period, these observers made no

psychophysical judgments. A *t*-test for related means revealed no difference between the 4 month retention and post-training thresholds ( $P > 0.05$ ).

#### SUMMARY

The major findings of the current study are that (1) repetitive practice leads to improved parafoveal vernier and resolution acuity for some, but not all observers; (2) there are substantial individual differences in the degree and time-course of learning, therefore presenting only averaged results in learning studies may lead to misinterpretation of the findings; (3) there is some transfer of learning between vernier and resolution acuity tasks; and (4) although the trained eye showed significant improvement after training, there is transfer of learning to the untrained eye particularly to the trained hemisphere.

Taken together, our results lead to the suggestion that (at least) two mechanisms may be involved in parafoveal learning: (i) a genuine neural learning, perhaps due to sharpening of neural responses, that is task and location specific and transfers predominantly to the corresponding hemifield; (ii) a general learning, perhaps related to higher level, cognitive changes such as assigning attention in the parafovea, which transfers between tasks and is responsible for some improvement in parafoveal performance.

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