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# Task-dependent changes of the psychophysical motion-tuning functions in the course of perceptual learning

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**Abstract.** In some cases, perceptual learning is task-specific. However, task-dependent effects of perceptual learning on psychophysical motion-tuning functions have yet to be clarified. In the present study, subjects performed motion detection or discrimination of the same stimulus over the course of four sessions held on separate days. Subjects who performed motion detection showed the most highly improved performance on the trained motion directions. However, after discrimination training, the highest improvement was not observed at the trained directions but shifted away from them. These results can be explained by lateral inhibition. Task demands may differentially modulate excitatory and inhibitory signals to directions in the vicinity of the trained directions.

## 1 Introduction

Repetitive practice of tasks on primitive visual features including orientation (Fiorentini and Berardi 1980), motion direction (Ball and Sekuler 1987; Liu 1999; Vaina et al 1995), spatial frequency (Fiorentini and Berardi 1980), and location (Crist et al 1997; Fahle et al 1995; Fiorentini and Berardi 1980; Mednick et al 2002), and tasks on low-level visual functions such as Vernier acuity (Beard et al 1995; Herzog and Fahle 1997; McKee and Westheimer 1978) enhance task performance (for a review see Fahle and Poggio 2002). This is regarded as a manifestation of underlying neural plasticity in low-level visual processing areas including V1—the cortical area onto which afferent visual signals are first projected (Crist et al 2001; Schoups et al 2001; Schwartz et al 2002).

Perceptual learning can be task-specific. First, practice of a task on a relevant feature does not necessarily improve the performance for tasks on features that are irrelevant to the task in the training phase (Ahissar and Hochstein 1993; Schoups et al 2001), although some studies show that training can occur for features which are irrelevant to the training task (Seitz and Watanabe 2003; Watanabe et al 2001, 2002). This suggests that in some cases attention selects the sensory population relevant to a given task. Second, studies have shown that learning does not transfer from one task to another (Crist et al 2001; Matthews et al 1999; Poggio et al 1992). Although, again, this is not always the case (cf Beard et al 1995), overall evidence suggests that perceptual learning can be highly task-specific.

No transfer between tasks found in some cases of perceptual learning suggests that different tasks may modify underlying visual processing in different ways. However, it has not yet been clarified how this occurs. One effective way to understand the underlying visual processing change due to perceptual learning is to measure change in psychophysical tuning functions to a visual feature (Ball and Sekuler 1987; Saarinen and Levi 1995; Seitz and Watanabe 2003; Watanabe et al 2001, 2002). In the present study, we measured changes in psychophysical motion-tuning functions to different motion directions due to training on two different tasks (motion coherence detection and motion direction discrimination) with the same set of stimuli presented with the same frequency in each block of the training. The detection training most highly improved performance on the

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trained motion directions. On the other hand, after the discrimination training, the highest improvement shifted away from the trained directions. This effect is well explained by lateral inhibition (Levine and Grossberg 1976; Marshak and Sekuler 1979; Mather and Moulden 1980). The results suggest that specific inhibitory signals to the directions in the immediate vicinity of a relevant direction are modulated by task demands.

## 2 Methods

### 2.1 Subjects

Twenty-five undergraduate and graduate students from Boston University participated in the study. The subjects ranged in age from 19 to 26 years. All subjects had normal or corrected-to-normal vision and were naïve with respect to the purpose of the experiment. Written informed consent was obtained from all subjects.

### 2.2 Stimulus

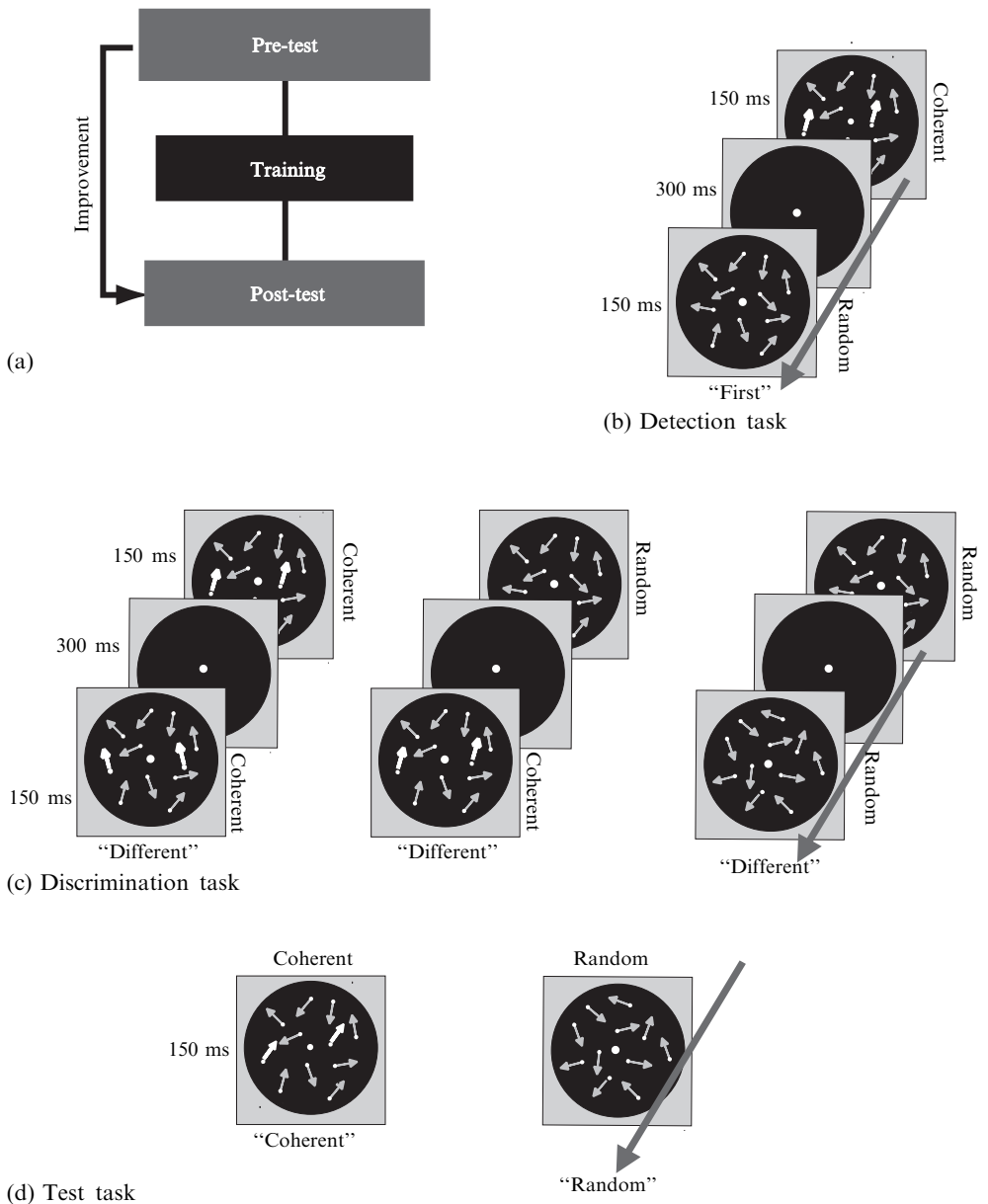
Each subject viewed displays from a distance of 2.28 m in a dark room with her/his head fixed in a chin-rest. Each stimulus consisted of 200 spatially random dots moving within a stationary circular aperture 6 deg in diameter. The size of a moving dot was 2 pixels (= 1 min of arc) in diameter, and its traveling speed was  $8.6 \text{ deg s}^{-1}$ . The dots appeared white ( $59.8 \text{ cd m}^{-2}$ ) against a black background ( $<1 \text{ cd m}^{-2}$ ). A bull's-eye fixation dot was presented at the center of the display during both the stimulus presentation and inter-stimulus interval. Each dot traveled from one edge to another within an invisible aperture. A certain proportion of the dots moved in the same direction in coherence, whereas the other dots moved in random directions. The display was similar to that developed by Newsome (Newsome and Pare 1988). However, while different groups of dots moving coherently were randomly chosen from one frame to another in that display, the same group of dots moved coherently with unlimited dot lifetimes in our display. The stimuli were generated by a Macintosh G4 computer and presented on a Hitachi SuperScan 801 monitor (21 inch,  $1280 \times 1024$  pixels, 75 Hz).

### 2.3 General procedure

A complete experiment consisted of a training stage (detection task or discrimination task) of four sessions which was preceded and followed by test stages in which the detection tasks were performed (figure 1a). In the training stage, one group of subjects (nine, four females and five males) participated in a detection training condition whereas the other group (sixteen, nine females and seven males) participated in a discrimination training condition. In summary, the subjects were tested on the detection task in the first session, trained on either detection or discrimination task in the following two sessions, and tested again on the detection task in the last session.

### 2.4 Detection training

Subjects viewed two successive signal/noise (S/N) displays (one with 100% randomly moving dots and the other with 18% of the dots exhibiting coherent motion) each for 150 ms with a blank interval of 300 ms between displays (figure 1b). Immediately after the second display disappeared, the subjects were instructed to judge whether the first or second display contained coherent motion and to respond by pressing either the key labeled "First" or the key labeled "Second". The number of trials in which coherent motion was presented in the first display was the same as that in which coherent motion was presented in the second display. The order of presentation of these two types of trials was randomized. Subjects did not receive feedback for their responses. The training consisted of four sessions each of which had 800 trials and lasted about 30 min. Coherent motion occurred in an upward direction at  $10^\circ$  rotated counterclockwise or clockwise. Each coherent motion direction was presented 400 times in one training session. Sessions were conducted on different days.



**Figure 1.** Procedures of the experiment. (a) A complete experiment consisted of a training stage (four sessions) preceded and followed by test stages. (b) The procedure of each trial of detection training: two modified Newsome type signal/noise (S/N) displays were successively presented for 150 ms with a blank interval of 300 ms. White and gray arrows represent coherent and random motion directions, respectively. (c) The procedure of each trial of discrimination training: the two successively presented displays were both 18% S/N displays (left), one 18% S/N display and one random display (center), or both random displays (right). (d) The procedure of each trial of the test stages: the judgment for the staircase method consisted of stating whether coherent motion was present or not (ie random motion).

### 2.5 Discrimination training

A different group of subjects participated in the discrimination training condition. In each trial two displays were presented successively as in detection training. The same two motion directions as in the detection training,  $10^\circ$  clockwise or counterclockwise

from upward motion, were used for the coherent motion in the discrimination training. However, unlike detection training, there were now three different types of combinations of displays. In the first type (figure 1c, left), a pair of S/N displays were presented successively, and the coherence level in each S/N display was set at a constant 18%, as in the detection task. The motion directions in the two displays were either the same or differed by  $20^\circ$ . In the second type (figure 1c, middle), one was an S/N display while the other was a random display in which all dots moved in random directions. In the third type (figure 1c, right), both were random displays. The first and third type of displays were presented in 320 trials and the second type in 160 trials in each training session, so that the total numbers of the presentation of S/N displays and random displays in one session were both 800 in order to make them equal to those in the detection training condition. The order of presentation of the three displays was randomized for each subject. The subjects were instructed to judge whether the directions of the global motion flow in the S/N displays were the same or different by pressing the key labeled “Same” or “Different”. They were told to make their best guess when the dots appeared to be random. The random–random and coherent–random trials were not used to compute subjects’ percentage of correct responses. No feedback as to correct or incorrect choices was provided. Sessions were conducted on different days.

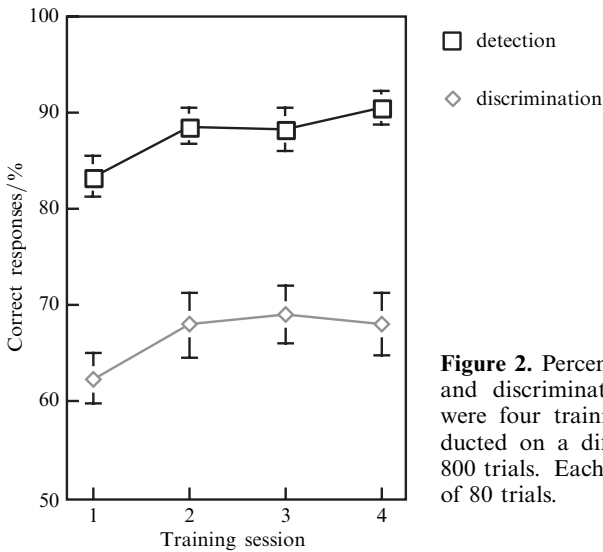
### 2.6 Pre- and post-training tests

In order to examine the effects of the two different types of training on subjects’ sensitivity to nine motion directions, including the two trained directions, the thresholds for coherent motion detection (ie the minimum percentage of the coherent motion detected) were measured for the nine directions both before and after the training. The motion directions were the upward motion, and  $\pm 5^\circ$ ,  $\pm 10^\circ$ ,  $\pm 15^\circ$ , and  $\pm 45^\circ$  from upward motion. The thresholds were determined at 50% correct, by means of a 2-down–2-up staircase method. On each trial, the subjects were presented with an S/N display for 150 ms and instructed to judge whether the dots moved in random directions or whether a subgroup of dots moved in the same direction, ie whether the stimulus contained coherent motion (figure 1d). Eighteen staircases (the upstream and downstream for the nine directions) were used in a random order determined for each subject. The thresholds were compared between the pre- and post-training tests.

## 3 Results

Figure 2 shows improvement in the subjects’ performance over the time course of detection and discrimination training. Performance tended to improve in both detection and discrimination training conditions. Figures 3a and 3b show the actual detection thresholds before and after the training for a representative subject (top), and the difference of the thresholds between the first and second test stages (bottom). As expected, sensitivity increase (threshold decrease) was highest for the direction trained in the motion detection task (figure 3a, bottom). However, after discrimination training, the sensitivity enhancement peaks (represented as troughs in the thresholds in figures 3a and 3b) shifted to the neighboring direction away from the trained direction (figure 3b, bottom).

The best-fit Gaussian curve also indicated a sensitivity enhancement peak shift in the discrimination training. In the detection training, the peak of the best-fit Gaussian curve [ $G(x) + C$ ] to the psychophysical data was near the trained direction (*Magnitude* =  $-0.62$ ,  $\sigma = 7.58$ , *Mean* =  $0.82$ ,  $C = -0.06$ , and  $R^2 = 0.87$ ). On the other hand, the sensitivity enhancement peak of the best-fit Gaussian curve in the discrimination training was at  $7.16^\circ$  off the trained direction (*Magnitude* =  $-0.99$ ,  $\sigma = 11.80$ , *Mean* =  $7.16$ ,  $C = -0.04$ , and  $R^2 = 0.89$ ). The 95% confidence interval of the mean for the best-fit curve for the discrimination training was between  $2.72^\circ$  and  $11.61^\circ$ ,

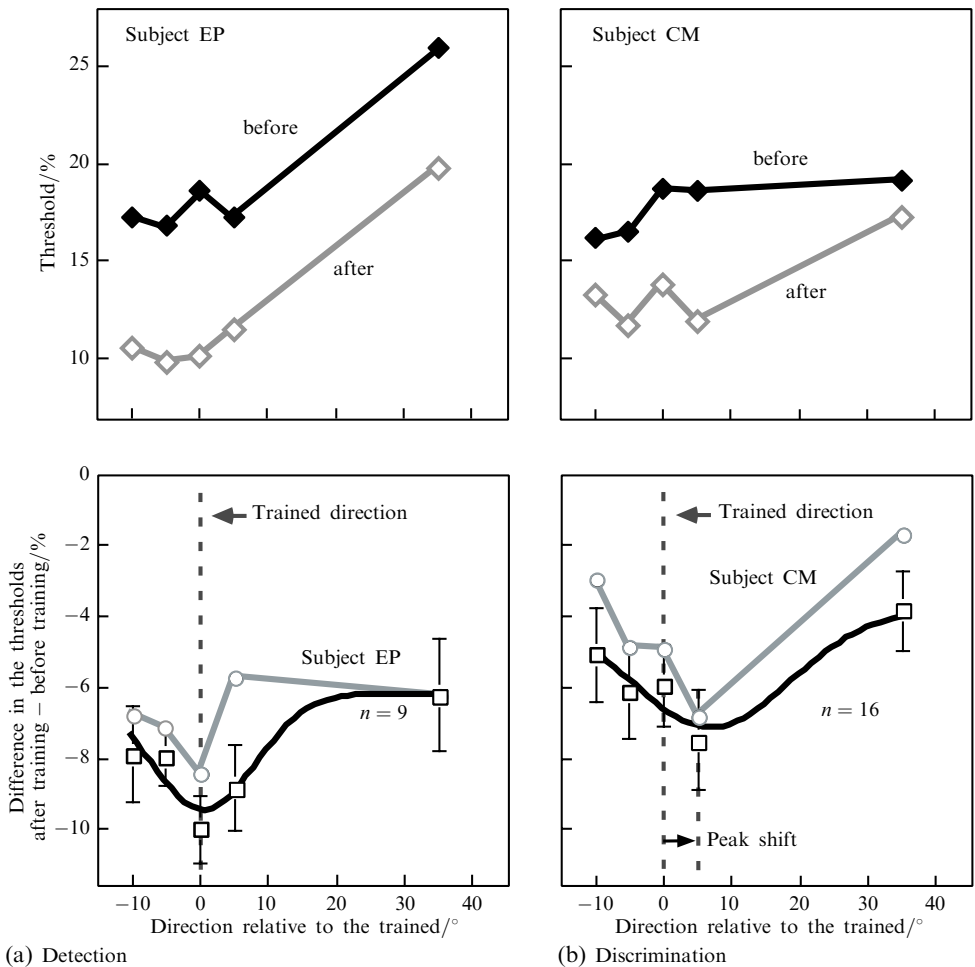


**Figure 2.** Percentage of correct responses for detection and discrimination training for each session. There were four training sessions, each of which was conducted on a different day. Each session consisted of 800 trials. Each session was divided into ten blocks of 80 trials.

and the trained direction ( $0^\circ$ ) was not included in the confidence interval. Moreover, when the Gaussian curve was fit with the sensitivity enhancement peak at the trained direction,  $R^2$  dropped to 0.71 ( $Magnitude = -0.68$ ,  $\sigma = 9.69$ ,  $Mean = 0.00$ ,  $C = -0.04$ ; not shown in the figure).

The different tuning characteristics of sensitivity enhancement were obtained for different types of task training with the same set of stimuli exposed at the same frequency. Since the exposure effects were controlled in this way, the differential results that the peak-shift was observed after discrimination training but not after detection training should be due to the difference in task demands.

Response biases in the training stages were also analyzed. In the detection training, there were significantly more ‘first’ responses (55%) than ‘second’ responses (45%) ( $\chi^2 > 24.36$ ,  $p < 0.01$ ), but the ratio did not change significantly across the sessions ( $F_{1,2} = 11.63$ ,  $p = 0.08$ ). In the discrimination training, the results from four subjects showed that there were significantly more “different” responses (64%) than “same” responses (36%) ( $\chi^2 > 24.36$ ,  $p < 0.01$ ), but the ratio did not change significantly across the sessions ( $F_{1,2} = 0.11$ ,  $p = 0.76$ ). No significant bias between the “same” and “different” responses was found in the coherent–coherent condition (51.4% for “same” and 48.6% for “different”) ( $\chi^2 = 2.83$ ,  $p = 0.09$ ), whereas there was a significant bias in the coherent–random (33.9% for “same” and 66.1% for “different”) ( $\chi^2 > 24.36$ ,  $p < 0.01$ ) and the random–random conditions (24.3% for “same” and 75.7% for “different”) ( $\chi^2 > 24.36$ ,  $p < 0.01$ ). This is in accord with the prediction of the noisy operator model. In the noisy operator model, subjects are more likely to report that two noisy signals look different than identical. Such response bias is thought to take place at a high cognitive level (Krueger 1979). There was indeed a response bias in the coherent–random and random–random conditions in the discrimination training. However, it is unlikely that the response bias caused the peak of the motion-detection-tuning curve obtained in test stages to be shifted for at least the following two reasons. First, the “same/different” response ratios did not change significantly across the training and no significant correlation was found between the ratio and performance ( $F_{1,2} = 3.47$ ,  $p = 0.20$ ). This indicates that there is no evidence that the bias affected the learning. Second, the “same” and “different” responses in a discrimination task of the training are qualitatively different from the response of perception of “coherent” versus “random” in the staircase method in the test sessions.



**Figure 3.** (Top) the detection thresholds before and after the training for a representative subject for detection training (a) and discrimination training (b). (Bottom) the subtraction of the thresholds in the first test stage from those in the second test stage, for detection training (a) and discrimination training (b). Thus, a lower value represents a higher sensitivity enhancement due to training. A sensitivity enhancement peak is represented as a trough in the curves. Since the curves around the two trained directions were almost symmetrical, these were averaged. The mean reduction in the detection threshold among subjects was calculated for each direction (black squares). Data points were interpolated by the best-fit (by the least-squares method) Gaussian curve.  $0^\circ$  as indicated by a vertical abutted line represents the trained directions. Error bars represent standard errors of the means across subjects. Gray circles indicate results from a representative subject.

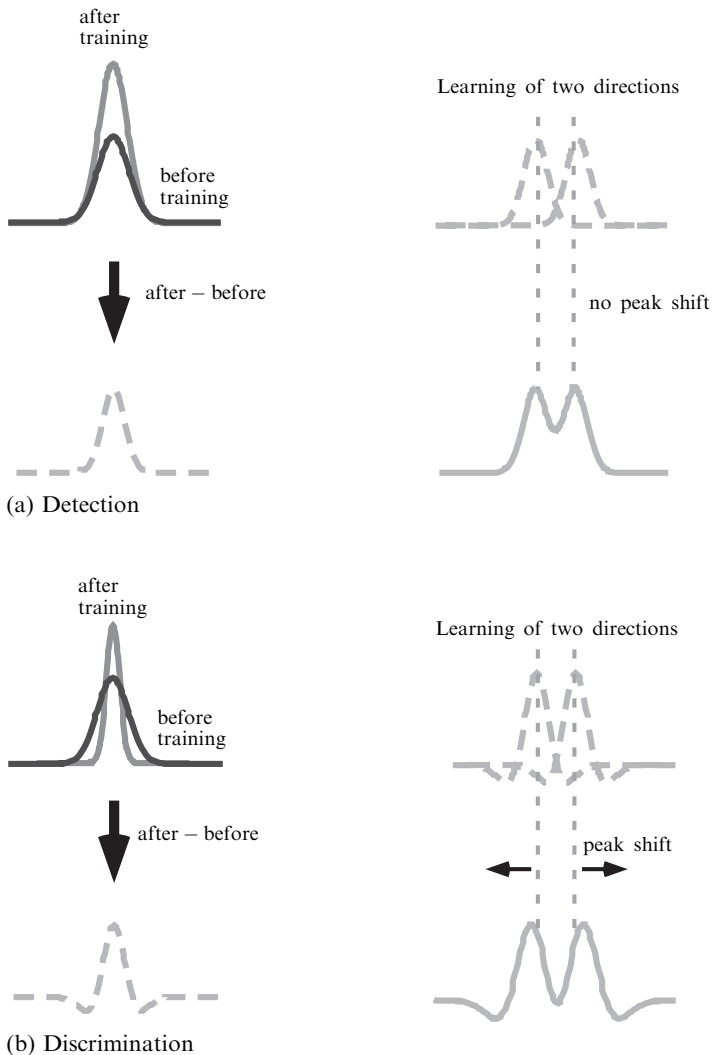
#### 4 Discussion

The results of the experiment indicate that the peak shift in the sensitivity enhancement curve was observed only after training of discrimination between directions in spite of the fact that the exposure to stimuli in the discrimination training was made equal to that in the detection training. It is unlikely that a random display induced global repulsion or assimilation effects, because the random motion consists of motion energy in all directions and did not form a global motion in a specific direction. Thus, the peak shift may be identified as an effect that the motion-discrimination training produced.

Why did the peak shift occur in the discrimination training condition but not in the detection training? In the detection task, all subjects had to do is to detect coherent motion. Thus, what is needed in the detection training is to simply enhance

the sensitivities to presented directions (figure 4a). In contrast, in the discrimination task, information of presented directions is important. One efficient way to discern a trained direction from others is by suppressing irrelevant direction signals while enhancing the trained direction signals, resulting in a Mexican-hat learning pattern for each direction. If the two are summed, peak shift can occur (figure 4b). This mechanism may be common to that for repulsion in the perception of motion direction or orientation (Levine and Grossberg 1976; Marshak and Sekuler 1979; Mather and Moulden 1980) (figure 4b).

Regan and Beverley (1985) showed that adaptation to luminance gratings of a particular orientation maximally elevated orientation discrimination thresholds for orientations some way away from that of the adaptation grating. They suggested that the reason for



**Figure 4.** Schematic illustrations of possible changes in sensitivity tuning characteristics. (a) In the detection training, sensitivity is most highly enhanced for a trained direction and the increase in sensitivity tapers off with increasing difference from the trained direction (gray solid curve on the left). Therefore the amount of enhancement will be described as a Gaussian curve (gray dotted curve on the left). For two directions, the summation of the two curves does not cause peak shift (right). (b) In the discrimination training, sensitivity is enhanced for the trained direction but lateral inhibition occurs around each of trained directions (gray dotted curve on the left). The summation of the two curves causes peak shift (right).

this is that filters with Gaussian-shaped tuning functions give the biggest differential response to pairs of orientations which fall on the limbs, rather than around the maximum of the tuning function, as it is on the limbs that sensitivity is changing most rapidly. Thus, discrimination is favored if locally high slopes to each side of the peak of a tuning curve is attained (see also Hol and Treue 2001). Prins and Kingdom (2002) obtained an analogous result for texture modulation detection. Their hypothesis is in accord with our model in that higher slopes of a tuning curve are utilized for discrimination tasks. At the same time, these adaptation effects are different from the result of the discrimination condition of our experiment in that (a) adaptation effects impute stimuli rather than tasks, and (b) the present study obtained the best rather than the worst performance at motion directions away from the learning directions. This may be because the mechanism for long-term task-driven perceptual learning and the mechanism for adaptation are not entirely the same (Matthews et al 2001).

Where does the mechanism for the peak shift in the discrimination training occur? It has been pointed out that task-driven perceptual learning involves a broad range of visual processing, from low-level stages (Ball and Sekuler 1987; Crist et al 1997, 2001; Fiorentini and Berardi 1980; Poggio et al 1992; Schoups et al 2001; Vaina et al 1995), to higher-level stages of weighing visual input for making visual processing decisions (Doshier and Lu 1998, 1999) and memory processing (Chun 2000).<sup>(1)</sup> Since lateral inhibition is known to occur in various stages, it is premature to conclude where the mechanism for the peak shift occurs. Further series of experiments are necessary to clarify this.

In summary, we conducted experiments in which motion-detection tasks and motion-direction discrimination tasks of identical stimuli were performed across multiple sessions by different groups of subjects with the same frequency. While the highest improvement was found for the trained directions in the detection task, in motion-discrimination training the peak performance improvement was shifted away from the trained directions. These results suggest that inhibitory signals to the directions in the vicinity of a relevant direction are modulated by task demands.

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<sup>(1)</sup> However, task-irrelevant learning seems to occur in low-level sensory and cortical stages (Watanabe et al 2001).

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