



# Contrast Masking Effects Change with Practice

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**Contrast detection thresholds are known to increase with background contrast, a phenomenon called contrast masking. We found that, under some conditions, observers improved their masked detection performance by repetitive practice of a masking experiment. This learning effect resulted in a cancellation of suprathreshold contrast masking within the contrast range measured. A two-alternative forced-choice discrimination paradigm was used, with stimuli consisting of Gabor signals as maskers and target, presented at the same location and time. Untrained observers showed increased detection thresholds with increasing mask contrast for suprathreshold mask contrasts, but perceptual learning caused an elimination of this classical effect, with masked thresholds reaching the no-mask level and below. Learning did not decrease, but rather somewhat increased, discrimination thresholds when target and mask shared the same Gabor signal parameters. Performance improvement was found to be specific for orientation and mask configurations, though it did transfer between mirror symmetric mask configurations and between eyes. These results argue against a static transducer function-based account for contrast masking and are consistent with a theory assuming multiple feature-based interactive network capable of long-term gain modifications. © 1997 Elsevier Science Ltd.**

Contrast discrimination    Detection    Gain control    Learning    Masking

## INTRODUCTION

Visual masking refers to a phenomenon where detectability of a test stimulus is affected by proximal stimuli. The magnitude of the effect depends on the similarity between the test target and the mask and on the maskers contrast (or intensity). For low mask contrasts target thresholds may decrease with increasing mask contrast, while for higher mask contrasts (above some “suppression threshold”) target threshold increases as a power function (exponent  $\leq 1$ , with  $\text{exp} = 1$  corresponding to Weber’s law) with mask contrast (Legge & Foley, 1980; Swift & Smith, 1983; Zenger & Sagi, 1995). This increase in target threshold with increasing mask contrast is attributed to compressive transducer functions underlying target detection (Legge & Foley, 1980; Ross & Speed, 1991), to gain control mechanisms (Foley, 1994; Heeger, 1992; Wilson & Humanski, 1993; Zenger & Sagi, 1995), or to a change in the decision strategy (Nachmias, 1993; Olzak & Thomas, 1991, 1992). While the first approach suggests a static system with limitations imposed by hardware properties (i.e., response saturation), the latter two approaches suggest a dynamic system where response properties may depend on context and on memory.

Here we are interested in performance changes over time while performing a masked detection task. Percep-

tual learning seems to affect a variety of psychophysical tasks including contrast detection and discrimination, texture segmentation and spatial acuity (Sagi & Tanne, 1994). Of particular interest is the absence of learning transfer within different dimensions such as location, orientation and eye used (Fahle *et al.*, 1995; Karni & Sagi, 1991; Polat & Sagi, 1994), indicating low level plasticity in the adult visual system. Swift & Smith (1983), using masks composed of eight-component noise gratings, described an improvement with practice in a masking experiment where the masks varied between trials, resulting in a decreasing exponent of the contrast masking curve from 1 to 0.65 (converging on the slope obtained without practice for single component gratings). They placed the learning effect at the decision stage, with practice affecting decision criteria. Zenger & Sagi (1996) found learning effects when using constant masks composed of two Gabor signal components. In this recent study the exponent of the contrast masking curve was found to be constant (0.89) with practice, but practice reduced the contrast range where the power law could be observed (resulting in an increase in “suppression threshold”). This type of improvement in performance with learning was accounted for by synaptic modifications within local gain control networks in early vision (Zenger & Sagi, 1996). In the present study we sought to gain more insight into the properties of the neuronal networks involved in contrast discrimination tasks and learning, by studying the specificity of the learning effects to different stimulus components.

Theoretical accounts of contrast detection assume

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contrast processing by multiple orientation-selective linear filters followed by a threshold device (Campbell & Robson, 1968; Graham & Nachmias, 1971). Models differ in the type of interactions assumed (if any) between the different filters. Assuming learning is determined by local activity-dependent learning rules (i.e., the strength of an interaction between two filters varies according to some rule taking into account only the current activities of these two filters), specificity of learning would depend on architecture only. We consider here four typical models of contrast masking with their implications for learning:

M1. At the simplest form, the increase in detection thresholds with increasing maskers contrast is accounted for by a compressive (Legge & Foley, 1980) or a saturating (Ross & Speed, 1991) transducer function. According to these models, the maskers raise the filter operating point when mask orientations are not very different from target orientation so that the mask activates directly the target filter. Within the context of perceptual learning a possible modification of the "compressive transducer" would be to reduce the compression factor and to increase the linear range of the transducer function with practice. Learning then should be specific to the filter used for target detection and thus selective for target orientation, but not for mask orientation. Alternatively, learning may induce a decrease in target-filter bandwidth, with the same consequences.

M2. Consider a simple feed-forward model (as above) with masking accounted for by inhibitory interactions (Foley, 1994; Zenger & Sagi, 1996). Zenger & Sagi (1996) assume the existence of *second stage* excitatory and inhibitory filters, each integrating the rectified (linear) responses of first stage orientation-selective filters. The thresholded excitatory filter response is assumed to be divided by the corresponding inhibitory filter response. Inhibition is assumed to increase with increasing activity in the inhibitory filter, thus predicting the classical masking effect. Learning can be accounted for by modifications in the efficacy of the inhibitory synapse (Zenger & Sagi, 1996), predicting independence of mask orientation, but specificity to target orientation. One may also consider changes in filters' receptive fields, that is the shape of the weighting functions used by the excitatory and the inhibitory second stage filters to integrate the weighted outputs of first stage filters. Thus, learning may also be specific for mask orientation. Note that as masks are processed by multiple first stage filters, with different filters processing the different mask orientation components, learning should transfer to masks consisting of the individual components.

M3. Some models assume a feedback architecture. Wilson & Humanski (1993) assume a gain control network with excitatory and inhibitory units as above, but inhibition is applied at the input to the excitatory filter, with the excitatory response fed back to the

inhibitory (normalization) unit. Heeger (1992), modeling cats' cortical cells responses, assumes a similar network with an orientation filter response normalized (divided) by the sum of all different orientation filters at the same location and of similar spatial frequency. Here the same normalization unit is used by all targets' filters. Learning is expected to be specific for target orientation, not necessarily for mask orientation, and is expected to transfer from compound masks to each of the orientation components. Wilson & Humanski (1993) suggested plasticity of inputs to the excitatory (normalization, second stage) filter as an explanation for adaptation. Within the context of the present study this would predict specificity of learning for mask orientation.

M4. It is possible that contrast discrimination under masking conditions is dependent on the compound pattern generated by the target and mask (Nachmias, 1993; Olzak & Thomas, 1991; Olzak & Thomas, 1992), thus reflecting a suprathreshold breakdown of first stage component processing. On this account, learning, if allowed for, can be specific to the particular target and mask used while training.

In the present masking experiments we test learning transfer across different target and mask orientations. All models discussed above predict specificity of learning, if it exists, for target orientation. Models assuming a nonlinear normalization process (second stage inhibitory/excitatory filters) may also accommodate mask specificity. Note that if we assume only local interactions and local learning rules (i.e., the interaction between two filters determined only by activity in these two filters) learning effects should be free of context. That is, learning to unmask a specific orientation would result in unmasking of this orientation in the presence of other orientations and vice versa. The task we used is a two-alternative forced-choice (2AFC) detection of a Gabor signal in the presence of Gabor masks. Observers repeatedly performed the task, using the same stimuli, showing a gradual decrease in the masking effect across a period of 40 sessions, often resulting in a reversal of the masking effect (threshold elevation of 0.2 log-units would turn to threshold enhancement of 0.2 log-units). The pattern of learning specificity provides some insight to the processes underlying visual masking.

## METHODS

### *Apparatus*

Stimuli were displayed as a gray-level modulation on an Hitachi HM-3619A color monitor, using an Adage 3000 raster display system. The video format was 56 Hz non-interlaced, with  $512 \times 512$  pixels occupying a  $9.6 \times 9.6$  deg area. The mean luminance was  $50 \text{ cd/m}^2$ . Stimulus generation was controlled by a Sun-3/140 workstation and the stimulus display by the Adage local processor. The data for the contrast discrimination experiments presented in Fig. 3 were collected using a

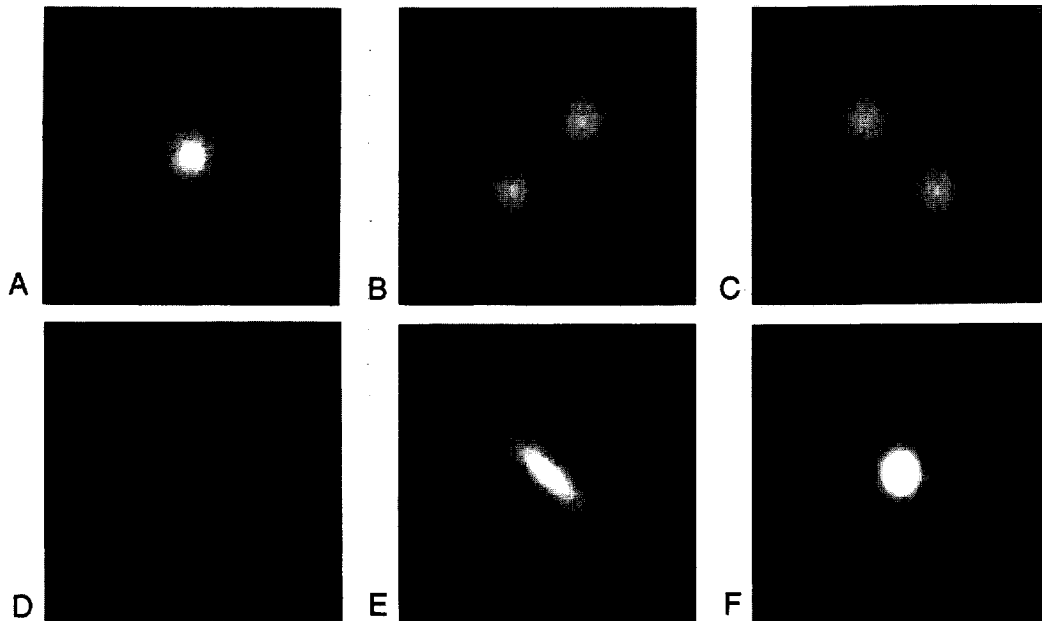


FIGURE 1. Masking stimuli. (A) Two overlapping Gabor signals of 45 and 135 deg, of same (positive) phase. (B) Two overlapping Gabor signals of 45 and 135 deg, of opposite (+-) phase. (C) Same as in (B), but with (-+) phase. (D) Two overlapping Gabor signals of 45 and 135 deg, of same (negative) phase. (E) A single 45 deg Gabor signal. (F) Example of mask-plus-target stimulus: the mask is as in (A), with a vertical Gabor target (the target contrast is exaggerated here compared to experimental conditions).

Crimson-Reality-Engine (SGI) computer with  $1280 \times 1024$  pixel resolution, 60 Hz non-interlaced. The stimuli were viewed from a distance of 1.5 m.

### Stimuli

Stimuli consisted of one target signal and one or two mask signals (see Fig. 1). The spatial luminance distribution of target and mask signals is described by a Gabor function, which can be interpreted as a cosine grating with its amplitude modulated by a Gaussian envelope:

$$G_{\theta}(x, y) = \cos \left( \frac{2\pi}{\lambda} ((x - x_0)\cos\theta + (y - y_0)\sin\theta) \right) \times \exp \left( - \left( \frac{(x - x_0)^2 + (y - y_0)^2}{\sigma^2} \right) \right)$$

with  $x$  and  $y$  being the horizontal and vertical coordinates. The spatial location of the Gabor signal is determined by  $x_0$  and  $y_0$ , its orientation by  $\theta$  (0 deg being vertical) and its wavelength  $\lambda$ . The standard deviation of the Gaussian envelope is given by  $\sigma$ . For all stimuli used in these experiments  $\lambda = 0.2$  deg,  $y_0$  and  $x_0$  (at the center of the screen), and  $\sigma = \lambda$  were kept constant, unless otherwise stated (in one experiment,  $\sigma$  was larger than  $\lambda$ ).

Mask signals and target signal were presented at the same location, but mask orientation differed from the target orientation by  $\pm\Delta\theta$  ( $\Delta\theta \geq 0$ ). The luminance distribution was thus:

$$L(x, y) = I + C_t G_{\theta} + C_{m+} G_{\theta+\Delta\theta} + C_{m-} G_{\theta-\Delta\theta}$$

with  $I$  being the average screen luminance,  $C_t$  as the target amplitude,  $C_{m+}$  and  $C_{m-}$  as the mask components amplitudes.  $|C_{m+}| = |C_{m-}|$  when two mask components

were used, with four possible combinations:  $C_{m+} = C_{m-} \geq 0$ ,  $C_{m+} \leq 0$  &  $C_{m-} \geq 0$ ,  $C_{m+} \geq 0$  &  $C_{m-} \leq 0$  and  $C_{m+} = C_{m-} \leq 0$  in the (++) , (-+), (+-) and (--) phase combinations, respectively. In some cases one mask component was used, with  $C_{m-} = 0$ . In all cases we define mask amplitude  $C_m = |C_{m+}| + |C_{m-}|$ .

### Experimental procedure

A 2AFC paradigm was used to measure observers' thresholds. Observers fixated a small cross at the center of the screen. When ready, they pressed a key to initiate a

trial. Each trial consisted of two stimuli, one of them containing the target. Both stimuli included identical mask patterns in the case of a masking task. The observer's task was to answer whether the target was on the first or the second stimulus presentation by pressing a key. The time-course of a trial was as follows: a 500 msec delay after initiating the trial, a first stimulus presentation of 90 msec, an inter-stimulus interval of 1000 msec, and a second stimulus presentation of 90 msec. Observers had unlimited time to respond, as well as to initiate the next trial. Feedback was given by means of a keyboard bell which rang when the observer made a mistake. The target contrast detection threshold was measured by a staircase method: after three consecutive correct responses, the target contrast would be reduced by 0.1 log unit, and increased by the same value after a single mistake. A block (defined as one

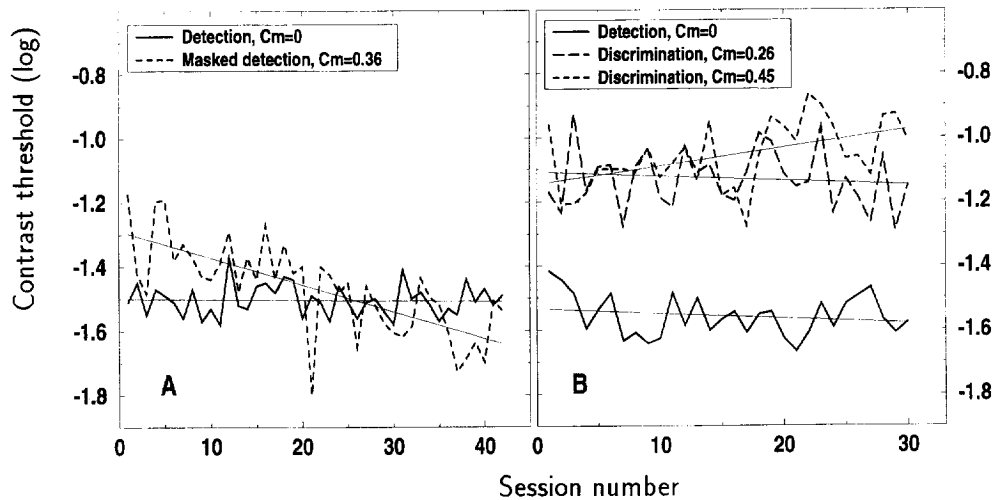


FIGURE 2. Comparison of the evolution of masked-detection and discrimination thresholds with practice. (A) Contrast thresholds (in log units) are shown as a function of session number for  $\theta = 0$  deg,  $\Delta\theta = 45$  deg,  $C_m = 0.36$  (masked detection) and  $C_m = 0$  (no-mask). See Fig. 4 for the corresponding masking contrast curves. (B) Contrast discrimination thresholds (in log-units) as a function of session number in experiments where target and masks assumed identical Gabor parameters ( $\theta = 0$  deg,  $\Delta\theta = 0$  deg,  $C_m = 0, 0.26, 0.45$ ). Observer AD, binocular viewing. Data for (A) and (B) were collected at different periods of time. Straight lines are fitted lines to the data (linearity is enforced).

staircase sequence) was terminated after 8 or 10 reversals of target contrast. The threshold was calculated by taking the average contrast at reversal points, disregarding the first two. This method was shown to establish the threshold at 79% correct detection (Levitt, 1971). Care was taken that the target contrast was at least 0.2 log units above threshold at the beginning of a block, based on previous data.

Apart from  $C_t$  all stimulus parameters were kept constant within one block. During one session (which lasted approximately 50 min) and between different blocks mask amplitudes ( $C_m$ ) were varied. The detection threshold of the target alone was measured in the beginning and the end of each session. Thus, a curve of threshold elevation as a function of mask contrast could be plotted after a single session.

### Observers

Results are presented from four naïve observers (AB, EC, IE, LM) and the first author (AD), all with normal or corrected to normal vision. EC and IE had participated in different psychophysical experiments before.

## RESULTS

### Learning effects

A typical practice session consisted of a set of eight to ten blocks, covering the whole range of mask contrasts shown in the graphs. Sessions were performed every day or two. Reference contrast detection thresholds (without mask) were measured before and after every session. These measurements did not show significant variations over the course of the learning period (see Fig. 2), indicating no learning on the contrast detection task. However, as can be seen in Fig. 2(A), masked detection

thresholds did improve with time. Though individual threshold estimations are not very stable (each datum point is based on one measurement, except for the no-mask condition where each point is based on two measurements), a significant difference can be seen between the first and last few days (see Fig. 4 for the corresponding contrast masking curve). The improvement rate during the first 15 sessions is 0.0097 as compared with 0.0044 log(C)/session during the last 15 sessions, indicating saturation in the learning process. Though normalizing the masking data by the individual session reference detection thresholds, or by the average contrast threshold over all the practice sessions did not seem to make a significant difference in the overall variation of the masking data, data presented are normalized to the within-session reference thresholds to accommodate daily variations (note that daily variations in sensitivity do not necessarily imply a positive correlation between reference thresholds and masked detection thresholds; some models would predict the opposite).

Not all observers showed learning. During the preliminary experiments we encountered one observer who performed exceptionally well during the first session and did not show a significant practice effect during the following sessions. On the other hand, the initial data of observers that had obvious difficulties with the task in general for the first session were not used in this study. From the time-course of the learning effect, which is slow and steady throughout several sessions (up to 42 in observer AD's case) it should be obvious that we are not measuring observers adapting to psychophysical set-ups, but a genuine improvement in their perceptual ability.

Not all target-mask configurations yielded improved performance with learning. Using test and masks of the

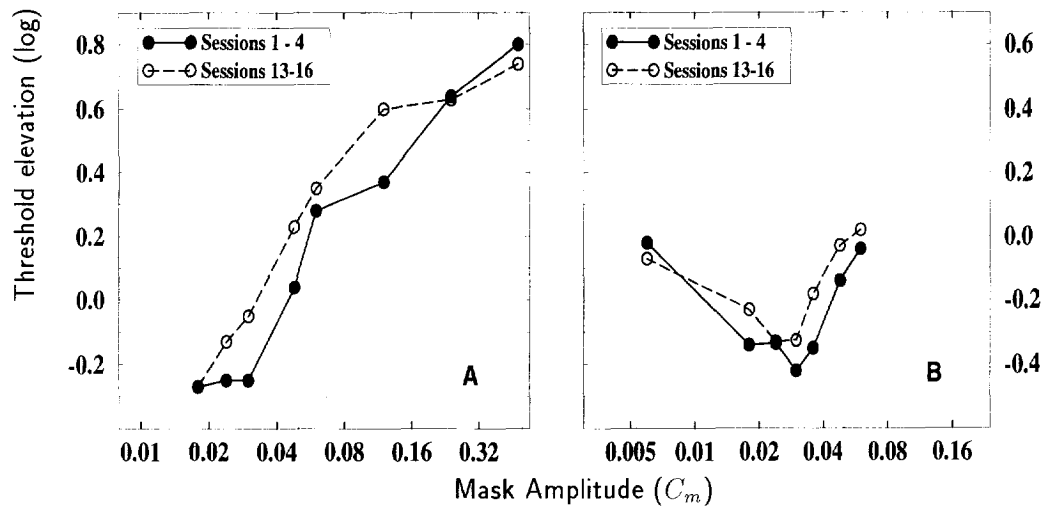


FIGURE 3. Threshold elevation as a function of mask contrast for contrast discrimination (target and mask with same Gabor parameters), comparison between data from the first four sessions and the last four sessions. Practice has the effect of increasing discrimination thresholds at most contrast levels. Observers (A) IE; and (B) AB, binocular viewing ( $\theta = 0$  deg,  $\Delta\theta = 0$  deg). Note the difference in scale between (A) and (B), as observer AB practised only low contrast stimuli. Data points are averages of eight threshold measurements, two in each session.

same orientation (vertical), observer AD showed very little improvement, if at all, over the course of 30 sessions [see Fig. 2(B)]. There was, however, a significant deterioration (correlation coefficient:  $r = 0.49$ ;  $P < 0.01$ ) of contrast discrimination performance with the higher base contrast ( $C_m = 0.45$ ). A similar effect was found for two additional observers we tested (see Fig. 3), showing an increase of discrimination thresholds with practice (0.07 log units on average, two observers,

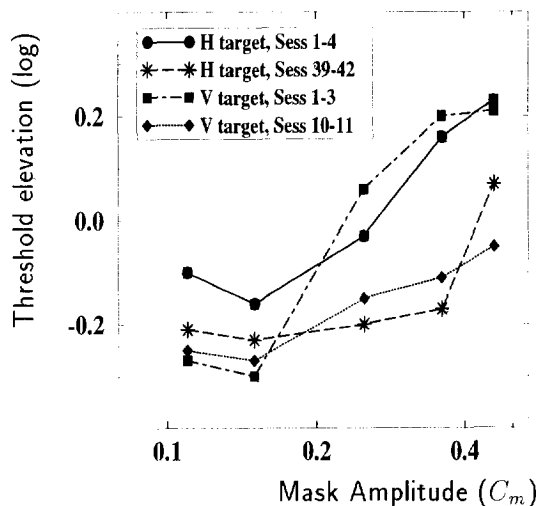


FIGURE 4. Threshold elevation as a function of mask contrast. The mask was a 45/135 deg compound, (++) phase. Target was either horizontal ( $\bullet$ ,  $*$ ) or vertical ( $\blacksquare$ ,  $\blacklozenge$ ). Practising with the horizontal target yielded a dramatic improvement from the first four sessions ( $\bullet$ ) to the last four ( $*$ ). However, this learning effect did not transfer to a vertical target (same masks), as the following three sessions with the vertical target ( $\blacksquare$ ) showed a return to the initial horizontal-target masking curve ( $\bullet$ ). Further training with vertical target yielded a significant reduction in thresholds ( $\blacklozenge$ ), similar to the one observed with the horizontal target. Observer AD, binocular viewing.

all contrast levels). Here, one of the observers [AB, Fig. 3(B)] was tested using only low contrast stimuli, to test the hypothesis that discrimination-threshold increase during practice is a result of excess inhibition on the target responding filter.

Experiments where target and masks assumed different orientations yielded performance improvement with practice. The main feature of this improvement is the development of threshold facilitation with mask contrasts that were previously yielding suppression, resulting in an extended facilitation range over mask contrast (e.g. Fig. 4). Some interesting parameters, such as the minimum mask contrast that yields suppression and the slope of the threshold curve at this region and beyond (slope =  $0.86 \pm 0.22$  for the first few sessions, average  $\pm$  SD of all initial curves shown in figures), were difficult to quantify as the suppression range was continuously reduced with practice, until complete elimination. The first few sessions seemed to yield threshold curves with constant slopes (Zenger & Sagi, 1996), as seen in Fig. 5(A). However, inspection of the changes in thresholds over time, for a given mask contrast, yields significant and consistent learning effects [see Fig. 2(A), correlation coefficient  $r = -0.72$ ,  $P < 0.01$ ].

#### Transfer of learning across stimulus and target orientation

The purpose of this experiment was to verify whether the decrease in masked thresholds was due to a general decrease in the masking power of the mask pattern. If this were the case, one would expect learning to transfer from one target orientation to the other, as long as the mask pattern remained the same.

The target was horizontal (90 deg) masked by a compound of two overlapping Gabor signals of 45 and

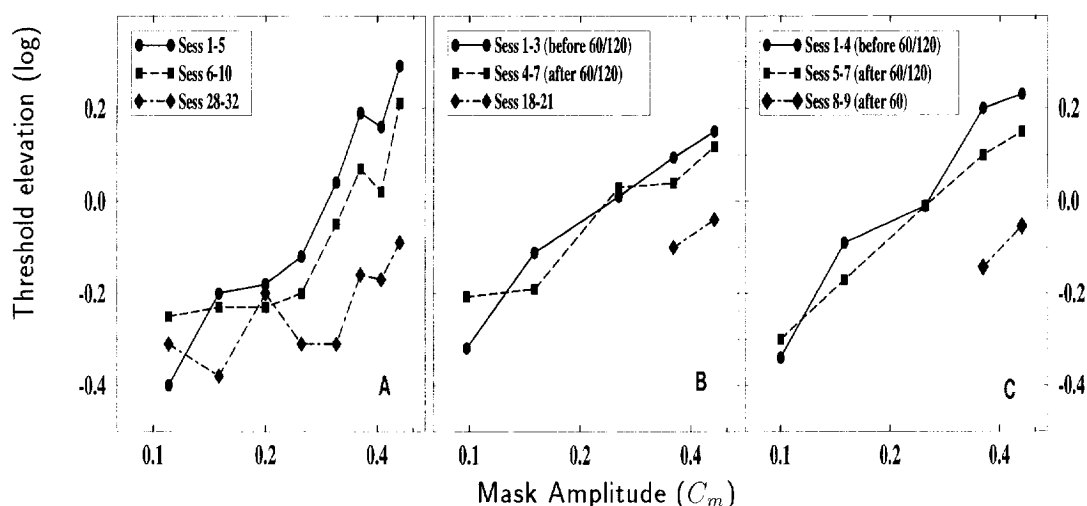


FIGURE 5. Threshold elevation as a function of mask contrast. (A) Evolution of a masked-detection curve with time, with a compound mask of two overlapping Gabor signals of 60 and 120 deg, horizontal target. (B) Masking with the 60 deg mask component alone, before learning with the 60/120 deg compound ( $\bullet$ ), and after learning the compound ( $\blacksquare$ ), showing the absence of transfer. Subsequent practice on the 60 deg component ( $\blacklozenge$ ) yielded elimination of contrast suppression. (C) Masking with the other mask component (120 deg), before ( $\bullet$ ) and after ( $\blacksquare$ ) learning with the 60/120 deg compound, showing absence of transfer from compound to components. Subsequent tests (sessions 8–9) on the 120 deg component ( $\blacklozenge$ ), following learning with the 60 deg mask, showed transfer of learning from the 60 to the 120 deg mask. Observer EC, binocular viewing.

135 deg orientation, and of the same phase. Practice sessions were performed until improvement seemed to slow down [see Fig. 2(A)], and afterwards the same masking pattern was used, with a vertical target. There are no pre-training data for the vertical target, however one can clearly see (Fig. 4) that the masking curve of the vertical target is very similar to that of the pre-training horizontal target's masking curve, except for the low contrast region; where enhancement is evident in the pre-training stage (though this difference between the low contrast masked thresholds of the vertical and horizontal targets is significant, it could reflect a difference in initial bandwidth, or transfer of learning with low masking contrasts). Further practice with the vertical target yielded learning effects similar to those obtained with the horizontal target before (Fig. 4), even though practice effects with the horizontal target had saturated. Therefore, we conclude that most of learning did not transfer across target orientation. In addition, as target rotation here is equivalent to stimulus rotation, the present result indicates specificity for *stimulus* orientation.

#### Transfer of learning to a compound mask's components

Masked contrast detection curves were measured for the two individual mask components (60 or 120 deg masks, 90 deg horizontal target) before and after learning with the compound mask (60 and 120 deg overlapping masks, horizontal target). Figure 5(A) shows the practice effects on the compound mask, where one can clearly see a drop in masked detection thresholds over the 32 sessions of practice. This effect, however, is not evident at all in the single component data [Fig. 5(B) and Fig. 5(C)], strongly suggesting that no transfer of learning to the component masks has occurred.

To verify that learning is possible with a single mask

component, we kept the observer practising on one of the component masks (60 deg, practice was performed on only two high contrast masks because of time constraints). After a few sessions of practice, a drop in masked thresholds became evident [Fig. 5(B)].

In a final transfer experiment, we tested whether learning with the 60 deg mask obtained above would transfer to the 120 deg mask. Surprisingly, we found complete transfer [Fig. 5(C)]. Note that the 60 and 120 deg masks are mirror images of each other.

#### Transfer of learning across phase of Gabor signals

In this experiment we addressed the question of phase selectivity of learning. Specifically, we looked for transfer of learning between compound masks that differ only by a 180 deg phase shift of one or both of their components. We also tested whether learning would transfer across target phase.

The experiments were carried as follows: after learning with both components of the same phase (see section: *Apparatus*), with positive-sign amplitudes ( $++$ ), a contrast masking curve was measured with the phase of one of the component Gabor signals shifted 180 deg ( $+ -$  phase). Despite the fact that there was no measure of the ( $+ -$ ) masking before practice, one can clearly see that the ( $+ -$ ) curve falls much above the final ( $++$ ) curve [Fig. 6(A)]. The same was done with a ( $--$ ) mask combined with a 180 deg phase-shifted target, with similar results. The same phenomenon was observed with observer EC, with the added control showing practice effects on the ( $--$ ) phase arrangement, after having learned the ( $++$ ) arrangement. The data show so far that a phase change in one or both maskers, or target plus masker, does not allow for a significant transfer of learning.

One phase manipulation led to a completely different

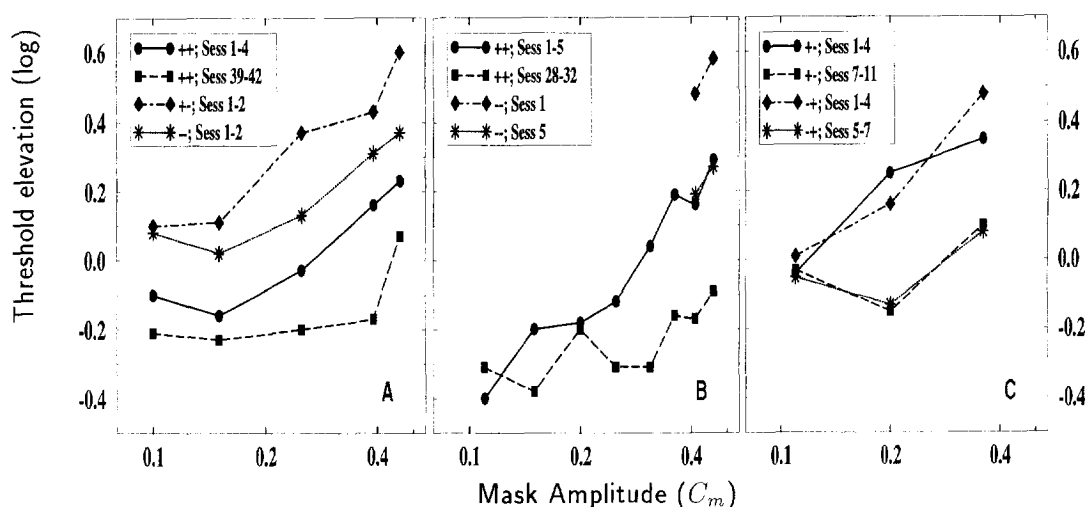


FIGURE 6. Threshold elevation as a function of mask contrast for 45/135 deg compound masks. (A) Evolution of masked detection thresholds with time for (+) phase combination. Data from the first four sessions (●) and the last four sessions (■) are shown. Post-learning test with a (+) mask (◆) and with a (–) phase mask and – target (\*) showed high detection thresholds, indicating no transfer. Observer AD, binocular viewing. (B) (●) and (■), learning effect shown in Fig. 5(A) reproduced. (◆) A subsequent session with both mask components of opposite phase from those practised (each datum point is the average of three threshold measurements). (\*) The fifth session with (–) phase mask, showing a practice effect. Observer EC, binocular viewing. (C) (●) First four sessions with (+) phase, 45/135 deg compound Gabor mask, and last five sessions (■), showing a practice effect. (◆) First four sessions with the (–) phase before practising on the (+) phase combination, followed by three sessions (\*) after practice with (+), showing complete transfer of learning. Observer LM, monocular viewing.

result, however. That is, a 180 deg phase shift of both components, with a mask made of opposite phase components (+– phase). In this case, the control (–+ phase) was measured before and after learning. Figure 6(C) shows the complete transfer from (+–) to (–+) phase. Similarly to the previous experiment (see section: *Transfer of learning to a compound mask's components*),

this instance of transfer occurs where the target–mask patterns are mirror images of each other.

#### Ocular transfer of learning

Learning with a vertical target and compound mask of 45 and 135 deg, and with  $\sigma = 0.4$  deg was performed monocularly, for each eye separately (Fig. 7, observer AD). Note that the pre-learning curves show a strong suppression at high contrasts, though previous binocular practice with the same target and mask orientations, but with  $\sigma = 0.2$  deg, yielded elimination of this suppression (Fig. 4). This absence of transfer across stimulus size may indicate size specificity of learning or locality, as the increasing size stimulated a previously untrained retinal region.

With the larger  $\sigma$  we tested first the left eye, then the right eye followed by extended practice, with the right eye yielding a decrease in high contrast suppression (Fig. 7). The contrast masking curve measured for the left eye after practising the right eye showed a strong deviation from its corresponding initial curve, indicating transfer of learning from the trained eye. In fact, the contrast masking curves for the individual eyes after learning were very similar, except for the low contrast region (Fig. 7), indicating an ocular transfer of learning with high masking contrasts. This is consistent with Legge's (1979) demonstration of the binocular nature of *suprathreshold* masking, with dichoptically presented mask and target.

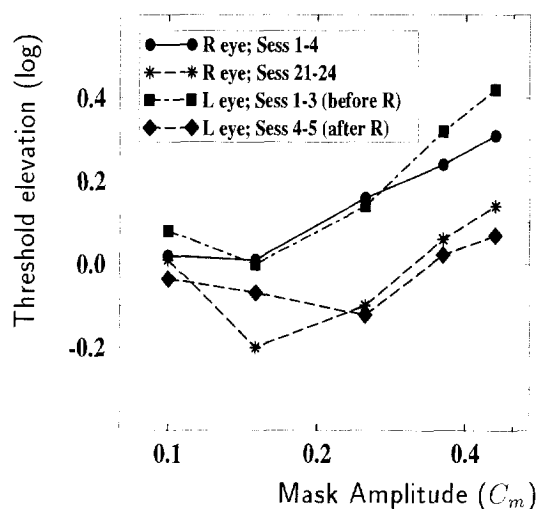


FIGURE 7. Interocular transfer: threshold elevation as a function of mask contrast. Practice with a larger Gabor mask than the other experiments,  $\sigma = 0.4$  deg, 45/135 deg, (+) phase. (●) and (\*), masking curve for the first and last four sessions using the right eye. (■) and (◆), masking curves for the left eye, measured before and after practising with the right eye, showing a transfer of learning with high contrast masks. Observer AD, monocular viewing.

## DISCUSSION

The experiments described here showed a dramatic improvement with practice of contrast detection thresh-

olds in the presence of masks. This effect was observed when target and mask orientation differed. Before training, target detection thresholds increased in the presence of high contrast masks, while after training target detection thresholds decreased in the presence of high contrast masks. The later improvement in masked detection thresholds often equaled the facilitation observed with low contrast masks. The time-course of learning was slow, sometimes developing through 40 sessions or more [Fig. 2(A)]. Contrast discrimination thresholds, with target and masks of the same orientation, tended to increase with practice. These findings argue for a dynamic gain mechanism controlling contrast perception, with gain parameters modifiable by experience.

Our results show specificity of learning for stimulus parameters such as orientation and phase. It was shown that learning to unmask a horizontal target did not transfer to a vertical target, though the same masks were used. Learning was shown also to be specific for the masks phase. Most surprisingly, learning with a compound mask (60 and 120 deg) did not affect discrimination threshold when only one of the masks was used. Considering that the masks components differing by 60 deg are processed by independent orientation filters (Campbell & Kulikowski, 1966), this result implies that learning involves interactions between orientation filters, or a higher level of processing, in agreement with the interactions observed for orthogonal orientations at suprathreshold contrasts (Derrington & Henning, 1989; Georgeson, 1992; Olzak & Thomas, 1991; Perkins & Landy, 1991). The interocular transfer of learning points to a cortical site of learning where information from the two eyes converges. As suprathreshold masking can be also obtained dichoptically (Legge, 1979), it is possible that learning takes place at the site where masking occurs.

Assuming that learning effects involve plasticity of neuronal modules implementing the masking effect and that learning follows *local learning rules* (Hebb, 1949), one may conclude from the pattern of learning specificities as for the architecture of the masking modules. In particular, specificity for the mask pattern predicts processes that involve interactions between filters, ruling out masking models based on single filter compressive response function (see Introduction: M1). We can also rule out a more general class of feed-forward multi-stage inhibitory/excitatory networks consisting of orientation selective filters (Introduction: M2), as learning with the two component masks does not transfer to the individual masks. This later result indicates a failure of orientation component processing, pointing toward a feedback network (Introduction: M3) as an underlying neuronal mechanism for the observed phenomena. However, the results with the same target and masks were unexpected. The absence of improvement with contrast discrimination tasks may reflect the presence of a fixed compressive transducer function, and/or response-dependent interactions. Recent research implicates contrast-dependent inhibition and excitation (Stemmler *et al.*, 1995; Polat & Norcia, 1996), supporting stronger inhibition on highly

*responding filters*. Target filters are strongly stimulated in the contrast discrimination experiments, but not in the masked-contrast-detection tasks, thus receiving more inhibition in the former. However, our contrast discrimination experiment with only low contrast stimuli also failed to improve thresholds.

It is possible that the observers use some local spatial features of the phenomenal appearance of the stimuli for the discrimination task (Nachmias, 1993; Nachmias & Rogovitz, 1983). If masking is produced by local spatial features created by the compound stimulus (masks plus target), learning may involve attenuation of these features and thus is predicted to be specific for target, mask components and compounds. The features involved should be invariant under mirror reflection, to account for the transfer of learning between mirror symmetric masks (sections: *Transfer of learning to a compound mask's components*; and *Transfer of learning across phase of Gabor signals*), but should not be rotation invariant, as learning is not transferred to stimuli rotated by 90 deg (section: *Transfer of learning across stimulus and target orientation*). Noting also the interocular transfer of the learning effect with high contrast masks, it is possible that learning here is dominated by processes beyond the primary visual cortex, like in some pop-out tasks (Ahissar & Hochstein, 1996). As learning is dependent on top-down gating processes (Ahissar & Hochstein, 1993; Sagi & Tanne, 1994; Tanne & Sagi, 1995), the specificity found here may reflect constraints on the gating process, or on the interface between gating and primary visual processes.

Regardless of the particular masking model adopted, the "unmasking" phenomenon can be viewed as an interference reduction process. The visual system seems to be able to separate target features from masking (or noise) features and to attenuate the latter to a level that can enhance target detection rather than suppress it. For this process to be successful, masking features should be distinguishable from target features, as was indeed observed here.

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