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Perceptual learning improves neural processing in myopic vision

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Visual performance is jointly determined by the quality of optical transmission of the eye and neural processing in the visual system. An open question is: Can effects of optical defects be compensated by perceptual learning in neural processing? To address this question, we conducted a perceptual learning study on 23 observers with myopic vision, targeting high frequency deficits by training them in a monocular grating detection task in the non-dominant eye near their individual cutoff spatial frequencies. The contrast sensitivity function and visual acuity in both eyes (without optical correction) were assessed for all the observers in the training group before and after training, and for all the observers in the control group twice with a 10-day interval between the tests. In addition, the threshold versus external noise contrast function was measured for five observers in the

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training group before and after training. We found that (a) training significantly improved contrast sensitivity at the trained spatial frequency, visual acuity, and contrast sensitivity over a wide range of spatial frequencies in both eyes; (b) training did not lead to any significant refractive changes; (c) the mechanism of improvements was a combination of internal additive noise reduction and external noise exclusion; and (d) the improvements in visual acuity and contrast sensitivity were almost fully retained for at least four months in the three observers tested. These results suggest that perceptual learning may provide a potential noninvasive procedure to compensate for optical defects in mild to modest myopia.

Introduction

Visual perception begins with optical transmission of visual input onto the retina, followed by photoelectric transformation and neural processing. The optics of the human eye is inherently imperfect, as reflected in various optical aberrations, inevitable diffraction, and scattering (Campbell & Gubisch, 1966). In the normal population, the dominant optical defects are the ordinary lower-order aberrations (LOA) associated with nearsightedness (myopia), farsightedness (hyperopia), and astigmatism, that cause blurry vision when an observer attempts to focus on near or far objects. LOA can degrade a variety of visual functions, including visual acuity (VA), contrast sensitivity (CS), spatial resolution, and may lead to amblyopia and/or strabismus if uncorrected in early development (Abrahamsson & Sjostrand, 1996, 2003; Aldebasi, Fawzy, & Alsaleh, 2013; Barrett, Bradley, & McGraw, 2004; Borchert et al., 2010; Ciuffreda, 1991; Dobson, Miller, Clifford-Donaldson, & Harvey, 2008; Freedman & Thibos, 1975; Freeman, 1975; Freeman, Mitchell, & Millodot, 1972; McNeer, 1980; Mitchell, Freeman, Millodot, & Haegerstrom, 1973; Schwiegerling, 2000; Weakley, 2001).

Neural processing in every stage of the visual system is also intrinsically and ubiquitously noisy (Geisler, 1989). Noise in the response of photoreceptors, including photon-absorption noise, channel noise, and fluctuations in cyclic guanosine monophosphate (GMP), fundamentally limits perceptual sensitivity (Angueyra & Rieke, 2013; Pelli & Farell, 1999). At the system level, psychophysical studies have also documented processing inefficiencies, including additive and multiplicative noises and nonoptimal perceptual templates (Ahumada & Watson, 1985; Burgess & Colborne, 1988; Burgess, Wagner, Jennings, & Barlow, 1981; Eckstein, Ahumada, & Watson, 1997; Foley, 1994; Foley & Legge, 1981; Klein & Levi, 1985; Legge & Foley, 1980; Levi, Klein, & Chen, 2005; Lu & Dosher, 1999, 2008; Pelli, 1981, 1985, 1990; Sperling, 1989; Spiegel & Green, 1981; Watson & Solomon, 1997).

Because visual performance is jointly determined by the quality of optical transmission of the eye and neural processing in the visual system (Artal et al., 2004; Thibos, 2000), an open question is: Can effects of optical defects be compensated by perceptual learning in neural processing? To address this question, we conducted a perceptual learning study on 23 observers with myopic vision.

As the most common type of refractive error that defocuses (blurs) retinal images of distant objects, myopia affects up to 50% of children, teenagers, and adults across different regions and ethnicities (Pan, Ramamurthy, & Saw, 2012). Inspired by many studies that demonstrated the potential of improving degraded visual functions in amblyopia through intensive perceptual training (Astle, Webb, & McGraw, 2011; Chen, Chen, Fu, Chien, & Lu, 2008; Chung, Li, & Levi, 2006; Huang, Lu, & Zhou, 2009; Huang, Zhou, & Lu, 2008; Hussain, Webb, Astle, & McGraw, 2012; Levi, 2005; Levi & Li, 2009; Levi & Polat, 1996; Levi, Polat, & Hu, 1997; Li, Klein, & Levi, 2008; Li, Provost, & Levi, 2007; Li, Young, Hoenig, & Levi, 2005; Liu, Zhang, Jia, Wang, & Yu, 2011; Polat, Ma-Naim, Belkin, & Sagi, 2004; Tsirlin, Colpa, Goltz, & Wong, 2015; Xi, Jia, Feng, Lu, & Huang, 2014; Zhai et al., 2013; Zhang, Yang, Liao, Zhang, & Liu, 2013; Zhou et al., 2006), several recent studies also attempted to evaluate the effects of perceptual learning on visual diseases related to optical defects of the eye, such as presbyopia (DeLoss, Watanabe, & Andersen, 2015; Durrie & McMinn, 2007; Polat, 2009; Polat et al., 2012) and modest myopia (Durrie & McMinn, 2007; Tan & Fong, 2008). Targeting lateral interactions between neurons, Durrie and McMinn (2007) and Tan and Fong (2008) found that training improved visual acuity by 2.1 lines and contrast sensitivity over a wide range of spatial frequencies in modest myopia. In a later study, the lateral masking paradigm was shown to be more effective than protocols based on single Gabor stimuli (Camilleri, Pavan, Ghin, & Campana, 2014).

In the current study, we directly targeted high frequency deficits in myopic vision and trained myopes in a monocular grating detection task near their individual cutoff spatial frequencies. The same training protocol has been shown to be effective in improving visual performance in both normal and amblyopic populations in our previous studies (Huang et al., 2008; Zhou et al., 2006; Zhou et al., 2012). We found that although it did not lead to any significant refractive changes, training significantly improved VA and CS over a wide range of spatial frequencies in both eyes through a combination of internal additive noise reduction and external noise exclusion. Moreover, effects of training were almost fully retained for at least four months in the three observers tested. Our results might be of particular interest to those with modest myopia whose visual functions were modestly affected by the condition (Durrie & McMinn, 2007; Tan & Fong, 2008). Perceptual learning may provide a potential noninvasive treatment for myopia.

Materials and methods

Observers

Twenty-three myopic observers (age 20 to 28 years; 11 females and 12 males; see Table 1 for details), each with a history of myopia for at least five years, participated in the study. They were randomly divided into the training (S1 to S15, aged 23.5 ± 0.6 years, mean ± *SE*) and control groups (S16 to S23, aged 24 ± 2.0 years). All observers were naive to the purpose of the study. Written informed consent was obtained from each of them before the experiment. The study was approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences.

Apparatus and stimuli

The experiment was controlled by a PC (Think Center M series, Lenovo Inc., Beijing, China) running MATLAB and PsychToolBox 2.54 extensions (Brainard, 1997; Pelli, 1997). The stimuli were displayed on a gamma-corrected Sony G220 color monitor (Sony Corporation, Tokyo, Japan) with a spatial resolution of 1600 × 1200 pixels and a refresh rate of 100 Hz. A special circuit was used to produce 14-bit gray-level resolution (Li & Lu, 2012; Li, Lu, Xu, Jin, & Zhou, 2003). The mean background luminance was 30 cd/m^2. During the whole experiment, the observer put her/his head on a chin rest and viewed the stimuli monocularly in a dimly lit room, with one eye naked (without glasses) and the other eye occluded. All tests were done without optical correction.

The stimuli were vertical sinusoidal gratings subtending a 3° × 3° visual angle at a distance of 1.14 m and 6° × 6° at a distance of 0.57 m, respectively. The different viewing distances were used to obtain appropriate contrast sensitivity function (CSF) measurements on observers with severe myopia. A half-Gaussian ramp ($\sigma = 0.5°$ at a distance of 1.14 m and 1° at 0.57 m) was added around the edges of the gratings to minimize edge effects.

We also measured threshold versus external noise contrast (TvC) functions before and after training to investigate the mechanisms of perceptual learning (Dosher & Lu, 1998, 1999). External noise images were constructed from 3×3 pixel patches ($0.013° \times 0.013°$ at a distance of 1.14 m and $0.026° \times 0.026°$ at a distance of 0.57 m, respectively). The contrast of each pixel patch was sampled from a Gaussian distribution with $\mu = 0$ and $\sigma \in [0\ 0.021\ 0.042\ 0.083\ 0.125\ 0.167\ 0.250\ 0.333]$.

Design

For the training group, the experiment consisted of three consecutive phases: pre-training measurements of VA and CSF in each eye, 10-day monocular contrast detection training in the non-dominant eye (defined by Porta's alignment method; Wade, 1998), and counterbalanced post-training measurements of VA and CSF in both eyes. For the control group, the experiment consisted of repeated VA and CSF measurements separated by about 10 days.

In addition, we measured pre- and post-training TvC functions in the trained eye of five observers to investigate the mechanism of perceptual learning (Lu & Dosher, 1999, 2008), and pre- and post-training refractive status of seven observers to assess effects of training on the optics of the eye. Retention of the CSF and VA improvements was also assessed several months after training.

To construct the CSFs, we measured observers' contrast thresholds in a two-interval forced choice grating detection task at seven spatial frequencies (0.5, 1, 2, 4, 8, 12, and 16 c/d for observers who viewed the stimuli at 1.14 m and 0.25, 0.5, 1, 2, 4, 6, and 8 c/d for observers who viewed the stimuli at 0.57 m) using a three-down one-up staircase procedure that decreased signal contrast by 10% (multiplied the previous value by 0.9) after every three consecutive correct responses and increased signal contrast by 10% after every incorrect response. The seven spatial frequency conditions were randomly mixed in seven blocks with 100 trials per block. The sequence of the CSF measurements in the two eyes was counterbalanced across observers. The cutoff spatial frequency, corresponding to a contrast sensitivity of 2 before training, was selected as the training frequency for each observer in the grating detection task. Training lasted 10 sessions (days). Each session consisted of 720 trials (120 trials/block × 6 blocks), which was typically finished within half an hour. Visual acuity was measured with the Chinese Tumbling *E* Chart and defined as the minimum angle of resolution (MAR) associated with 75% correct identification (Mou, 1966). An optometrist who was naive to the purpose of the experiment evaluated the refractive status of the eyes.

The TvC functions for grating detection were sampled in eight external noise conditions and two performance levels (79.4% and 70.7% correct). The

Group	Sub	Symbol	Sex	Age	Eye	Refractive error	Acuity (logMAR)	Trained SF (c/d)
Training group	*S 1*	○	M	23	NE	−4.00DS	0.850	6
					DE	−1.00DS	0.156	
	S 2	+	M	27	NE	−3.25DS	0.850	4
					DE	−2.75DS	0.663	
	S 3	*	F	21	NE	−0.50Ds/−1.75DC×35	0.575	12
					DE	−0.50DS/−1.75DC×132	0.467	
	S 4	□	F	22	NE	−2.75DS	0.775	8
					DE	−2.50DS	0.500	
	S 5	◇	F	25	NE	−2.25DS	0.450	8
					DE	−2.75DS	0.625	
	S 6	▽	F	24	NE	−7.50DS/−0.75DC×28	0.675	7.5
					DE	−6.00DS/−0.50DC×146	0.475	
	S 7	△	F	24	NE	−3.25DS	0.725	5
					DE	−2.75DS	0.550	
	S 8	◁	M	22	NE	−6.25DS	1.231	4
					DE	−5.75DS/−1.25DC×5	1.098	
	S 9	▷	F	24	NE	−3.00DS	0.950	6.5
					DE	−4.00DS	0.975	
	S 10	☆	M	21	NE	−1.75DS	0.275	10
					DE	−2.25DS	0.375	
	S 11	◀	F	20	NE	−2.00DS	0.567	7.5
					DE	−2.75DS	0.762	
	S 12	▶	M	24	NE	−4.75DS/−1.00DC×135	0.875	6
					DE	−5.25DS/−0.50DC×45	0.875	
	S 13	✡	F	26	NE	−3.50DS/−0.25DC×14	0.725	6
					DE	−2.75DS/−0.50DC×3	0.338	
	S 14	▼	F	23	NE	−1.25DS	0.450	15
					DE	−2.00DS/−0.25DC×163	0.550	
	S 15	▲	F	28	NE	−0.50DS/−0.50DC×20	0.142	15
					DE	−0.75DS/−0.50DC×128	0.190	
Control group	*S 16*		M	27	NE	−2.50DS/−1.00DC×3	0.294	
					DE	−5.75DS	0.550	
	S 17		M	25	NE	−3.75DS	0.950	
					DE	−3.50DS	0.950	
	S 18		M	27	NE	−3.75DS/−0.50DC×50	0.400	
					DE	−4.50DS	0.500	
	S 19		M	25	NE	−3.25DS/−0.50DC×80	0.550	
					DE	−3.50DS	0.450	
	S 20		M	22	NE	−3.25 DS	0.663	
					DE	−1.50DS/−0.50DC×12	0.575	
	S 21		M	23	NE	−5.75DS	0.725	
					DE	−5.50DS	0.725	
	S 22		M	21	NE	−2.75DS	0.663	
					DE	−3.00DS	0.762	
	S 23		F	22	NE	−1.50DS	0.294	
					DE	−0.50DS/−0.50DC×135	0.050	

Table 1. Observer characteristics.

spatial frequency of the test grating for the five observers was 2, 3, 2, 3, and 8 c/d, respectively. The spatial frequency of the test grating was slightly lower than the trained spatial frequency such that we can measure contrast thresholds in high external noise conditions. We then extracted thresholds at 79.4% and 70.7% correct from the best fitting Weibull functions (see Data analysis). Thresholds at 79.4% and 70.7% correct were measured with 80 trials of three-down one-up and 64 trials of two-down one-up staircases, respectively. All conditions were intermixed during the TvC measurement. In total, there were 1,152 (64 × 8 + 80 × 8) trials in each TvC session, lasting about one hour.

Procedure

A two-interval forced-choice task was used for both the training and the threshold measurements. Prior to the experiment, observers completed 100 practice trials with the same experimental paradigms but different stimuli, in which they were asked to report which of two intervals contained a white square box.

In contrast sensitivity measurements, each trial started with a 220-ms fixation cross in the center of the display, followed by two 100-ms intervals separated by a 430-ms blank screen, each signified by a brief tone at its onset. A signal grating was randomly presented in one of the two intervals, while the other interval contained a blank screen with background luminance. Observers reported the interval that contained the signal with a key-press. For pre- and post-training CSF measurements, a brief tone followed each response regardless of its accuracy; during the training phase, a tone followed each correct response.

In TvC measurements, each trial started with a 220-ms fixation cross in the center of the display, followed by two 150-ms intervals separated by a 430-ms blank screen, each signified by a brief tone at its onset. Each interval consisted of five frames: two frames of external noise, one frame of the signal grating or blank screen, and two additional frames of external noise. The signal grating was randomly presented in one of the two intervals. All external noise frames were independently sampled. Observers chose the signal-interval by a key-press and received a brief tone following each response regardless of its accuracy.

Data analysis

For both the training and control groups, the pre- and post-training CSFs were compared by within-observer repeated measurement analysis of variance (ANOVA); Improvements in visual acuity and contrast sensitivity were analyzed with two-tailed paired t tests. The magnitudes of the improvements in visual acuity and contrast sensitivity in both the trained and untrained eyes of an observer were calculated by:

$$I_{individual} = 20\log_{10}\frac{VA_{post}}{VA_{pre}} \text{ and } 20\log_{10}\frac{CS_{post}}{CS_{pre}} \text{ dB.} \tag{1}$$

The average group percentage improvement was computed as:

$$P_{group} = (10^{\mathrm{I}_{group}/20} - 1) \times 100\%, \tag{2}$$

where $\mathrm{I}_{group} = \sum \mathrm{I}_{individual}/N$, and N is the number of observers.

The retention of training effects on visual acuity and contrast sensitivity was calculated by $\frac{VA_{retest}-VA_{pre}}{VA_{post}-VA_{pre}} \times 100$ % and $\frac{CS_{retest}-CS_{pre}}{CS_{post}-CS_{pre}} \times 100\%$, respectively.

To obtain TvC functions, we first fit the Weibull function to all the individual trials of the staircase procedure using a maximum likelihood procedure:

$$P_c = 1.0 - 0.5 \times \exp\left(-\left(\frac{c}{\alpha}\right)^{\eta}\right), \tag{3}$$

where α is the contrast threshold at 81.6% correct, and η is the slope of the psychometric function and kept constant in all the external noise conditions (Chen et al., 2014; Lu & Dosher, 2004).

The perceptual template model (Lu & Dosher, 1999) was used to evaluate the mechanisms of perceptual learning. Before learning, the TvC function was described by:

$$\begin{aligned}\log(c_\tau) = {} & \frac{1}{2\gamma}\log\left[(1 + N_m^2)N_{ext}^{2\gamma} + N_a^2\right] \\ & - \frac{1}{2\gamma}\log(1/d'^2 - N_m^2) - \log(\beta),\end{aligned} \tag{4}$$

where γ, N_m, and N_a, and β are the exponent of the nonlinear transducer, the proportional constant of multiplicative noise, the standard deviation of internal additive noise, and the gain to a signal-valued stimulus, respectively, N_{ext} denotes the standard deviation of external noise, and c_τ is the signal contrast threshold. $d' = 1.643$ for 79.4% correct and $d' = 1.089$ for 70.7% correct.

In the perceptual template model (PTM)-based theoretical framework, perceptual learning impacts performance via three possible mechanisms (Dosher & Lu, 1998; Lu & Dosher, 1999): (1) reducing internal additive noise after training by a factor of A_a; (2) retuning the perceptual template to improve external noise exclusion by a factor of A_f; (3) reducing internal multiplicative noise by a factor of A_m. The effects can be summarized in the following equation:

$$\begin{aligned}\log(c_\tau) = {} & \frac{1}{2\gamma}\log\left[\left(1 + (A_m N_m)^2\right)(A_f N_{ext})^{2r} + (A_a N_a)^2\right] \\ & - \frac{1}{2\gamma}\log\left(1/d'^2 - (A_m N_m)^2\right) - \log(\beta).\end{aligned} \tag{5}$$

For the five observers who participated in the TvC tests, the contrast threshold ratio between the two criterion performance levels was essentially constant across eight external noise levels, $F(7, 28) = 1.542$, $p = 0.194$. The results suggest that training did not alter the

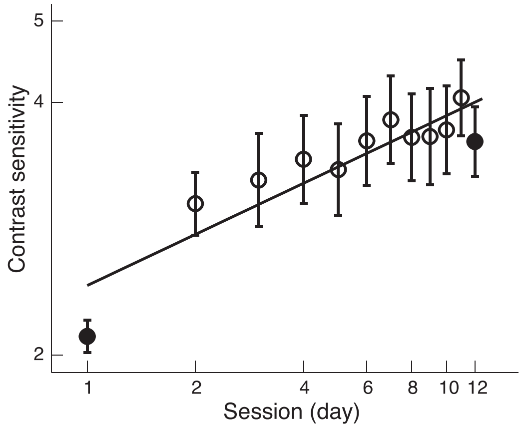

Figure 1. Effects of cutoff-frequency training on the contrast sensitivity at the trained frequency. Filled circles correspond to the contrast sensitivity derived from the pre-training and post-training CSFs; open circles are from the 10-day training sessions. Solid line reflected linear regression with a slope of 0.20 ($r^2 = 0.821$, $p = 4.8771\text{E}{-}5$). Error bars, *SEM*.

multiplicative noise or the contrast gain-control properties of the perceptual system (Dosher & Lu, 1998; Lu & Dosher, 1999). We thus considered four variations of the PTM-based models: (1) one model with no significant learning ($A_a = A_f = 1$), (2) two models with either change of A_a or A_f, and (3) one model with a mixture of two mechanisms (changes of both A_a and A_f).

All fits were implemented in Matlab using a least-square procedure to minimize $\Sigma(Y_{predicted} - Y_{measured})^2$. $Y_{predicted}$ is the model-predicted contrast sensitivity in a CSF measurement or the signal contrast threshold in a TvC measurement, and $Y_{measured}$ is the measured contrast sensitivity or the signal contrast threshold. The goodness-of-fit was then evaluated by r^2:

$$r^2 = 1.0 - \frac{\sum(Y_{predicted} - Y_{measured})^2}{\sum[Y_{measured} - mean(Y_{measured})]^2}, \qquad (6)$$

and different model variants were compared with an F-test for nested models:

$$F(df_1, df_2) = \frac{(r^2_{full} - r^2_{reduced})/df_1}{(1 - r^2_{full})/df_2}, \qquad (7)$$

where $df_1 = k_{\text{full}} - k_{\text{reduced}}$, and $df_2 = N - k_{\text{full}}$. The ks are the number of parameters in each model and N is the number of data points.

Results

Training group

Learning curves

Training of the non-dominant eye near each individual's cut-off spatial frequency resulted in highly significant (t(14) = −4.237, $p = 0.001$) improvement of contrast sensitivity at the trained spatial frequency in the trained eye (Figure 1). Averaged across observers, training improved contrast sensitivity by 4.6 dB (or 70.7%; $SE = 0.8$ dB; range: 1.2 dB to 10.4 dB). The learning rate was 0.20 log units per log session ($r^2 = 0.821$, $p = 4.8771\text{E}{-}5$). Excluding data from pre- and

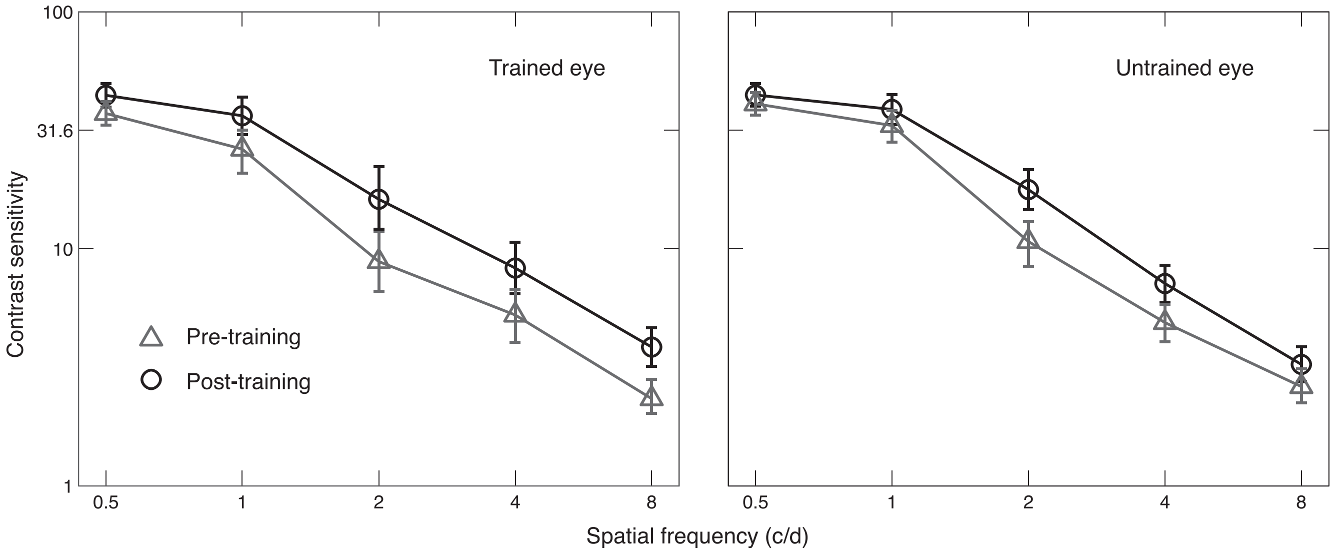

Figure 2. Effect of cutoff-frequency training on the contrast sensitivity functions of the trained and untrained eyes. Error bars, *SEM*.

		Trained eye (naked)			Untrained eye (naked)		
Group	Observer	Pre	Post	Improvement (dB)	Pre	Post	Improvement (dB)
Training group	*S 1*	0.850	0.400	9.0	0.156	0.050	2.1
	S 2	0.850	0.762	1.8	0.663	0.625	0.8
	S 3	0.575	0.190	7.7	0.467	0.275	3.8
	S 4	0.775	0.567	4.2	0.500	0.175	6.5
	S 5	0.450	0.338	2.2	0.625	0.625	0
	S 6	0.675	0.450	4.5	0.475	0.338	2.7
	S 7	0.725	0.550	3.5	0.550	0.467	1.7
	S 8	1.231	0.875	7.1	1.098	0.875	4.5
	S 9	0.950	0.294	13.1	0.975	0.550	8.5
	S 10	0.275	0.142	2.7	0.375	0.156	4.4
	S 11	0.567	0.358	4.2	0.762	0.338	8.5
	S 12	0.875	0.675	4	0.875	0.575	6.0
	S 13	0.725	0.358	7.3	0.338	0.112	4.5
	S 14	0.450	0.250	4.0	0.550	0.294	5.1
	S 15	0.142	0.060	1.6	0.190	0.156	0.7
	Average			5.1			4.0
Control group	*S 16*	0.294	0.250	0.9	0.550	0.575	−0.5
	S 17	0.950	0.975	−0.5	0.950	0.975	−0.5
	S 18	0.400	0.400	0	0.500	0.375	2.5
	S 19	0.550	0.500	1	0.450	0.375	1.5
	S 20	0.663	0.663	0	0.575	0.550	0.5
	S 21	0.725	0.725	0	0.725	0.725	0
	S 22	0.663	0.625	0.8	0.762	0.675	1.7
	S 23	0.294	0.275	0.4	0.050	−0.025	1.5
	Average			0.3			0.8

Table 2. Improvement in visual acuity (in logMAR) for training and control groups

post-training sessions the slope of improvement was 0.14 log units per log unit of training session ($r^2 = 0.864$, $p = 1.0064\text{E}{-4}$).

Contrast sensitivity function

In the trained eye, training near the cutoff spatial frequency improved contrast sensitivity over a wide range of spatial frequencies (Figure 2). A within-observer analysis of variance showed that contrast sensitivity varied significantly with both spatial frequency, $F(4, 56) = 17.350$, $p = 2.5963\text{E}{-9}$; training, $F(1, 14) = 11.426$, $p = 0.004$; and their interaction, $F(4, 56) = 2.544$, $p = 0.049$. Averaged across observers and spatial frequencies, training improved contrast sensitivity by about 3.6 dB (or 51.0%; *SE*: 0.4 dB; range: −1.5 to 10.1 dB).

In addition, the contrast sensitivity function in the untrained eye was also significantly improved, $F(1, 14) = 7.188$, $p = 0.018$, with an average improvement of 2.3 dB (or 30.7%; *SE*: 0.4 dB; range: −2.7 to 11.9 dB). The improvements in contrast sensitivity across all the tested spatial frequencies were not significantly different between the trained and untrained eyes, $F(1, 14) = 3.650$, $p = 0.077$.

Visual acuity

After training, visual acuity in both the trained, $t(14) = 6.287$, $p = 1.9982\text{E}{-5}$, and untrained eyes, $t(14) = 5.756$, $p = 4.9683\text{E}{-5}$, of almost all observers improved, with an average magnitude of 5.1 dB (or 80.5%; *SE*: 0.8 dB; range: 1.6 to 13.1 dB) and 4.0dB (or 58.2%; *SE*: 0.7 dB; range: 0 to 8.5 dB) of improvement, respectively (Table 2). The magnitude of improvement in the trained eye was not significantly greater than that in the untrained eye, $t(14) = 1.485$, $p = 0.160$.

The pre- and post-training visual acuities of each observer are shown in Figure 3. Almost all observers improved, as indicated by the clustering of data below the identity line. The best-fitting linear regression model had a slope of 0.69 for the trained eyes, $r^2 = 0.673$, $p = 1.7860\text{E}{-4}$) and 0.76 for the untrained eyes, $r^2 = 0.753$, $p = 2.7738\text{E}{-5}$, suggesting greater acuity

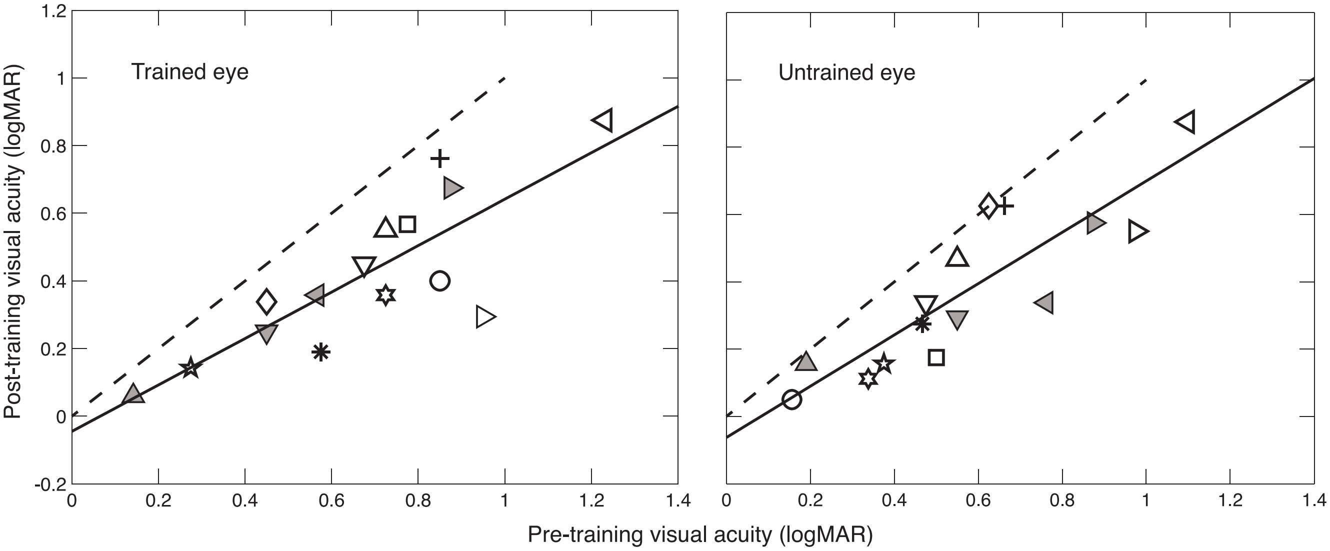

Figure 3. Effect of cutoff-frequency training on the visual acuity of the trained and untrained eyes. Visual acuity is expressed as logMAR. Each symbol represents one observer. The dashed line is the identity line (slope = 1). Data points below this line indicate improved visual acuity.

improvement for observers with worse pre-training visual acuity.

If we set the normal visual acuity (MAR) as 1, we can calculate the compensatory rate of perceptual learning for optical defects on visual acuity by $\frac{post-pre}{1-pre} \times 100\%$. We found that the average compensatory rate for myopic observers was 55.8% and 50.1% in the trained and untrained eyes, respectively.

Refractive status

We also measured the pre- and post-training refraction status of seven observers (S9, S10, S11, S12, S13, S14 and S15). The results are shown in Figure 4. Obviously, training did not lead to any significant refractive changes [trained eye: $t(6) = 0.420$, $p = 0.689$; untrained eye: $t(6) = -1.000$, $p = 0.356$], indicating that learning was not due to improved optical transmission.

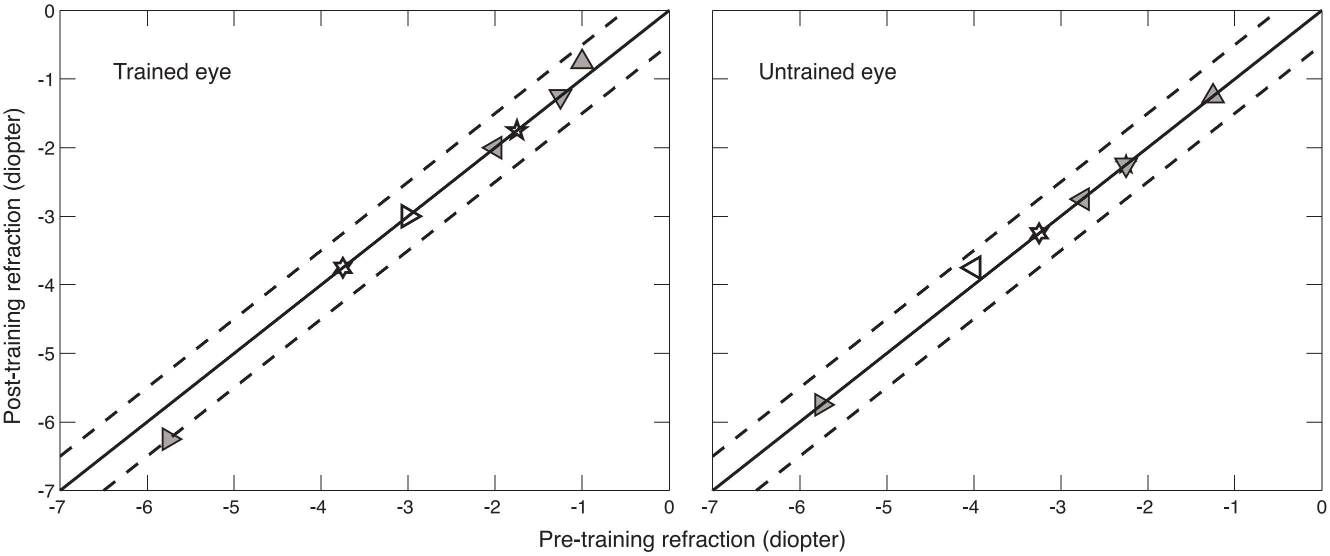

Figure 4. Effects of cutoff-frequency training on the refractive status of seven trained observers. The two dashed lines define the region in which $|\text{refraction}_{\text{pre-training}} - \text{refraction}_{\text{post-training}}| \leq 0.5$, i.e., the region of no refractive change. Each symbol represents one observer.

Observers Parameters	*S9* (2 c/d)	*S10* (3 c/d)	*S13* (2 c/d)	*S14* (3 c/d)	*S15* (8 c/d)	*Average*
λ	1.931	2.021	3.6523	4.7949	2.2876	2.2942
N_a	0.046	0.020	0.0017	1.0167E−05	0.0312	0.0158
N_m	0.023	0.001	0.5990	0.0019	0.5970	0.5394
β	2.730	1.842	0.9239	1.7860	5.6720	2.1326
A_a	0.337	0.266	0.4247	0.5636	0.7751	0.6471
A_f	0.866	0.688	0.7910	0.8908	0.8713	0.8324
r^2_{full}	0.950	0.945	0.9619	0.9596	0.9511	0.9782
$F_{\text{full vs Af}}$	115.284***	50.013***	26.1678***	10.4983**	5.1743*	23.7942***
$F_{\text{full vs Aa}}$	6.898*	41.926***	31.5312***	15.1645***	5.0773*	31.7362***
$F_{\text{full vs reduced}}$	73.329***	62.174***	31.5949***	8.6222**	6.4649**	34.8606***
$F_{\text{Af vs reduced}}$	5.815*	25.765***	18.8120***	4.9410*	6.6827*	24.4723***
$F_{\text{Aa vs reduced}}$	113.920***	32.020***	14.5605***	1.3464	6.7880*	17.4071***

Table 3. Parameters of the best fitting perceptual template model (PTM).

Control group

For the control group, there was no significant change in contrast sensitivity and visual acuity [non-dominant eye: $t(7) = 1.687$, $p = 0.135$; dominant eye: $t(7) = 2.119$, $p = 0.072$]. Averaged across observers and spatial frequencies, contrast sensitivity improved by 0.7 dB (or 7.8%; *SE*: 0.8 dB; range:–2.3 to 4.6 dB) in the non-dominant eye, and 0.6 dB (or 7.7%; *SE*: 0.7 dB; range: −1.8 to 4.8 dB) in the dominant eye. Visual acuity in the non-dominant and dominant eyes improved by 0.3 dB (or 3.7%; SE: 0.2 dB; range: –0.5 to 1.0 dB) and 0.8 dB (or 10.2%; *SE*: 0.4 dB; range: –0.5 to 2.5 dB), respectively (Table 2).

Mechanism of improvement

The pre- and post-training TvC functions were measured in the trained eyes of five observers (S9, S10, S13, S14, and S15). To evaluate the mechanism of perceptual improvement, we fit the perceptual template model (PTM) to the pre- and post-training TvC functions. For all five observers and the average observer, model comparison revealed that training decreased the internal additive noise and improved external noise exclusion. Parameters for the best fitting model are listed in Table 3. Accounting for 97.8% of the variance, training reduced the internal additive noise by 35.3%, and improved external noise exclusion by 16.8% for the average observer.

Retention

We remeasured the contrast sensitivity function and visual acuity of the trained eye: 8, 4, and 4 months after training for S7, S8, and S9, respectively. Averaged over spatial frequencies, contrast sensitivity improvements at the trained spatial frequency were retained by 113.8% for S7, 134.6% for S8, and 70.7% for S9 (log(CS), S7: pre, 1.02, post, 1.17, retest, 1.19; S8: pre, 0.59, post, 0.69, retest, 0.73; S9: pre, 1.18, post, 1.43, retest, 1.4). In other words, the improvements in contrast sensitivity were fairly robust over time, consistent with previous reports (Sagi & Tanne, 1994; Sowden, Rose, & Davies, 2002). Similarly, improvements of visual acuity were also well retained (logMAR, S7: pre, 0.725, post, 0.550, retest, 0.447; S8: pre, 1.231, post, 0.875, retest, 0.875; S9: pre, 0.950, post, 0.294, retest, 0.301). The retention ratios of visual acuity improvements for the three observers were 158.8%, 100%, and 98.9% in the trained eye.

Discussion

In the current study, we set out to test the potential of perceptual learning in improving visual functions in myopic vision, and to investigate the extent to which training can compensate for the degraded vision. We found that monocular training of grating contrast detection in the non-dominant eye near each individual observer's cutoff spatial frequencies significantly improved contrast sensitivity by 3.6 dB and visual acuity by 5.1 dB in the trained eye, and 2.3 dB and 4.0 dB in the untrained eye. The learning effects also transferred to a wide range of spatial frequencies. The training effect we found here must be in neural origin because optical transmission was not improved after training. The average compensatory rate of perceptual learning for optical defects was 55.8% in the trained eye and 50.1% in the untrained eye. Neither contrast sensitivity nor visual acuity improved significantly in the control group. Further study indicated that the improvements

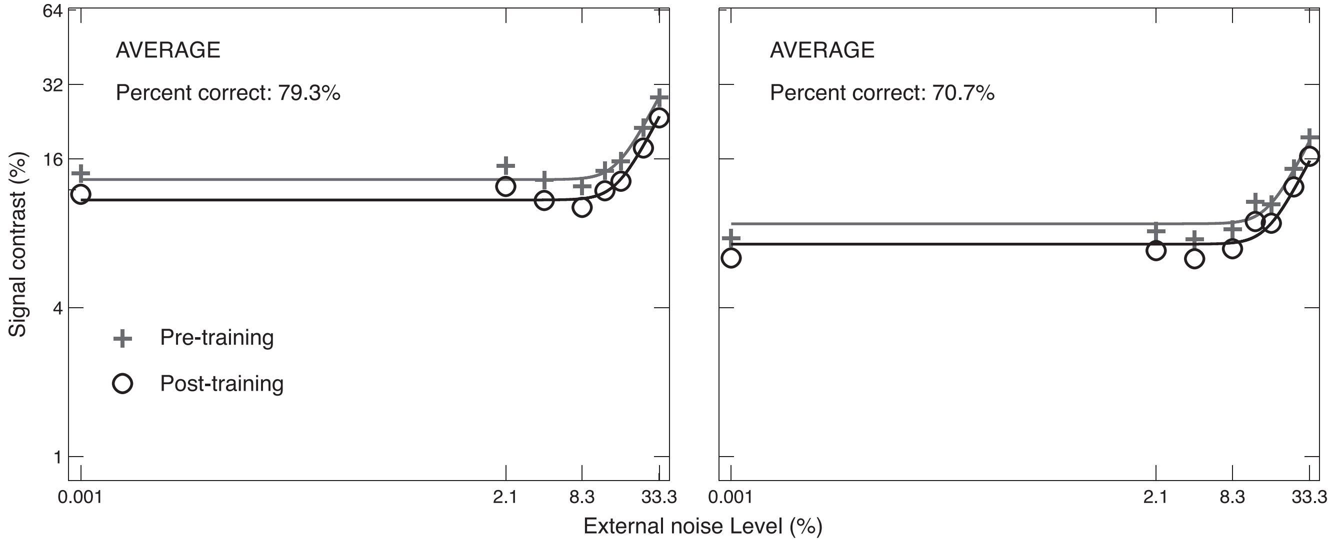

Figure 5. Threshold contrast versus external noise contrast functions as one spatial frequency of the average observer. TvC functions at 79.4% and 70.7% correct are shown in the left and right panels, respectively. "+" signs represent thresholds after training; "○" signs represent the pretraining thresholds.

in contrast sensitivity were due to a combination of internal additive noise reduction and improved external noise exclusion.

Our training paradigm focused on each individual's cutoff spatial frequency and the difficulty of the task was fixed using a three-down one-up staircase method. Such a training protocol has also been investigated in both amblyopic (Huang et al., 2008; Zhou et al., 2006) and normal adults (Zhou et al., 2012). Our study extends the cutoff-frequency training protocol and demonstrates that it was effective in adults with myopia. The application of the same training method in different populations enables us to quantitatively compare the learning effects across studies. In general, training induced significant improvements at the trained spatial frequency with about 10 dB in adults with amblyopia (Huang et al., 2008; Zhou et al., 2006) and 3 ∼ 6 dB in normal adults (Huang et al., 2008; Zhou et al., 2012). The improvement in the current study is 4.5 dB in myopic adults, comparable to the previously reported magnitude in normal adults. However, even though a similar amount of improvement at the trained frequency was found, previous training studies on normal adults failed to find improvement in visual acuity and transfer to untrained frequencies. One possible reason is that training may have involved different mechanisms in normal (or corrected-to-normal) and myopic vision. Huang et al. (2009) has demonstrated that perceptual learning of contrast detection at the cutoff spatial frequency in normals with corrected vision only improved external noise exclusion, with effects that are thought to be frequency specific (Huang et al., 2009; Zhou et al., 2012). For observers with high internal noise in the visual system, e.g., amblyopes (Huang, Tao, Zhou, & Lu, 2007; Xu, Lu, Qiu, & Zhou, 2006), training at the cutoff spatial frequency mainly decreases the elevated internal noise (Huang et al., 2009), triggering substantial improvement in visual acuity and broad transfer to untrained spatial frequencies (Huang et al., 2008). Since myopia blurs retina images and may induce higher internal noise in processing of blurry images, it is quite possible that training at the cutoff frequency may also decrease the elevated internal noise and therefore induce broad transfer across frequencies (Dosher & Lu, 2006).

In summary, we show that perceptual learning could effectively improve contrast sensitivity and visual acuity in adults with myopia. The improvements mainly come from reduction in internal noise instead of amelioration of optical transmission. Our results demonstrated that neural plasticity may be robust in adult myopic vision and perceptual learning may be a potential noninvasive treatment to compensate optical deficits in myopia. The learning curves in the current study suggest that our observers did not reach their asymptotic performance level even after 10 days' training. Whether prolonged training (Li et al., 2008) can lead to further improvements in adults with myopia remains an interesting question for future studies.

Keywords: myopia, perceptual learning, contrast sensitivity function, perceptual template model, external noise method

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