Perceptual learning improves neural processing in myopic vision

Fang-Fang Yan*
Key Laboratory of Behavioral Science, Institute of Psychology, Chinese Academy of Sciences, Beijing, China
University of Chinese Academy of Sciences, Beijing, China

Jiawei Zhou*
McGill Vision Research, Department of Ophthalmology, McGill University, Montreal, Canada

Wuxiao Zhao
Center for Optometry and Visual Science, Department of Optometry, People’s Hospital of Guangxi Zhuang Autonomous Region, Nanning, China

Min Li
Department of Ophthalmology, People’s Hospital of Guangxi Zhuang Autonomous Region, Nanning, China

Jie Xi
Key Laboratory of Behavioral Science, Institute of Psychology, Chinese Academy of Sciences, Beijing, China

Zhong-Lin Lu
Laboratory of Brain Processes (LOBES), Center for Cognitive and Behavioral Brain Imaging, Center for Cognitive and Brain Sciences, Department of Psychology, The Ohio State University, Columbus, OH, USA

Chang-Bing Huang
Key Laboratory of Behavioral Science, Institute of Psychology, Chinese Academy of Sciences, Beijing, China

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

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).


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/m². 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 ($\sigma = 0.5^\circ$ 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° × 0.013° at a distance of 1.14 m and 0.026° × 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
The 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.

Table 1. Observer characteristics.

<table>
<thead>
<tr>
<th>Group</th>
<th>Sub</th>
<th>Symbol</th>
<th>Sex</th>
<th>Age</th>
<th>Eye</th>
<th>Refractive error</th>
<th>Acuity (logMAR)</th>
<th>Trained SF (c/d)</th>
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<tr>
<td>Training group</td>
<td>S1</td>
<td>○</td>
<td>M</td>
<td>23</td>
<td>NE</td>
<td>−4.00DS</td>
<td>0.850</td>
<td>6</td>
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<td></td>
<td>DE</td>
<td>−1.00DS</td>
<td>0.156</td>
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<td>S2</td>
<td>+</td>
<td>M</td>
<td>27</td>
<td>NE</td>
<td>−3.25DS</td>
<td>0.850</td>
<td>4</td>
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<td></td>
<td></td>
<td>DE</td>
<td>−2.75DS</td>
<td>0.663</td>
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<td></td>
<td>S3</td>
<td>⋄</td>
<td>F</td>
<td>21</td>
<td>NE</td>
<td>−0.50DS/−1.75DC×35</td>
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<td></td>
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<td>S5</td>
<td>◊</td>
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<td>NE</td>
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<td>S6</td>
<td>▽</td>
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<td>0.675</td>
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<td></td>
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<td>◁</td>
<td>M</td>
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<td>0.950</td>
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<td>0.275</td>
<td>1.0</td>
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<td></td>
<td>S11</td>
<td>▶</td>
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<td>NE</td>
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<td>7.5</td>
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<td>−2.75DS</td>
<td>0.762</td>
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<td></td>
<td>S12</td>
<td>▶</td>
<td>M</td>
<td>24</td>
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<td>−4.75DS/−1.00DC×135</td>
<td>0.875</td>
<td>6</td>
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<td></td>
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<td>⋆</td>
<td>F</td>
<td>26</td>
<td>NE</td>
<td>−3.50DS/−0.25DC×14</td>
<td>0.725</td>
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<td>1.5</td>
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<td>DE</td>
<td>−2.00DS/−0.25DC×163</td>
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<td></td>
<td>S15</td>
<td>△</td>
<td>F</td>
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<td>0.142</td>
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<td>Control group</td>
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<td>M</td>
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<td>−2.50DS/−1.00DC×3</td>
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<td>−5.75DS</td>
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<td>S17</td>
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<td>S18</td>
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<td></td>
<td>S19</td>
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<td>DE</td>
<td>−0.50DS/−0.50DC×135</td>
<td>0.050</td>
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</table>
respectively. All conditions were intermingled 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
sensitivity were calculated with two-tailed paired
(ANOVA); Improvements in visual acuity and contrast
observer repeated measurement analysis of variance
and post-training CSFs were compared by within-

\[
P_{\text{group}} = (10^{I_{\text{group}}/20} - 1) \times 100\%,
\]

where \(I_{\text{group}} = \sum I_{\text{individual}} / N\), and \(N\) is the number of
observers.

The retention of training effects on visual acuity and
contrast sensitivity was calculated by

\[
\frac{VA_{\text{post}} - VA_{\text{pre}}}{VA_{\text{post}} - VA_{\text{pre}}} \times 100\%
\]

and

\[
\frac{CS_{\text{post}} - CS_{\text{pre}}}{CS_{\text{post}} - CS_{\text{pre}}} \times 100\%,
\]

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:

\[
P_c = 1.0 - 0.5 \times \exp \left( -\left( \frac{c}{\eta} \right)^{d'} \right),
\]

where \(x\) is the contrast threshold at 81.6% correct, and
\(\eta\) 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:

\[
\log(c_x) = \frac{1}{2\gamma} \log \left[(1 + N_{mN}^2) (N_{\text{ext}}^2) + N_a^2 \right] - \frac{1}{2\gamma} \log(1/d^2 - N_m^2) - \log(\beta),
\]

where \(\gamma\), \(N_m\), and \(N_a\) 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, \(N_{\text{ext}}\) denotes the standard deviation of
external noise, and \(c_x\) 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 \(A_i\); (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:

\[
\log(c_x) = \frac{1}{2\gamma} \log \left[ 1 + (A_mN_m^2)^2 \right] (A_fN_{\text{ext}})^2 + (A_aN_a)^2\right] - \frac{1}{2\gamma} \log \left( \frac{1}{d^2} - (A_mN_m^2) \right) - \log(\beta).
\]

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
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 $\sum (Y_{predicted} - Y_{measured})^2$. $Y_{predicted}$ 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 $r^2$:

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

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

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

where $df_1 = k_{full} - k_{reduced}$, and $df_2 = N - k_{full}$. The $k$s 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 ($r^2 = 0.821, p = 4.8771E-5$). Excluding data from pre- and...
post-training sessions the slope of improvement was 0.14 log units per log unit of training session ($r^2 = 0.864, p = 1.0064 \times 10^{-4}$).

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, $F(4, 56) = 17.350, p = 2.5963 \times 10^{-4}$; 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, $F(1, 14) = 6.287, p = 1.9982 \times 10^{-5}$, 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, $t(14) = 6.287, p = 1.9982 \times 10^{-5}$, and untrained eyes, $t(14) = 5.756, p = 4.9683 \times 10^{-5}$, 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 4.0 dB (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, $r^2 = 0.673, p = 1.7860 \times 10^{-4}$ and 0.76 for the untrained eyes, $r^2 = 0.753, p = 2.7738 \times 10^{-5}$, suggesting greater 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 $\frac{\text{post} - \text{pre}}{1 - \text{pre}} \times 100\%$. 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.
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: 0.5 to 2.3 dB) in the non-dominant eye, and 0.6 dB (or 7.7%; SE: 0.7 dB; range: 0.5 to 2.5 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

<table>
<thead>
<tr>
<th>Observers Parameters</th>
<th>S9 (2 c/d)</th>
<th>S10 (3 c/d)</th>
<th>S13 (2 c/d)</th>
<th>S14 (3 c/d)</th>
<th>S15 (8 c/d)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>1.931</td>
<td>2.021</td>
<td>3.652</td>
<td>4.7949</td>
<td>2.2876</td>
<td>2.2942</td>
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<tr>
<td>$N_a$</td>
<td>0.046</td>
<td>0.020</td>
<td>0.0017</td>
<td>1.0167E-05</td>
<td>0.0312</td>
<td>0.0158</td>
</tr>
<tr>
<td>$N_m$</td>
<td>0.023</td>
<td>0.001</td>
<td>0.5990</td>
<td>0.0019</td>
<td>0.5970</td>
<td>0.5394</td>
</tr>
<tr>
<td>$\beta$</td>
<td>2.730</td>
<td>1.842</td>
<td>0.9239</td>
<td>1.7860</td>
<td>5.6720</td>
<td>2.1326</td>
</tr>
<tr>
<td>$A_a$</td>
<td>0.337</td>
<td>0.266</td>
<td>0.4247</td>
<td>0.5636</td>
<td>0.7751</td>
<td>0.6471</td>
</tr>
<tr>
<td>$A_f$</td>
<td>0.866</td>
<td>0.688</td>
<td>0.7910</td>
<td>0.8908</td>
<td>0.8713</td>
<td>0.8324</td>
</tr>
<tr>
<td>$r_f$</td>
<td>0.950</td>
<td>0.945</td>
<td>0.9619</td>
<td>0.9596</td>
<td>0.9511</td>
<td>0.9782</td>
</tr>
<tr>
<td>$F_{full}$</td>
<td>115.284***</td>
<td>50.013***</td>
<td>26.1678***</td>
<td>10.4983***</td>
<td>5.1743*</td>
<td>23.7942***</td>
</tr>
<tr>
<td>$F_{full}$ vs $A_f$</td>
<td>6.898*</td>
<td>41.926***</td>
<td>31.5312***</td>
<td>15.1645***</td>
<td>5.0773*</td>
<td>31.7362***</td>
</tr>
<tr>
<td>$F_{full}$ vs $A_a$</td>
<td>73.329***</td>
<td>62.174***</td>
<td>31.5949***</td>
<td>8.6222***</td>
<td>6.4649***</td>
<td>34.8606***</td>
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<tr>
<td>$F_{Af}$ vs reduced</td>
<td>5.815*</td>
<td>25.765***</td>
<td>18.8120***</td>
<td>4.9410*</td>
<td>6.6827*</td>
<td>24.4723***</td>
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<tr>
<td>$F_{Aa}$ vs reduced</td>
<td>113.920***</td>
<td>32.020***</td>
<td>14.5605***</td>
<td>1.3464</td>
<td>6.7880*</td>
<td>17.4071***</td>
</tr>
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</table>

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

![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.](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/934263/ on 10/20/2018)
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*FFY and JZ contributed equally to this article.
Commercial relationships: none.
Corresponding author: Chang-Bing Huang.
Email: huangcb@psych.ac.cn.
Address: Key Laboratory of Behavioral Science, Institute of Psychology, Chinese Academy of Sciences, Beijing, China.

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