Supplementary Online Material for

The eye limits the brain's learning potential

Jiawei Zhou, Yudong Zhang, Yun Dai, Haoxin Zhao, Rong Liu, Fang Hou, Bo Liang, Robert F. Hess, Yifeng Zhou

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Materials and Methods

Observers. Twenty seven adults (Age: 19-26) with normal or corrected to normal vision (slightly myopic, ≤-3.0D) were randomly assigned into three groups. There were 13 observers, 8 observers and 6 observers in Group1, Group2 and Group3, respectively. Group1 were trained at HOAs-corrected cut-off spatial frequency (spatial frequency when contrast threshold at HOAs-corrected condition is 0.4), when HOAs were corrected; Group2 were trained at HOAs-uncorrected cut-off spatial frequency (spatial frequency when contrast threshold at HOAs-uncorrected condition is 0.4), when HOAs were uncorrected; Group3 were same with Group1, except they were trained at a lower spatial frequency (spatial frequency corresponding to peak contrast sensitivity at HOAs-corrected condition). The study was approved by the Institutional Review Board of University of Science and Technology of China. All subjects were naive to the purpose of the experiment; informed consent was obtained from all subjects and all investigations were conducted in accord with the principles expressed in the Declaration of Helsink.

Apparatus.

All experiments were conducted on a real-time closed-loop adaptive optics visual stimulator system (AOVS)[1] in a dark room. **Fig. S1** shows a schematic diagram of this system. It consists of a Hartmann-Shack wavefront sensor (WFS) with 97 lenslets, operating at 25 Hz, and a 37-actuator PZT deformable mirror with a stroke of about 2 microns, and the control bandwidth of the system is about 1Hz. A 905nm laser beam from the laser diode (LD) is collimated after passing through a spatial filter and beam expander, reflected by the mirror and the beam splitter before entering the subject's eye. The laser beam is then reflected backward from the retina and projected into the Hartmann-Shack wavefront sensor after passing through a deformable mirror (DM) and pupil matching system. The wavefront slope measured by the WFS is calculated by a computer and transformed into voltage data, using a direct-slope control algorithm, to drive the DM for correcting ocular aberration or inducing different aberration patterns in real-time through a 4.0 mm pupil. The exposure level at the cornea of the 905nm laser diode is set at about 5μW, which is well below the American National Standards Institute (ANSI) safe exposure level. (American National Standard for the Safe Use of Lasers ANSI Z136.1 (Laser Institute of America, Orlando, Fla.,1993)). The system amplification is 11.6, and field of view is 1.5 degree in diameter.

Experiments were controlled by a PC running Psychophysics Toolbox[2]. Stimuli were sinusoidal gratings displayed on a 12mm*9mm SVGA+ Monochrome Green OLED minidisplay (eMagin Corporation) with 800*600 pixel resolution, a frame rate of 60 Hz. The display subtended a 3.14*(1.5/2) * (1.5 /2) deg^2 area at the pupil plane. Retinal luminance, defined as the product of the luminance in the pupil plane (18.9 cd/m^2) with the pupil area (3.14*2mm*2mm), was 237 Troland (Td). Using a special circuit, the display system produced 14-bit gray-level resolution[3]. Observers used a chin rest and viewed the displays monocularly. They were instructed to fixate at the centre of the display, and not move fixation or head when performing the task.

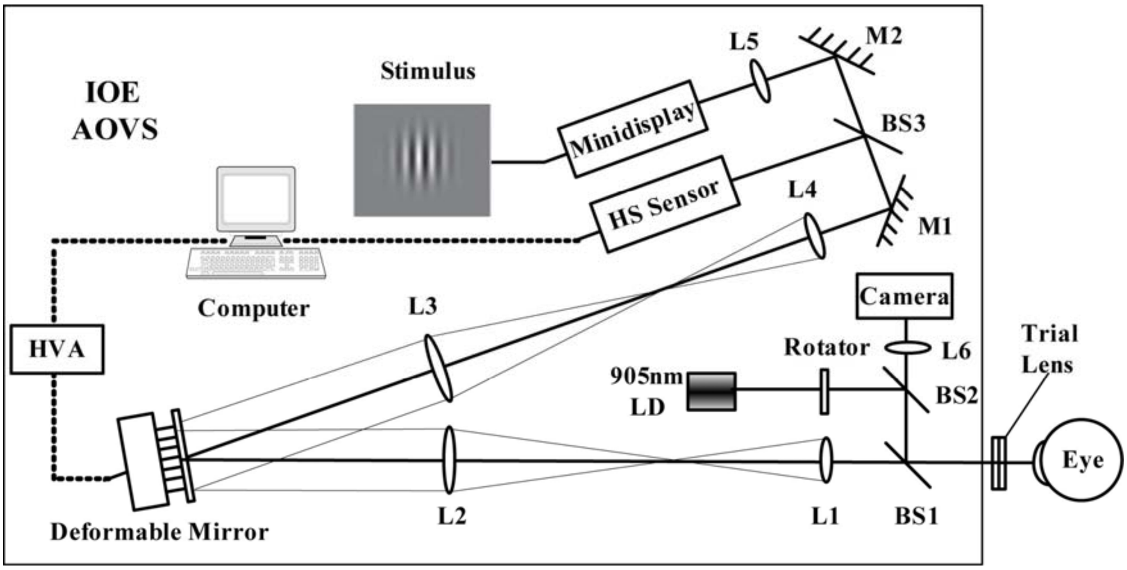


Fig. S1 Schematic of our adaptive optics vision simulator.

Design.

The experiment in each group consisted of four consecutive stages: a pre-training practice stage, a pre-training test stage, a training stage and a post-training test stage. For each subject, only one eye was used in the experiment, the other eye was covered by an opaque fabric. The tested eye having normal or corrected to normal vision was selected randomly for each observer.

At the pre-training practice stage, subjects were practiced to familiarize themselves with the apparatus and the contrast sensitivity test procedure for two days, a total 1.5 hr.

At the pre- and post-training test stages, visual acuity was measured under condition where the higher order aberrations (HOAs) were uncorrected. Contrast sensitivity functions (CSFs) were measured under both the HOAs corrected and uncorrected conditions. Visual acuity corresponding to 75% correct identification was measured with the Chinese Tumbling E Chart, and converted to MAR acuity. Contrast sensitivity, defined as the reciprocal of contrast threshold for detecting a sine-wave grating with 79.3% accuracy, was measured at spatial frequencies 0.6, 1, 2, 4, 8, 16, 24, 36 c/deg on the

AOVS. A testing session to collect contrast sensitivity data had eight blocks of 88 trials each and lasted about 1hr. Subjects could take an optional rest after finished one block. All of the spatial frequencies were randomly intermixed in each session. The orders of CSF testing at these two kinds of aberration conditions were counterbalanced for different observers, and kept consistent at the pre- and post-training test stages for each observer.

For 4 subjects in Group1, contrast thresholds corresponding to 79.3% correct under the HOAs-corrected condition as functions of external noise levels (i.e. Threshold versus external noise contrast, TvCs) for a spatial frequency of 2c/d and 16 c/d were also collected before and after training. The external noise images were made up of 3*3 pixel patches (0.013deg*0.013deg). Contrast of each patch was sampled from a Gaussian distribution with mean 0 and standard deviation that ranged from 0 to 0.33 in different trials. Eight standard deviations were used: 0.0, 0.021, 0.042, 0.083, 0.125, 0.167, 0.250, and 0.333.

At the training stage, only one single spatial frequency was used for each observer. Observers in Group1 were trained at their HOAs-corrected cut-off spatial frequency (spatial frequency when contrast threshold at HOAs-corrected condition is 0.4); observers in Group2 were trained at their HOAs-uncorrected cut-off spatial frequency (spatial frequency when contrast threshold at HOAs-uncorrected condition is 0.4); observers in Group3 were trained at their optimal spatial frequency in HOAs-corrected condition (defined as the spatial frequency at which the contrast threshold was lowest in HOAs-corrected condition). Each subject received a 10 sessions' training. Each training session consistent of seven blocks of 90 trials each and lasted about 50min. Subjects could take an optional rest after finished one block.

Procedure.

A two-interval forced-choice procedure was used for both training and threshold measurements.

In training and CSF measurements, the presentation sequence in each trial was as follows: a 267-ms fixation cross signalled by a brief tone in the beginning, a 117-ms interval, a 500-ms inter-stimulus interval (ISI) blank, a 267-ms fixation signalled by a brief tone in the beginning, a 117-ms second interval, and blank until response. In TvCs measurements, the presentation sequence in each trial was as follows: a 233-ms fixation cross signalled by a brief tone in the beginning, two 33-ms random noise frames, a 17-ms interval, two 33-ms random noise frames, a 500 ms inter-stimulus interval (ISI) blank, a 233-ms fixation cross signalled by a brief tone in the beginning, two 33-ms random noise frames, a 17-ms second interval, two 33-ms random noise frames, and blank until response. A sine-wave grating was randomly presented in one of the two intervals. The other interval was blank. The participant responded with a key press to indicate if the grating was at the first or second interval. The next trial started immediately after the response.

During training, a brief tone following each correct response was provided. During threshold measurements, a brief tone followed each response regardless of its accuracy. In both the training and test stages, thresholds were measured with a three-down one-up staircase procedure in which three consecutive correct responses resulted in a reduction of signal contrast (C_{n+1}=0.90C_n), and one wrong response resulted in an increase in contrast (C_{n+1}=1.10C_n), converging to a performance level of 79.3% correct. In the CSFs or TvCs test procedure, eighty eight trials were used to measure the contrast threshold at each spatial frequency or external noise level; the starting contrast for each staircase was set close to the expected threshold based on results from pilot testing at each aberration condition. In the training procedure, the starting contrast was set as 0.4 for the first training session, and was set as last trial's contrast in the last training session for other training sessions.

Data Analysis.

Statistics:

Post- and pre-training CSFs, TvCs, modulation transfer functions (MTFs) or neural transfer functions (NTFs) were compared using within-subject ANOVA. Post- and pre-training contrast sensitivities at the training spatial frequency or visual acuity were compared using within-subject T tests. Improvements of CSF or NTF between different groups were compared using between-subject ANOVA. Improvements of visual acuity between different groups were compared using independent T tests.

Improvement in contrast sensitivity at the training spatial frequency or visual acuity was defined as:

$$I = 20 \times log10\left(\frac{Post\_measure}{Pre\_measure}\right)dB$$

Analysis of learning effects:

Subjects that had significant contrast sensitivity improvement were selected in the analysis of learning effects. These subjects were selected by the following criteria: i) we fitted CSFs before and after training with full model and reduced model separately. For the full model, pre-training CSF was fitted with a difference of Gaussian (DOG) function (G1-G2), which is often used to fit CSF functions[4-7]; post-training CSF was fitted with: G1-G2+G3. The model will be assumed that learning will increase CSF and the improvement could be modelled with a Gaussian distribution (G3). For the reduced model, both pre- and post-training CSFs were fitted with G1-G2. ii) An F-test for nested models[8] was then used to statistically compare these two models. For two nested models with k_{full} and $k_{reduced}$ parameters, the F statistic is defined as:

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

Where $df_1 = k_{full} - k_{reduced}$, and $df_2 = N - k_{full}$; N is the number of data points.

If $P<0.05$, we chose full model, which indicates there was a significant improvement of CSF after training; otherwise, we chose reduced model, which indicates no significant improvement.

Average normalized improvement curves of the selected subjects that had significant improvement of CSF were then drawn using a similar method to that of Huang et.al [9].

The average normalized improvement curves were fitted with a full model:

$$I_f = a \times exp\left[-\left(\frac{f-b}{c}\right)^2\right] + d;$$

and a reduced model:

$$I_f = a \times exp\left[-\left(\frac{f-b}{c}\right)^2\right];$$

Here, I_f represents the average normalized improvement (the magnitudes of contrast sensitivity improvements were normalized to that at the training spatial frequency); f represents normalized spatial frequency (expressed as difference in octaves relative to the training frequency); a represents the amplitude of improvement; b represent the normalized frequency that has peak improvement; c represents the standard deviation of the Gaussian function; d represents a general improvement amplitude at all frequencies.

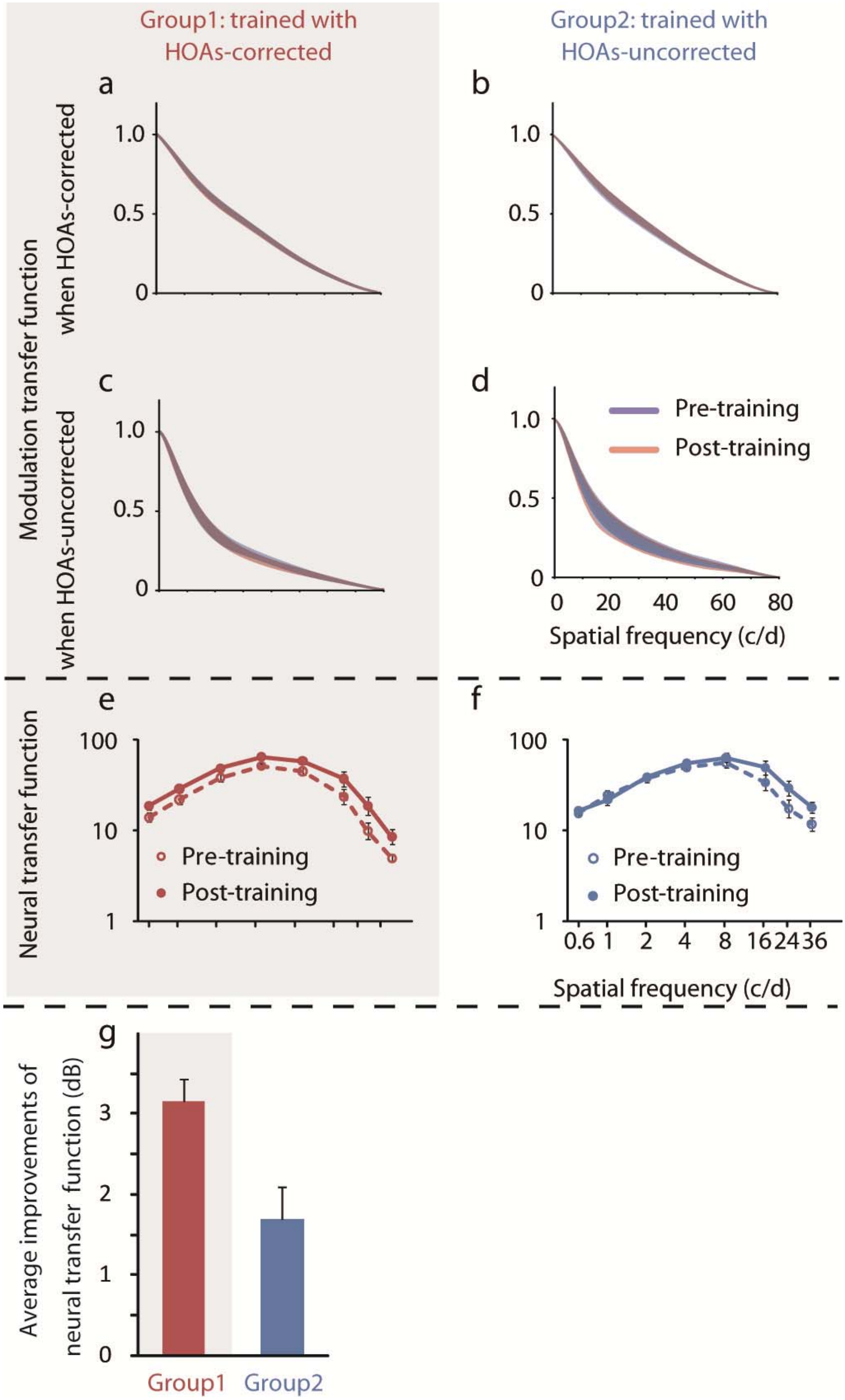
We then used an F-test for a nested model to statistically compare these two models. If $P<0.05$, we chose full model, which indicate there was a general benefit over all frequencies; otherwise, we chose reduced model, which indicates there was no general benefit.

The bandwidth of perceptual learning was then calculated by:

$$B = 2\sqrt{ln2}c$$

Results

1. Post- and pre-training modulation transfer function (MTF) measurements and neural transfer function (NTF) in Group1 and Group2. We found, after training, the MTFs either before or after HOAs corrected did not have significant change in both groups. Properties of post- and pre-training neural transfer functions (NTFs), which can be calculated from CSF minus MTF, were similar with their corresponding CSFs'. There were significant improvements of NTFs after training in both groups.



Group1: trained with HOAs-corrected
Group2: trained with HOAs-uncorrected
a
b
c
d
Modulation transfer function
when HOAs-corrected
when HOAs-uncorrected
1.0
0.5
0
Pre-training
Post-training
0
20
40
60
80
Spatial frequency (c/d)
e
f
Neural transfer function
100
10
1
0.6
1
2
4
8
16
24
36
g
Average improvements of neural transfer function (dB)
3
2
1
0
Group1
Group2

Fig.S2 Post- and pre-training optical modulation transfer functions (MTFs) and neural transfer functions (NTFs) in Group1 and Group2. Error bars, SEM. (a) MTFs when higher order aberrations (HOAs) were corrected in Group1, and where training was under the HOAs-corrected condition. Blue data represent pre-training; red data represent post-training. Post- vs. pre-training MTFs: $F(1, 12) = 1.77$, $P=0.21$; (b) MTFs when HOAs corrected in Group2, where training was under the HOAs-uncorrected condition. Post- vs. pre-training MTFs: $F(1, 7) = 0.22$, $P=0.65$; (c) MTFs when HOAs uncorrected in Group1. Post- vs. pre-training MTFs: $F(1, 12) = 0.08$, $P=0.78$; (d) MTFs when HOAs uncorrected in Group2. Post- vs. pre-training MTFs: $F(1, 7) = 2.54$, $P=0.15$; (e) NTFs before (open circles) and after training (filled circles) in Group1. Post- vs. pre-training NTFs: $F(1, 12) = 74.61$, $P<0.00001$; (f) NTFs before (open circles) and after training (filled circles) in Group2. Post- vs. pre-training: $F(1, 7) = 8.22$, $P=0.024$); (g) Average magnitude of NTF improvements across observers and spatial frequencies was 3.16dB in Group1 and 1.70dB in Group2. NTF improvements in Group2 were far less than those in Group1, $F(1, 19) = 4.93$, $P=0.039$.

2. CSFs prior to training:

CSF when HOAs corrected VS. HOAs uncorrected: in Group1, $F(1,12)=5.25$, $P=0.04$; in Group2:, $F(1,7)=12.57$, $P=0.009$; in Group3, $F(1,5)=13.20$, $P=0.015$;

Average benefit of HOAs correction per se (aver±SD): in Group1, 0.96±2.54dB; in Group2, 1.37±2.64dB; in Group3, 1.19±2.25dB. Not significantly different between groups: $F(1,2)=0.27$, $P=0.765$;

Average CSFs when HOAs were corrected were not significantly different between groups: $F(1,2)=1.85$, $P=0.179$.

3. Performances of contrast sensitivity at HOAs-uncorrected condition in Group1 significantly improved after training.

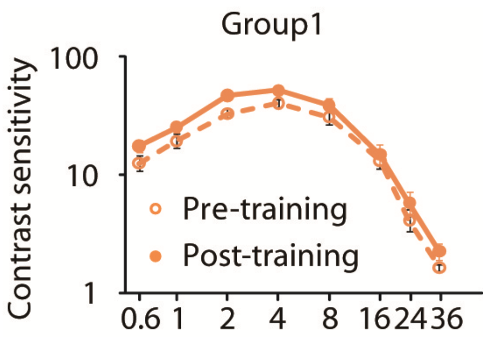


Fig.S3 Average post- and pre- training CSFs at HOAs-uncorrected condition in Group1. Error bars, SEM. Post vs. pre: $F(1, 12) = 64.91$, $P<0.00001$.

Group1_4mm (pre-training)			Yoon & Williams, 2002_3mm		
SF	AVER	SE	SF	AVER	SE
0.600	1.124	0.095			
1.000	1.116	0.080			
2.000	1.129	0.098	2.000	1.250	0.230
4.000	1.163	0.078	4.000	1.090	0.210
8.000	1.230	0.124	8.000	1.000	0.220
16.000	1.225	0.148	16.000	1.140	0.360
24.000	1.271	0.128	24.000	1.650	0.400
36.000	1.077	0.062	32.000	1.320	0.620

Table S1. Comparison of the contrast sensitivity improvements as a result of the adaptive optics per se (prior to training) for the present results with a 4 mm pupil with those of Yoon and Williams (2002) for a 3 mm pupil.

Group1:

	sx	zlb	yz	tny	zy	yh	ls	drq	lxr	dcr	sbs	syj	zyq	AVE	SE
0.000	0.430	0.383	0.399	0.380	0.383	0.392	0.465	0.413	0.406	0.389	0.379	0.418	0.344	0.399	0.008
0.301	0.405	0.508	0.609	0.412	0.441	0.625	0.473	0.613	0.677	0.285	0.569	0.718	0.315	0.512	0.038
0.477	0.467	0.501	0.513	0.515	0.494	0.843	0.491	0.735	0.792	0.503	0.590	0.820	0.489	0.597	0.040
0.602	0.662	0.707	0.684	0.743	0.394	0.660	0.560	0.863	0.757	0.426	0.813	0.796	0.324	0.645	0.047
0.699	0.593	0.772	0.548	0.787	0.624	0.662	0.553	0.911	0.831	0.540	0.694	0.806	0.591	0.686	0.034
0.778	0.627	0.838	0.885	0.843	0.664	0.926	0.377	0.870	0.933	0.447	0.724	0.754	0.597	0.730	0.050
0.845	0.460	0.752	0.875	0.769	0.601	0.664	0.505	0.841	0.893	0.624	0.957	0.838	0.740	0.732	0.042
0.903	0.529	0.852	0.880	0.669	0.668	0.803	0.615	1.012	0.625	0.636	0.889	0.834	0.688	0.746	0.039
0.954	0.455	0.776	0.852	0.786	0.765	0.888	0.589	1.087	0.898	0.898	0.887	0.881	0.705	0.805	0.044
1.000	0.468	0.732	0.837	0.777	0.742	0.894	0.681	0.988	0.800	0.644	0.907	0.765	0.769	0.770	0.036
1.041	0.612	0.687	0.902	0.749	0.923	0.945	0.412	1.019	0.953	0.611	0.985	0.777	0.772	0.796	0.050
1.079	0.586	0.785	0.678	0.589	0.569	0.707	0.564	0.703	0.816	0.469	0.901	0.830	0.694	0.684	0.035

Group2:

	gnt	Jzd	ly	Ll	pyq	Lb	Zgh	Kxw	AVE	SE
0.000	0.398	0.257	0.426	0.389	0.309	0.690	0.378	0.385	0.404	0.045
0.301	0.633	0.213	0.593	0.773	0.407	0.748	0.603	0.654	0.578	0.065
0.477	0.533	0.262	0.590	0.650	0.450	0.766	0.635	0.558	0.556	0.053
0.602	0.605	0.305	0.849	0.829	0.559	0.741	0.557	0.555	0.625	0.063
0.699	0.613	0.312	0.741	0.940	0.492	0.793	0.465	0.710	0.633	0.072
0.778	0.609	0.385	0.621	0.877	0.595	0.805	0.512	1.047	0.681	0.076
0.845	0.664	0.356	0.687	1.054	0.531	0.752	0.456	0.721	0.653	0.075
0.903	0.658	0.406	0.399	1.067	0.466	0.741	0.413	0.771	0.615	0.084
0.954	0.545	0.442	0.641	1.191	0.476	0.517	0.520	0.785	0.640	0.088
1.000	0.511	0.510	0.485	1.048	0.520	0.708	0.412	0.695	0.611	0.072
1.041	0.558	0.582	0.486	0.986	0.428	0.644	0.464	0.769	0.615	0.066
1.079	0.553	0.477	0.795	0.982	0.429	0.631	0.471	0.420	0.595	0.071

Table S2. Individual leaning curves for Group 1 and 2. Contrast sensitivity (log10(contrast sensitivity)) is plotted for the training spatial frequency in sequential training sessions (log10(session), session 1 and session 12 were derived from pre- and post-training contrast sensitivity function (CSF) measurements, respectively. The average improvement and standard error across subjects is shown on the far right for each session.

Pre-Training Benefit in Group1

SF	sx	zlb	yz	tny	zy	yh	ls	drq	lxr	dcr	sbs	syj	zyq	AVE	SE
0.6	1.16	0.72	1.03	1.39	0.98	1.70	1.22	0.83	0.88	0.80	1.32	1.78	0.82	1.12	0.10
1	1.08	0.94	1.21	1.00	0.98	1.87	1.17	0.72	1.36	1.14	0.97	1.27	0.80	1.12	0.08
2	0.88	0.90	1.09	1.29	0.92	2.22	1.14	1.09	1.15	0.88	0.94	0.95	1.23	1.13	0.10
4	1.22	0.97	1.18	1.74	0.99	1.09	1.05	1.71	1.09	1.13	1.25	0.97	0.75	1.16	0.08
8	0.87	0.62	0.71	1.55	1.75	2.03	1.27	1.28	1.15	1.17	1.83	0.91	0.85	1.23	0.12
16	1.88	0.53	0.77	2.24	0.95	0.70	0.99	0.88	1.14	1.74	1.73	1.50	0.89	1.23	0.15
24	0.94	0.91	1.26	1.68	1.06	1.09	1.16	1.08	1.25	2.60	1.03	1.54	0.93	1.27	0.13
36	1.28	0.71	1.08	1.10	0.93	1.06	1.48	0.91	1.44	1.01	1.13	1.05	0.81	1.08	0.06

Table S3. Contrast sensitivity improvements (contrast sensitivity with AO/contrast sensitivity without AO) as a function of the adaptive optics correction per se prior to the training are given for each subject in Group1 for a range of spatial frequencies.

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