## Supplementary materials

| Patient class | Patient # | Age at testing (years) | Age at operation (years) | Years since operation | Pre-op acuity | Pre-op GF (cpd) | Current GF (cpd) | Eyes gaze effect (ms) | Head gaze effect (ms) | Explicit gaze understanding result | Eyes S | Card-object preference index | Head preference index | "faces" dwell times on eyes region (ms) | "faces" dwell times on mouth+nose region (ms) |
|---------------|-----------|------------------------|--------------------------|-----------------------|---------------|----------------|------------------|----------------------|-----------------------|-------------------------------|---------|-----------------------------|---------------------|---------------------------------|---------------------------------|
| Early-treated | 5         | 5.3                    | 0.0                      | 5.3                   |               |               |                  |                      |                      |                               |         |                            |                     |                                 |                                 |
| Early-treated | 6         | 11.9                   | 0.5                      | 11.4                  |               |               |                  |                      |                      |                               |         |                            |                     |                                 |                                 |
| Early-treated | 7         | 13.7                   | 0.3                      | 13.4                  |               |               |                  |                      |                      |                               |         |                            |                     |                                 |                                 |
| Early-treated | 8         | 8.4                    | 0.3                      | 8.2                   |               |               |                  |                      |                      |                               |         |                            |                     |                                 |                                 |
| Early-treated | 9         | 9.6                    | 0.5                      | 9.1                   |               |               |                  |                      |                      |                               |         |                            |                     |                                 |                                 |
| Early-treated | 10        | 5.9                    | 0.5                      | 5.4                   |               |               |                  |                      |                      |                               |         |                            |                     |                                 |                                 |
| Early-treated | 11        | 14.6                   | 0.6                      | 14.0                  |               |               |                  |                      |                      |                               |         |                            |                     |                                 |                                 |
| Early-treated | 15        | 11.4                   | 1.1                      | 10.3                  |               |               |                  |                      |                      |                               |         |                            |                     |                                 |                                 |
| Early-treated | 16        | 10.0                   | 0.4                      | 9.5                   |               |               |                  |                      |                      |                               |         |                            |                     |                                 |                                 |
| Early-treated | 17        | 14.1                   | 0.4                      | 13.8                  |               |               |                  |                      |                      |                               |         |                            |                     |                                 |                                 |
| Early-treated | 18        | 6.6                    | 0.4                      | 6.1                   |               |               |                  |                      |                      |                               |         |                            |                     |                                 |                                 |
| Late-treated  | 11        | 12.3                   | 8.1                      | 4.1                   | LP            | 9.6            | -47.2            | 17.4                 |                      |                               |         |                            |                     | 859                             | 1171                            |
| Late-treated  | 24        | 12.3                   | 9.1                      | 3.2                   | FC 100m       | 2.1            | -27.1            | 90.0                 |                      |                               |         |                            |                     | 415                             | 648                             |
| Late-treated  | 29        | 18.6                   | 16.2                     | 2.3                   | HM            | 0.2            | 12.1            | 20.8                 | 49.7                 | V                             |         |                            |                     |                                 |                                 |
| Late-treated  | 33        | 14.5                   | 12.2                     | 2.3                   | FC 150cm      | 2.3            | 13.6            | 24.2                 | 16.5                 |                              |         |                            |                     |                                 |                                 |
| Late-treated  | 37        | 13.8                   | 12.2                     | 1.6                   | FC 300cm      | 3.7            | 6.8             | 16.1                 | 61.4                 | V                             |         |                            |                     | 567                             | 732                             |
| Late-treated  | 41        | 6.7                    | 5.1                      | 1.6                   |               | 6.8            | >19              | 16.2                 |                      |                               |         |                            |                     |                                 |                                 |
| Late-treated  | 47        | 9.2                    | 9.1                      | 0.1                   | HM            | 1.7            | 2.5             | 15.0                 | 163.2                | X -0.26                       |         |                            |                     | 415                             | 648                             |
| Late-treated  | 49        | 20.9                   | 19.8                     | 1.1                   | FC 10cm       | 0.7            | 2.9             | 11.9                 | -29.0                | X                             |         |                            |                     |                                 |                                 |
| Late-treated  | 52        | 11.3                   | 10.2                     | 1.1                   | LP            | 0.1            | 3.0             | 64.3                 | 68.4                 |                              |         |                            |                     | 1124                            | 548                             |
| Late-treated  | 53        | 11.3                   | 10.2                     | 1.1                   | FC 50cm       | 1.6            | 2.5             | -28.0                | 115.1                | X                             |         |                            |                     |                                 |                                 |
| Late-treated  | 56        | 10.2                   | 10.1                     | 0.1                   | HM            | 2.0            | 5.6             | -0.7                 | -13.3                | X -0.19                       |         |                            |                     | 821                             | 687                             |
| Late-treated  | 57        | 11.2                   | 11.1                     | 0.1                   | HM            | 1.9            | 2.3             | -8.5                 | 66.7                 | X                             |         |                            |                     |                                 |                                 |
| Late-treated  | 59        | 16.4                   | 15.4                     | 1.0                   | FC 200cm      | 1.3            | 6.3             | 17.7                 | 42.0                 | V 0.34                        |         |                            |                     | 1612                            | 170                             |
| Late-treated  | 60        | 11.3                   | 10.3                     | 1.0                   | FC 300cm      | 2.6            | 4.4             | -25.3                | 67.2                 | X 0.00                        |         |                            |                     | 1090                            | 938                             |
| Late-treated  | 61        | 9.3                    | 8.3                      | 1.0                   | FC 100cm      | 0.7            | 7.1             | -26.9                | 129.9                | X -0.23                       |         |                            |                     | 584                             | 529                             |
| Late-treated  | 65        | 15.6                   | 14.2                     | 1.4                   |               | 6.2            | 10.8            |                      |                      |                               |         |                            |                     | 0.09                            | 0.69                            |
| Late-treated  | 69        | 11.1                   | 10.0                     | 1.0                   | LP-HM         | 0.1            | 10.0            |                      |                      |                               |         |                            |                     | -0.43                           | 0.02                            |
| Late-treated  | 72        | 13.6                   | 13.2                     | 0.4                   |               | 0.5            | 8.1             |                      |                      |                               |         |                            |                     | 1237                            | 773                             |
| Late-treated  | 79        | 11.5                   | 11.0                     | 0.5                   | HM            | 2.5            | 16.9            |                      |                      |                               |         |                            |                     | 0.48                            | 0.45                            |

**Supplementary Table 1.** Clinical and behavioral results of all patients in the various tests conducted.
Supplementary Fig. 1. CSF experiment design.

The contrast sensitivity function (CSF) was calculated using a sinusoidal grating patch presented on a screen. The test began using gratings at 100% contrast at the lowest spatial frequency (1 cycle per 512 pixels = 0.077 cycles per cm) and proceeded to higher spatial frequencies (up to 1 cycle per 2 pixels = 19.7 cycles per cm) if the subject reported the correct orientation. Upon the first error, the criterion for looking from changing the spatial frequency to higher (up) or lower values (down) was changed to 3:1 staircase to better assess the spatial threshold frequency (SF_{thresh}) observed at maximum contrast. In the next testing blocks the spatial frequency remained constant (testing one frequency in each block) and the contrast was manipulated (using a similar 3:1 staircase) to find the threshold contrast for each spatial frequency. The tested frequencies were evenly spaced in log scale. Thus, for each spatial frequency (beginning one frequency step higher than SF_{thresh}) the contrast was manipulated to best sample the appropriate dynamic range and assess the threshold contrast. Finally, the spatial frequency was translated to retinal coordinates (i.e., cpd) by considering the viewing distance. The sensitivity (1/contrast threshold) for each frequency was plotted in a logarithmic scale. The resulting CSF was fitted with an inverse parabola function similar to Watson and Ahumada (A. B. Watson, A. J. Ahumada, A standard model for foveal detection of spatial contrast. J. Vis. 5, 717–740 (2005)) to get the CSF cutoff frequency (the crossing point of the fitted parabola with the minimal sensitivity of 1, corresponding to a threshold contrast of 100%). The cutoff frequency reflects the maximal spatial frequency, beyond which no information is available to the subject. Screen luminance was calibrated using a photometer (L202 PMS). The maximum and minimum luminance levels were 164 cd/m² and 0.85 cd/m², respectively. The Gamma correction function was measured, to allow use of the correct RGB levels for a given luminance contrast.
Supplementary Text 1. Gaussian filter standard deviation and corresponding cutoff frequency

The poorest visual acuity among our post-operated late-treated patients who participated in our behavioral study was 2.1 cpd. To assure that differences in performance between patients and controls do not arise from this limitation we generated a similar image blur (in fact, slightly greater blur) in our control group. To that end, we convolved stimuli images with a 2D Gaussian filter kernel with a spatial standard deviation of 8 pixels, corresponding to a cutoff frequency 1.6 cpd. The technical details are provided below:

The impulse response of this filter is given by: \( g(x,y) = \frac{1}{2\pi\sigma_s^2} e^{-\frac{x^2+y^2}{2\sigma_s^2}} \), where \( \sigma_s \) is the spatial standard deviation (in our simulations the filter kernel radius \( r \) was set as twice the spatial standard deviation: \( r = 2\sigma_s \)).

The cutoff frequency at \( 1/\delta \) of the maximum spectrum power is defined as: \( f_c = \sqrt{2 \ln \delta \cdot \sigma_f} \), where \( \sigma_f \) is the standard deviation in the frequency domain, defined as: \( \sigma_f = \frac{1}{2\pi\sigma_s} \). In our simulation we used the cutoff frequency at tenth of the maximum power (i.e., \( \delta = 10 \)): \( f_{c, tp} = \sqrt{2 \ln 10} \cdot \sigma_f \approx 2.15 \cdot \sigma_f \).

Face image stimuli, in our experiments, were displayed on a computer screen (face width was 330 pixels). From a distance of about 40cm, a displayed face subtended 8.5 visual degrees, equivalent to a real face (normally 15cm wide) seen from a distance of 1m.

In these settings, a Gaussian filter with spatial standard deviation of 8 pixels \( (\sigma_s) \) has a cutoff frequency of about 1.6 cpd at tenth of the maximum power:

\[
f_{c, tp} \approx 2.15 \cdot \sigma_f = 2.15 \cdot \frac{1}{2\pi \cdot 8[\text{pixels}]} \cdot \frac{330[\text{pixels}]}{8.5[\text{degrees}]} \approx 1.6[\text{cpd}]
\]
Supplementary Fig. 2. Inclusion criteria.

All patients were subject to the following pre-tests. Only those that exceeded 90% correct (beside the eye-gaze direction detection that required 75% correct) were included in the main behavioral tests. (a) Face recognition: the face, which was later presented in the main experiment, appeared together with two similarly shaped distractors. These consisted of 12 trials, in 6 of the trials the distractors shared the same color as the face. The participant was instructed to touch the face image. (b) Eye recognition: Next, the same face was presented at random locations on the screen and participants were instructed to touch the eyes of the face (see figure below; (b) eye recognition). A touch in the eyes’ surroundings (a rectangle containing both eyes at the center with the eyebrows as the edges) was considered a correct response. (c)+(d) Gaze direction detection: three faces were shown, one of which changed gaze, and participants were asked to touch the moving/changing element. (c) In 12 trials, head direction was changed back and forth, thereby generating head rotation movement, until response. (d) In further 12 trials, eye direction was changed in the same manner.
Supplementary Table 2. Describing the 3X2 ANOVA results showing the effects of group (late-treated, early-treated and controls) and cue (eyes, head) on the gaze compatibility effect.

| Source          | Type III Sum of Squares | df | Mean Square | F     | Sig. |
|-----------------|-------------------------|----|-------------|-------|------|
| Corrected Model | 36211.977               | 5  | 7242.395    | 6.895 | 0.000|
| Intercept       | 140991.800              | 1  | 140991.800  | 134.224| 0.000|
| group           | 7484.378                | 2  | 3742.189    | 3.563 | 0.031|
| experiment      | 3848.811                | 1  | 3848.811    | 3.664 | 0.058|
| group ^ experiment | 27501.048             | 2  | 13750.524   | 13.090| 0.000|
| Error           | 143908.173              | 137| 1050.425    |
| Total           | 432049.246              | 143|              |
| Corrected Total | 180120.150              | 142|              |

a. R Squared = .201 (Adjusted R Squared = .172)

Supplementary Fig. 3. Dependence of the eye-gaze cue compatibility effect on various parameters which vary among the early vs late cataract-treated population, and within each population. Eye-gaze compatibility effect versus acuity and visual deprivation. Plots depict early-treated (blue) and late-treated (yellow) patients’ eye-gaze compatibility effect, as a function of the age at surgery, the time since surgery, and the pre- and post-op cutoff frequencies. R² is calculated on the basis of the late-treated results. Note, however, that the head/eye cueing effect was highly variable due to the inherent variability in RT measurements and the limited number of trials. Across groups, the average reliability of the eye-gaze cueing effect at the individual level, assessed using a split-half reliability approach, was r=0.2. Thus, although the group difference is evident, it is practically impossible to extract factors which may explain the variance in the eye-gaze cueing behavior within the late treated patients, given the noisy data at the individual level. However, the difference between the late-treated and control groups is highly significant and robust (see Fig. 3C).
Supplementary Text 2. Explicit gaze understanding details

We also tested 10 of the late-treated participants’ explicit gaze understanding. With the aid of a bi-lingual translator, we instructed them to produce explicit reports of gaze directions.

The experiment started with a presentation of a face changing its head-gaze direction (following a touch on the nose, as in the head-gaze main experiment) followed by the appearance of two balloons (instead of just one in the main experiment). Participants were asked to touch the balloon that the person was gazing at. This task was repeated 8 times for each participant. All 10 participants succeeded in all 8 trials. Next, participants were asked to perform the same task, with an eye-gaze cue signal (as in the eye direction experiment). Only three participants succeeded above chance level with a score of 7 or 8 out of 8 trials (binomial distribution; p = 0.03). All 10 participants were able to discriminate between left and right eye positions (i.e. report the location of the pupil: at the right or left side of the eye). Thus, failure to explicitly understand eye gaze, was not due to a failure in detecting the eye position in its orbit. Rather it reflected a failure in generating an association between gaze, and the object of gaze (e.g. its position in space).

Supplementary Text 3. Eye-gaze cueing learning procedure

As we report above, unlike controls, our late-treated patients failed to use eye-gaze cues to guide their eye-movements in free-viewing conditions. To see if eye-gaze following can be learned using explicit feedback, we first had the patients (N=11) point to the direction of the actor’s eye-gaze towards one of the two identical objects (as in Fig. 4A, “baseline”, n=12 trials). Here, we provided them with feedback on their success. They were initially correct on 75% (group average) of these trials. Control participants (N=18; age 12.0±3.1yrs) who were tested on a blurred version of the same “baseline” test performed flawlessly (100% correct). Thus, there was a significant difference between initial performance of the control group and the late-treated group (t(10)=3.57; p=0.002).

Next, we trained the late-treated patients on a task in which they saw a video clip, consisting of an “actor” first looking straight ahead. Upon touching the face, the actor shifted his eyes to the target object (for 1 second), followed by orienting his head to the target (1 second), and finally moving his hand and grasping the object (thereby initiating a “mover event”). If the patient correctly identified the object of gaze (based on all the above cues), the video clip was shortened to omit the last stage of the clip using a staircase procedure. The aim of this procedure was to reach the eye-gaze only stage, thereby teaching patients to recognize the gaze direction based on eye position alone. The patients did indeed get better, and most advanced in the staircase to the point of discriminating gaze direction based on the eye-position alone. When we repeated the “baseline” test after this training procedure, their performance improved (to 85%) and their reaction times were considerably faster.

The last step was to test the effect of learning on automatic eye following. For this purpose, 5 of the late treated patients performed additional free viewing tasks while their eyes were tracked, as described in the main text in section 1.4. The same task was performed twice: once before the learning task (‘baseline’) and once after the learning task (‘post-training’). These patients failed to show generalization of automatic eye gaze-following in the free viewing task. The patients’ showed no preference to the eye gaze-cued object in their fixation patterns. The results are shown in Supplementary Fig. 4.
Supplementary Fig. 4. Effect of explicit training on eye movements and behavior

(a) Late treated patients (N=11) show mild (non-significant) improvement when asked to point to the actor's gazed-upon object (indicated here by arrow), after completing a training task, which encouraged them to use eye information (see text). Notably, controls' performance was perfect, without exception, and without any training. A subset of the late-treated patients (N=5) performed also a free-viewing task, while their eye movements were recorded before and after the training. Their behavioral data is shown in (b) on the left, and their object-preference based on their eye tracking data is shown on the right. The eye tracking data is presented as the ratio between dwell time on the target and the distractor. Positive values mean spending more time on the gaze-cued object. The short training session does not affect their object preference, which is no different from zero in both cases. Error bars denote standard error of the mean (SEM). ** denotes p<.005.

Supplementary Text 4. Detection reliability of ‘mover’ events in blur conditions

‘Mover’ events serve as the internal teaching signal for gaze following. The reliability of the teaching signal is measured by means of the precision and recall of detecting ‘mover’ events. The detection precision (indicating the fraction of true hand-object contacts out of all of the model’s ‘mover event’ detections) is discussed in the main text and methods. In supplementary Fig. 5 we present also the detection recall, which indicates the fraction of detected hands out of all the hand-object contacts in the data. At some point, a very low recall rate (i.e. extraction of sufficient number of good hand-object contact examples) may be too slow for effective learning.
Supplementary Fig. 5. Reliability of the internal teaching signal for gaze following (‘mover’ detection) under degraded input conditions.

The reliability of the ‘mover’ teaching signal remains high (>60%) even under degraded input conditions (less than 1 cpd), thus allowing the learning of gaze following for head orientation but not for eye gaze direction, due to the low acuity conditions. The reliability is measured by means of precision (in solid gray) indicating the number of positive hand-object contacts (tp) out of all detections (tp+fp): whether true positive (tp) or false positive (fp). Precision = tp/(tp+fp). The detection recall (in gray pattern) indicates the number of correctly detected hands (tp) out of all hand-object contacts in the data (tp+fn): true positive (tp) or miss detection (false negative; fn). Recall = tp/(tp+fn). The input cutoff frequencies (15.7, 1.7, 0.8, 0.4, 0.3 cpd) indicate the blur produced by convolving each image in the video with a Gaussian filter kernel of size 0,8,16,32, or 64 pixels, respectively. Error bars represent standard error over multiple input sequences at a given blur level.

Supplementary Text 5. Upright vs. inverted Eye-Gaze Posner effect

This auxiliary experiment was designed to test whether the Eye-Gaze Posner effect missing in the late-treated group relies on global or local processes of face perception.

Face inversion disrupts global face processing. We therefore inverted the images in the Eye-Gaze Posner task to see its effect on eye-gaze cueing. 45 typically sighted children (28 females) ages 5-19 (average 10.0±3.0) participated in this study after their legal guardian signed an informed consent. The study was approved by the Hebrew University local ethical committee.

The Blurred Eye-Gaze Posner test was repeated twice. First, in an identical manner to that reported for the control group in the main text and second, when the whole test was inverted upside down. In half of the participants the order was reversed. After excluding trials with reaction times (RT) longer than average RT + 3 standard deviations and RTs smaller than 200ms (as we did in the main experiment) the remaining average of trials was 84 trials per participant in each of the two tests.

There was no significant difference between the upright (M=36±21ms) and the inverted (M=27±24ms) Posner effects (p=0.08; t(44)=1.8). Both the upright (p<0.0001; t(44)=11.0) and the inverted (p<0.0001; t(44)=7.5) effects were significantly greater than zero. Furthermore, patients’ eye-gaze effect was smaller (M = 1.5±29) and differed from both the upright (p=0.0001; t(58)=4.1) and the inverted (p=0.014; t(58)=2.5) effect of the control participants tested in this experiment. We therefore conclude that the lack of Eye-Gaze Posner effect that we have observed in the late-treated group was not a result of merely impairment in holistic face processing.