



Kent Academic Repository

Lev, Maria, Gilaie-Dotan, Sharon, Gotthilf-Nezri, Dana, Yehezkel, Oren, Brooks, Joseph L, Perry, Anat, Bentin, Shlomo, Bonne, Yoram and Polat, Uri (2015) *Training-induced recovery of low-level vision followed by mid-level perceptual improvements in developmental object and face agnosia*. *Developmental Science*, 18 (1). pp. 50-64. ISSN 1363-755X.

Downloaded from

<https://kar.kent.ac.uk/37494/> The University of Kent's Academic Repository KAR

The version of record is available from

<https://doi.org/10.1111/desc.12178>

This document version

Author's Accepted Manuscript

DOI for this version

Licence for this version

UNSPECIFIED

Additional information

Versions of research works

Versions of Record

If this version is the version of record, it is the same as the published version available on the publisher's web site. Cite as the published version.

Author Accepted Manuscripts

If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in *Title of Journal*, Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

Enquiries

If you have questions about this document contact ResearchSupport@kent.ac.uk. Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our [Take Down policy](https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies) (available from <https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies>).

Training-induced recovery of low-level vision followed by mid-level perceptual improvements in developmental object and face agnosia

Maria Lev^{1,#}, Sharon Gilaie-Dotan^{2,#,*}, Dana Gotthilf-Nezri¹, Oren Yehezkel¹, Joseph L. Brooks³, Anat Perry^{4,α}, Shlomo Bentin^{4,5,‡}, Yoram Bonne⁶, and Uri Polat¹

1 Faculty of Medicine, Goldschleger Eye Research Institute, Tel Aviv University, Tel Hashomer, Israel

2 Institute of Cognitive Neuroscience, University College London, London, UK

3 School of Psychology, University of Kent, Canterbury, UK

4 Department of Psychology, Hebrew University of Jerusalem, Jerusalem, Israel

5 Center for Neural Computation, Hebrew University of Jerusalem, Jerusalem, Israel

6 Department of Human Biology, University of Haifa, Haifa, Israel

α Currently at the Department of Psychology, University of Haifa, Israel

These authors contributed equally to this study

‡ Deceased, July 13, 2012

* Corresponding author:

Sharon Gilaie-Dotan, UCL Institute of Cognitive Neuroscience, 17 Queen Square, London WC1N 3AR, UK, E-mail: shagido@gmail.com, s.gilaie-dotan@ucl.ac.uk

Training-induced recovery of low-level vision followed by mid-level perceptual improvements in developmental object and face agnosia

ABSTRACT

Long-term deprivation of normal visual inputs can cause perceptual impairments at various levels of visual function, from basic visual acuity deficits, through mid-level deficits as contour integration and motion coherence, to high-level face and object agnosia. Yet it is unclear whether training during adulthood, at a post-developmental stage of the adult visual system can overcome such developmental impairments. Here, we visually trained LG, a developmental object and face agnostic individual. Prior to training, at the age of 20, LG's basic and mid-level visual functions such as visual acuity, crowding effects, and contour integration were underdeveloped relative to normal adult vision, corresponding to those of 5-6 year olds (Gilaie-Dotan, Perry, Bonneh, Malach, & Bentin, 2009). Intensive visual training, based on lateral interactions, was applied for a period of nine months. LG's directly trained but also untrained visual functions such as visual acuity, crowding, binocular stereopsis and also mid-level contour integration improved significantly and reached near-age-level performance, with long-term (over 4 years) persistence. Moreover, mid-level functions that were tested post-training were found normal in LG. Some possible subtle improvement was observed in LG's higher order visual functions such as object recognition and part integration, while LG's face perception skills have not improved thus far. These results suggest that corrective training at a post-developmental stage, even in the adult visual system, can prove effective, and its enduring effects are the

Visual training and perceptual changes

basis for a revival of a developmental cascade that can lead to reduced perceptual impairments.

INTRODUCTION

Sensory experience shapes neural structures and functions dramatically during the early period of life, termed the "critical period" (Horton & Hocking, 1997; Hubel & Wiesel, 1970). While different visual cortical structures and functions may develop at different rates (Atkinson, 2000; Levi & Carkeet, 1993), the general notion is that "basic" functions typically develop earlier and more complex functions develop at a later stage, and recent studies show that visual functions processed at higher levels within the visual cortex have a later "critical period" than functions processed at lower levels (Daw, 1998). Furthermore, functions involving higher cortical areas which reach maturity much later, have a much shorter critical period (Elleberg, Lewis, Maurer, Brar, & Brent, 2002). Consequently, a developmental cascade in time may be paralleled by a maturation hierarchy of cortical visual areas, where the maturation of each visual function or cortical visual area may rely on the maturation of the ones preceding it.

Amblyopia is a visual disorder manifested by monocular (anisometropia and strabismus) or binocular (binocular deprivation due to congenital cataract) reduction of visual acuity following abnormal binocular visual experience during the "critical period" (Daw, 1998; Horton & Hocking, 1997; Hubel & Wiesel, 1970). It is characterized by several spatial vision abnormalities in the amblyopic eye (for reviews, see (Ciuffreda, Levi, & Selenow, 1991; Hess, Field, & Watt, 1990; Levi, 1991; Levi & Carkeet, 1993)) including reductions in visual acuity, contrast sensitivity, abnormal suppressive and facilitatory spatial interactions (Elleberg,

Visual training and perceptual changes

Lewis, et al., 2002; Levi, Hariharan, & Klein, 2002; Lewis et al., 2002; Polat, Ma-Naim, Belkin, & Sagi, 2004)), as well as impaired contour detection (Hess, McIlhagga, & Field, 1997; Kovacs, Polat, Pennefather, Chandna, & Norcia, 2000) possibly due to the lack of collinear facilitation (Bonneh, Sagi, & Polat, 2004; Ellemberg, Hess, & Arsenault, 2002; Polat, 2008; Polat et al., 2004).

While monocular amblyopia might affect mainly monocular processing (e.g. primary visual cortex (V1)), with visual processing receiving already-integrated binocular information relying on normal input through the fellow (sound) eye, binocular amblyopia, due to binocular congenital cataract, affects binocular processing at levels higher than V1 (Ellemberg, Lewis, et al., 2002; Lewis et al., 2002). Nevertheless, even monocular amblyopia affects areas beyond V1 (Hess, Thompson, Gole, & Mullen, 2010; Ho et al., 2006; Sharma, Levi, & Klein, 2000). Thus, visual deprivation during the critical period affects visual processing at brain areas higher than V1, with binocular deprivation having a greater effect on visual processing than monocular deprivation (Ellemberg, Lewis, et al., 2002).

An unusual case of abnormal visual development of a young male (LG) was recently described including neuroimaging examinations (Ariel & Sadeh, 1996; Gilaie-Dotan, Bentin, Harel, Rees, & Saygin, 2011; Gilaie-Dotan et al., 2009). LG has developmental visual object and face agnosia resembling the “associative” type (Biran & Coslett, 2003), but without other neurological disorders and no apparent cortical structural abnormality. He completed high school with high scores, and functions normally in all other aspects. fMRI and ERP examinations revealed that LG has significant ventral stream processing abnormalities (Gilaie-Dotan et al., 2009). His intermediate visual areas (V2 and V3) are abnormally deactivated in response to visual stimulation, and his higher order category selective regions do not exhibit the expected

Visual training and perceptual changes

object and face sensitivity. In contrast, his motion-sensitive area, MT+/V5, responds in a typical manner to visual motion, consistent with the finding that normal sensitivity to motion is typical in developmental prosopagnosia (Le Grand et al., 2006).

At the onset of the current study LG, aged 20, had a binocular reduction in visual acuity (VA), which did not result from a known optical deficiency and could not be corrected by spectacles. His visual acuity at that time was 0.5-0.6 LogMAR in each eye (visual acuity of 0.6 LogMAR (i.e. “20/80”) is 4 times worse than the standard adult vision of 0 LogMAR (“20/20”); LG’s right-left eye Snellen equivalents: 6/19-2/24 m; 20/63/-20/80 ft) which could not be attributed to optical refractive error. Moreover, a significant part of the acuity deficit was due to visual crowding (~0.3 log units, twice as worse as standard adult vision), as measured with crowded and uncrowded displays of tumbling E patterns (Bonneh et al., 2004). Two tests suggested abnormal early and mid-level integration mechanisms. First, in a lateral masking experiment (Polat & Sagi, 1993) LG exhibited no collinear facilitation, indicating impairment in local integration mechanisms. Second, in a contour-in-noise detection card test, that tests mid-level contour integration mechanisms (Chandna, Pennefather, Kovacs, & Norcia, 2001; Kovacs, Kozma, Feher, & Benedek, 1999), his performance was significantly worse than normal adult vision, similar to that of 5-6 year olds (with a threshold spacing ratio of ~1) (Kovacs et al., 1999). Contour integration is a fundamental mid-level stage in visual processing that involves cooperative interactions between local processing elements, with contributions to higher level tasks such as perceptual grouping, image segmentation, and object recognition (Kovacs et al., 1999; Kovacs et al., 2000).

In the current study we sought to reduce LG’s severe visual impairments including mid-level visual functions, and possibly also his object and face agnosia by

Visual training and perceptual changes

means of visual training involving low-level visual mechanisms. We hypothesized that LG's mid-level and higher-level impairments stem from abnormal binocular input during development (with currently an unknown cause), a condition that resembles binocular amblyopia. Therefore, his condition prevented the typical developmental cascade, resulting in immature integration mechanisms and abnormal development of many visual functions.

Perceptual learning can improve visual functions in amblyopia (Levi & Li, 2009a, 2009b; Levi & Polat, 1996; R. W. Li, Ngo, Nguyen, & Levi, 2011; Polat, 2009a, 2009b; Polat et al., 2004; Polat, Ma-Naim, & Spierer, 2009; Polat & Sagi, 1994b), and videogame playing can also improve visual function in amblyopia (Jeon, Maurer, & Lewis, 2012; R. W. Li, Klein, & Levi, 2008; R. W. Li et al., 2011) and in normal vision (R. Li, Polat, Makous, & Bavelier, 2009; R. Li, Polat, Scalzo, & Bavelier, 2010). Therefore, we further hypothesized that a corrective treatment for LG, even at the monocular level, would affect his binocular functions and might facilitate maturation of mid-level and perhaps even higher-level perceptual functions. To test this theory, we decided to train LG with the lateral masking paradigm (Polat et al., 2004). The lateral-masking paradigm is an established method of effective vision correction for various conditions such as amblyopia (Elleberg, Hess, et al., 2002; Levi et al., 2002; Polat et al., 2004) and presbyopia (Polat et al., 2012) and has been extensively studied in psychophysical and physiological studies (e.g., (Kapadia, Ito, Gilbert, & Westheimer, 1995; Kasamatsu, Miller, Zhu, Chang, & Ishida, 2010; Kasamatsu, Polat, Pettet, & Norcia, 2001; Lev & Polat, 2011; Mizobe, Polat, Kasamatsu, & Norcia, 1996; Solomon & Morgan, 2000; Sterkin, Yehezkel, Bonneh, Norcia, & Polat, 2007; Woods, Nugent, & Peli, 2002). Therefore, we employed lateral-masking treatment of amblyopia (Polat et al., 2004) especially tailored for LG,

Visual training and perceptual changes

by training him twice a week for a few months, monocularly and binocularly. The results show a marked improvement in visual acuity, crowding, and mid-level functions including contour integration, with possible subtle improvement in object recognition and part integration but not in face perception.

METHODS

Case description

LG was 20 years old at the beginning of this study (before starting the training). He is a right-handed male and has developmental visual agnosia and prosopagnosia. LG's perceptual impairments were already evident in early childhood (Ariel & Sadeh, 1996). A recent study examined his low-level visual functions and high-level visual performance, including reading, object, and face recognition (Gilaie-Dotan et al., 2009). A brief description of his low-level vision, as described in that study, is described within the Results section (pre-training performance). That study also reported fMRI and ERP neuroimaging investigations of LG's visual system, and a high-resolution structural MRI scan of his brain, which was examined by a neuro-radiologist who was blind to LG's condition and found no evidence of structural abnormality. LG has always functioned as a fully independent person and successfully finished high school. He is now a university student, and works, reads, and travels on his own. The current study started about a year after that study took place (Gilaie-Dotan et al., 2009).

Several visual functions including basic, mid- and high-level vision of LG's were tested before the training began ("pre-training"), during, and after training ("post-

Visual training and perceptual changes

training”). Additionally, we administered to LG an additional set of mid-level vision tests only post-training to assess more thoroughly his mid-level visual functioning.

Low-level vision

Visual acuity (VA) was measured according to the best visual correction at a distance of 3 m (distance VA) or 40 cm (near VA), using a modified Bailey–Lovie (LogMAR) chart (ETDRS, see Figure 1A). We report LogMAR units as well as their Snellen equivalents.

The *crowding effect* was measured in an identical way to that described previously (Bonneh et al., 2004). In short, VA was measured by a “Tumbling-E patterns test”: a LogMAR chart equivalent, monitor-based paradigm (see Fig. 2A). The stimuli correspond to a subset of the LogMAR chart; pattern size corresponding to 6/6 (20/20) on a Snellen chart is equivalent to 0.0 on a LogMAR chart. Three rows of five black E-patterns each, on a white background, each pattern facing one of four directions (crowded). The task was to determine the direction of the central E. Auditory feedback was provided with different tones for correct and incorrect responses. A staircase procedure with pattern size and spacing modified by 0.1 log units in each step was used to determine the size for 50% accuracy (chance is 25%). The performance when the central E, presented alone (single), was measured separately. The crowding effect was then calculated by *subtracting the crowded from the single* pattern results (difference on a log scale), in other words, normalizing the crowded condition by the acuity for a single pattern.

Lateral interactions were measured in the current study following procedures described earlier (Polat et al., 2012; Sterkin, Yehezkel, & Polat, 2011). In short, stimuli consisted of Gaussian-modulated grating signals (termed “Gabor patch”) with

Visual training and perceptual changes

spatial frequencies of 3, 6, or 9 cycles per degree modulated from a background luminance of 40 cd.m^{-2} (Fig. 3A), with the standard deviation of the Gabor patch equal to the wavelength ($\sigma = \lambda$). The contrast detection threshold was measured by a two-interval forced choice procedure, in which the target, which was presented for a duration of 60 to 120 ms, depending on the contrast threshold, appeared randomly in one of two intervals separated by 800 ms. A visible white fixation circle indicated the location of the target before each trial began. Subjects started each trial by pressing a button and auditory feedback was given following wrong answers only. A 3:1 staircase method was used to determine the contrast threshold level of the target at 79% correct performance (Levitt, 1971) with steps of 0.1 log units; a test block was terminated after eight reversals of the staircase procedure, and the geometric mean of the last six reversal values was used to estimate the contrast threshold. Lateral masking was measured similarly, with additional flankers at different distances (2, 3, 4, and 6 wave-lengths from the target), which appeared in both of the two interval forced choice displays. Backward masking was measured by introducing a varied temporal displacement between the onsets of the target and the flankers (Polat et al., 2012; Sterkin et al., 2011).

Stereo acuity was measured using a Randot Stereo test, which tests the ability to identify geometric forms from a random dot background using polarized glasses. Charts with a stimulus disparity of 20-600 seconds of arc were used at a distance of 40 cm from the participant's eyes to determine the minimal disparity needed to extract depth information.

Visual training and perceptual changes

Mid-level vision

Contour detection threshold was measured using charts consisting of a smoothly aligned, closed path of Gabor patches embedded in a randomly oriented array of Gabor patches of identical spatial frequency and contrast (Fig. 4A, (Kovacs et al., 2000)). The angular difference between adjacent contour segments was assigned within a range of 0 to 30°. Each card was presented and correct or incorrect answers were recorded. The threshold was defined as the average spacing between background elements relative to the average spacing between the contour elements that allowed successful contour detection. This paradigm was identical to that described earlier (Kovacs et al., 2000).

Motion coherence threshold was measured in the current study following procedures described earlier (Gilaie-Dotan, Kanai, Bahrami, Rees, & Saygin, 2013; Gilaie-Dotan et al., In press). In short, in a two interval forced choice experiment, where each trial consisted of two intervals, each interval displayed a disc of moving dots, participants had to detect the disc that consisted of coherently moving dots (target) while the other disc (distracter) consisted of white noise only. The amount of coherent motion in the target disc was adjusted in an adaptive manner in order to estimate individual coherence thresholds that allow performance accuracy of 75%.

Perceptual organization mechanisms were measured with the Leuven Perceptual Organization Screening Test (L-POST, see <http://gestaltrevision.be/tests>, (Crawford, Garthwaite, & Slick, 2009; Torfs, Vancleef, Lafosse, Wagemans, & de-Wit)) which is a new diagnostic tool for detecting perceptual mid level impairments. LG's performance was compared to norms of more than 1500 individuals. Percentile scores

Visual training and perceptual changes

of the test are based on established neuropsychological procedures (Crawford et al., 2009).

High-level vision: Object recognition and part intergation

LG's object recognition and part intergation were measured using different tests:

"The Birmingham Object Recognition Battery Test no. 6" (Riddoch & Humphreys, 1993) measures the ability to identify letters, geometric forms, and line drawings, which are shown either separately, near each other or overlapping. One important measure is the ratio between the reaction times (RTs) for naming pairs or triplets of objects when they are not overlapping versus overlapping. Normal object recognition is determined by a ratio of or approaching 1:1.

"The Hooper Visual Organization Test" (Hooper, 1983) measures an individual's ability in spatially organizing visual stimulus parts. This task is considered particularly sensitive to neurological impairments such as visual agnosia. The test consists of 30 line drawings, each showing a common object or animal - such as a ball or a fish - that has been cut into several pieces. The pieces are scattered on the page like parts of a puzzle. The participant's task is to say what the object would be if the pieces were put back together correctly.

The Visual Object and Space Perception Battery (VOSP) is a set of tests that examine object and space perception relative to norms of brain damaged patients, including object perception screening, incomplete letters, silhouettes, object decision, and progressive silhouettes subtests, as well as a few space perception subtests, from which LG was only tested on the cube analysis.

Visual training and perceptual changes

The completion experiment measures individual ability to name line drawings of animals either from intact (“whole” condition) or from partly hidden displays when a grid of vertical stripes is superimposed on them (“grid” condition, see Fig. 6C). The experiment is also described elsewhere (Gilaie-Dotan et al., 2009; Lerner, Hendler, Ben-Bashat, Harel, & Malach, 2001). Performance was measured as naming accuracy either at the basic (e.g., “cat”) or at the subordinate level (e.g., “lion”, “cheetah”). Each stimulus was presented for 500 ms, followed by a 1500 ms (controls) or 3000 ms (LG) blank screen during which the overt naming of the image has been recorded. LG was tested pre-training as described previously (Gilaie-Dotan et al., 2009). Post-training, LG was tested more than 4 years after training ended. In that testing session, he was tested with the original line drawings, but also with new and unfamiliar line drawings of animals of similar difficulty, to account for possible familiarity influences on his performance.

High-level vision: Face recognition

LG’s face recognition was assessed by the *“The Benton Face Recognition Test”* (BFRT; (Benton, Sivan, Hamsher, Varney, & Spreen, 1994)), at the same time as when we assessed his object recognition skills (more than two years post training). In each trial item, LG was presented with a target face placed above six test faces, and was asked to indicate which of the six images below matched the target face. There are no time limits for any item. Male and female face images were used in this test; they were cropped so that no clothing and little hair were visible. In the first six trials, only one of the six test faces matched the target face, and the target image and the test image were identical. In the next 16 trials, however, three of the test faces matched the target face, and the poses of the test images or their lighting conditions were different

Visual training and perceptual changes

from those of the target image. The task was to detect all the test faces that are the same as the target's, a point for each correct detection.

The training procedure

The perceptual learning procedure that we applied for training LG's vision used principles similar to previous training studies (Polat et al., 2004; Polat & Sagi, 1994b; Polat et al., 2012). These studies indicate that the training resulted in improved spatial and temporal neural processing. In each session, LG trained on tasks that included (a) contrast detection of a Gabor target, (b) contrast detection of a target arranged between two other Gabor flankers arranged in collinear configuration (also termed “lateral masking”), (c) lateral masking followed by delayed identical flankers without a target (termed backward masking), as described previously (Polat et al., 2012; Sterkin et al., 2011). The training covered a range of spatial frequencies (3-12 cycles per degree) and orientations (0, 45, 90, and 135 degree angles); the inter-stimulus-interval between the target and the backward masking stimulus was decreased (from 180ms to 60ms) according to the progress of the training. LG trained from a distance of 150 cm either monocularly (either right or left eye in separate conditions), or binocularly (both eyes open). Auditory feedback was provided with different tones for correct and incorrect responses. The training, which was performed in a darkened room, took about 30 min per session, and took place at least 3 times a week for a continuous period of approximately 9 months. Following this period, LG stopped training for a period of 4 years. After 4 years off training (i.e. approx. 57 months from training onset), LG decided he wanted to return to training for a few sessions. So the measurements from the ‘60 months from training onset’ time point (in Figure 1, 2, 3D, 4, and 5) were

Visual training and perceptual changes

taken during that period, after LG has returned to training for a few sessions following the 4 years off training.

RESULTS

Low-level vision

Visual acuity

Before training, LG's distance visual acuity (VA) was abnormal: 0.66 LogMAR in his right eye (6/30- m; 20/200- ft) and 0.5 LogMAR in his left eye (6/18 m; 20/63 ft) (see Fig. 1B, left panel). This level of vision resembled a condition of binocular amblyopia (Ellemberg, Lewis, et al., 2002; Lewis et al., 2002). After 9 months of training, LG's distance VA improved by more than a factor of 2 for the right eye (from 0.66 to 0.3 LogMAR units, $\approx 109\%$; from 6/30- m; 20/200- ft. to 6/12 m; 20/40 ft), and by 66% for the left eye (from 0.5 to 0.28 LogMAR units; from 6/18 m; 20/63 ft to 6/12+ m; 20/40+ ft), as presented in Fig. 1B. The improvement in LG's right eye was higher (109%) than the average reported improvement (about 80%) that follows a similar perceptual learning technique for amblyopia and presbyopia (Polat, 2008, 2009a; Polat et al., 2004; Polat et al., 2012).

Before training, LG's subjective refraction showed no improvement on the visual chart for any myopic prescription, and thus no glasses were recommended at that stage. After training, however, his objective refraction (retinoscopy) showed a small myopic optical error, and therefore the best optical correction (-0.5 diopter in each eye) that met the objective prescription was prescribed. Consequently, LG was able to discriminate better between the letters on the distance visual chart using the small

Visual training and perceptual changes

myopic correction than without the optical correction (the post test of distance VA performed without the new optical correction). His level of binocular distance VA after the training was below 0.3 LogMAR (6/12 m; 20/40 ft) within the range that legally qualifies him for a driving's license.

LG's near VA improved from 0.48 to 0.34 (38%, 6/19+ to 6/12- m; 20/63+ to 20/40-ft) and from 0.4 to 0.3 LogMAR units (26%; 6/15 to 6/12 m or 20/50 to 20/40 ft) for the right and left eyes, respectively (see Figure 1C, right panel). This VA enabled him to read a letter size of 6.3 points, slightly larger than the common newspaper letter size. LG was tested 24 months after his training ended (33 months after training onset) and his distance VA was found to be stable (right eye: 0.32, left eye: 0.34, in LogMAR units, see Fig. 1B). Furthermore, 60 months after training onset (51 months from the end of training), LG's near and distance VA have even improved further (see Fig. 1B and C).

Visual Crowding

The normal range of the crowding effect in control adult subjects tested with this technique is around zero (0 ± 0.05 LogMAR; mean \pm SEM, (Bonneh et al., 2004; Bonneh, Sagi, & Polat, 2007; Doron & Polat, 2011)). Before training, LG's crowding effects were much higher (right eye, 0.23; left eye 0.17) and were reminiscent of the crowding effects pronounced in strabismic amblyopia (Bonneh et al., 2004, 2007; Jeon, Hamid, Maurer, & Lewis, 2010; Levi, 2008; Pelli & Tillman, 2008), and in young children up to the age of 7 (Doron & Polat, 2011). After training, however, LG's crowding effects were reduced, reaching normal adult level, as shown in Figure 2B. LG's crowding improvements were maintained close to adult normal range even 60 months after training onset. For comparison, crowding effects in 10 normally

Visual training and perceptual changes

sighted adults were not significantly different on a test-retest basis ($t(8) = 0.11$, $p > 0.9$, paired t-test).

Lateral interactions

Prior to training, LG's lateral interactions (Figure 3A) were measured for a spatial frequency of 3 cycles per degree. In normal vision, facilitation is found for target-flankers separation of 2-6 wavelengths (λ), being maximal at 3λ and decreasing with increased target-flankers separations (Polat & Sagi, 1993, 1994a, 1994b), as shown in Fig. 3B for controls. The function of lateral interactions in LG before training was different with very minimal facilitation in his left eye and dominated by suppressive effects for his right eye (Fig. 3B). These suppressive effects in his right eye resembled strabismic amblyopia, and his left eye, with less severe suppression, resembled anisometric amblyopia (Bonneh et al., 2004, 2007; Elleberg, Hess, et al., 2002; Levi et al., 2002; Polat, 2008; Polat, Bonneh, Ma-Naim, Belkin, & Sagi, 2005; Polat et al., 2004) and supports our hypothesis that LG's vision before training resembled effects found in amblyopia. After training (Fig. 3C), suppression-wise, LG's suppression was reduced remarkably by about 0.15-0.2 log units in his right eye (41-58%), while facilitation-wise, both eyes reached facilitation levels that resembled amblyopes' facilitation post-training (see Figure 3C, (Polat et al., 2004)). The effect of improvement was even more impressive because at the beginning of the training LG was able to practice only on Gabor patches of 3 cycles per degree (the highest spatial frequency he could detect), but after 9 months of training he was able to detect and practice on Gabor patches of 9 cycles per degree. Furthermore, the changes in LG's facilitation endured, so that even more than 4 years post-training, both of his eyes still showed facilitation effects for target-flankers separation of 2- 3λ (Figure 3D).

Visual training and perceptual changes

This pattern of improvement with training is similar to that found in amblyopia following training (Fig. 3C), leading to improvements in other visual functions such as VA, contrast sensitivity function, and binocular vision (Polat et al., 2004).

Stereopsis

LG's stereo acuity, measured with the RanDot test (RanDot, Stereo Optical Co., Inc.), improved from a threshold of 30 arcsec before training (within the normal range of adults) to 20 arcsec 6 months after training onset, which is the finest stereo sensitivity that can be measured with this test, with less than half of the adult population reaching this sensitivity level (Birch et al., 2008). This improvement does not seem to stem from test-retest effects, as the RanDot test shows high test-retest reliability (Birch et al., 2008) and our control data also support that. From 10 age-matched controls that were tested twice with RanDot, as LG was, 4 had stereo acuity worse than 20 arcsec (i.e. 25 arcsec), and only one of these improved in the retest session, while the other 3 remained at 25 arcsec sensitivity.

Mid-level vision

Contour integration

LG's contour integration threshold ratio (background element density to target spacing ratio, see Fig. 4A) before training was ~ 1 , impaired relative to normal adult vision (see Figure 4B), and corresponding to that of 5-6 year olds when using similar technique (see Fig. 4B). After training, however, LG's contour integration threshold reached 0.65 (see Fig. 4B), which is within the range of normal adults, typically reaching maturity at the age of 9 (Doron & Polat, 2011; Kovacs et al., 2000). This threshold was maintained for more than four years after the training ended (Fig. 4B).

Motion coherence

Motion coherence threshold, which is considered a mid-level vision process (Le Grand et al., 2006), was assessed in LG only three years post-training. His coherence threshold reached 18.39%, not significantly different from the threshold of 32 age-matched controls with normal or corrected to normal vision aged 24.3 ± 5 (S.D.) years (controls' mean coherence threshold $14.6 \% \pm 4.1\%$ (S.D) (Gilaie-Dotan et al., 2013), LG vs. controls: $t(31) = 0.909$, $p > 0.37$ (Crawford & Howell, 1998)).

Perceptual organization

To assess a wide range of mid-level visual abilities following training in LG and compare his mid-level visual performance to normative data, we additionally assessed LG's mid-level vision using the Leuven Perceptual Organization Screening Test (L-POST, see Methods) which is based on normative data of more than 1500 individuals. This test assesses functions such as fine shape discrimination, contour integration (similar to our contour integration assessment), global motion detection (similar to our motion coherence assessment), recognition of missing parts, embedded figure detection, figure ground segmentation from static cues, kinetic object segmentation, and more. LG's performance was within the normal range for all the subtests, as can be seen in Figure 5, and this is consistent with results we obtained while assessing LG on some of these visual functions independently (e.g. motion coherence and contour integration in the current study, biological motion (Gilaie-Dotan et al., 2011), and figure-ground segmentation based on dynamic local cues (Brooks, Gilaie-Dotan, Rees, Bentin, & Driver, 2012)).

Visual training and perceptual changes

High-level vision

Object recognition and part integration

LG's performance on the overlapping figures test of the Birmingham Object Recognition Battery was better with simple geometrical shapes than with letters or more complex line drawings, both pre- and post-training. His difficulty with letters and complex line drawings was reflected both in his errors (see Figure 6A) and in his RT ratios. Pre-training, LG made no mistakes in the 180 geometrical shapes, but he made 16 errors in the overlapping pairs and triplets of letters (out of 180 letters all together), and 4 mistakes in the paired-overlapping line drawings (out of 36 pairs; 72 drawings all together). To minimize familiarity effects, we tested LG four years post-training on these tests (more than 4.5 years between testing sessions). Post-training, LG made 6 errors in the paired and triplet-overlapping letters section (mostly between similar letters, e.g., I and J); 3 mistakes in the paired-overlapping line drawings, and one mistake in the geometrical shapes. There was also an improvement in the average RTs under most conditions, as evident by shorter post-training reaction times. Another aspect relevant to the norms of the overlapping figures test from the Birmingham Object Recognition Battery is the RT ratio (between RTs of isolated stimuli and RTs of overlapping stimuli). Pre-training, LG's RT ratios were as follows: Paired letters 1:2.8, Tripled letters: 1:2.1; Paired line drawings: 1:2.7; Paired geometrical shapes: 1:1.2, Tripled geometrical shapes: 1:1.6, whereas post-training, LG's ratios were as follows: Paired letters 1:2.1, Tripled letters: 1:2.3; Paired line drawings: 1:2.3; Paired geometrical shapes: 1:1.2, Tripled geometrical shapes: 1:1.5. For the simple geometric shapes and the complex line drawings the pre-training and post-training error rates were mostly similar (see Fig. 6A). However, even though LG's performance was still

Visual training and perceptual changes

below the norm of the RT ratios (i.e. close to a ratio of 1:1), an improvement was seen in the number of errors in the letter section (see Figure 5A), in the absolute RTs under most of the conditions, and some improvement in the RT ratios was evident, especially for paired letters.

LG's pre-training score on the Hooper Visual Organization Test was 12.5/30, defined as a "very high probability of impairment", whereas his post-training score was 20/30, defined as a "moderate probability of impairment" (see Figure 6B).

LG was tested on the Visual Object and Space Perception Battery more than 4 years post training. LG passed all the object perception subtests (when compared to norms of aged < 50 y.o.) except the object decision test (he scored 13 points and the pass cutoff is at 15), placing him above the 5% cutoff scores of these tests. He also passed the Cube analysis space perception subtest.

LG's pre-training and post-training performance in the completion experiment is shown in Figure 6C. His animal recognition ability was impaired even for images presented in the intact view condition ("whole" Figure 6C), before and after training, indicating on his difficulty to recognize animals from such feeble stimuli. No apparent improvement was evident post-training for these intact "whole" images. In the "grid" condition however, when LG had to overcome the occluding bars to recognize the animals, while before training his recognition was at 17%, post-training he successfully recognized 25% of the animals from the previously viewed set of pictures, and 50% from the newer set of line drawings that were unfamiliar to LG. We do not anticipate that the newer line drawings were easier to recognize since in the intact condition LG did not perform better at recognizing them.

Visual training and perceptual changes

Thus, although LG is still considered impaired in object recognition, the tests we administered indicate that his object recognition abilities might have moderately improved following training.

Face recognition

In the Benton Face Recognition Test LG scored 33/54 pre-training, and 32/54 post-training, scores categorized as "severe impairment" in face recognition. Thus, there was no indication of improvement in his face recognition abilities.

DISCUSSION

In this study we applied a dedicated visual corrective training program to a 20-year old man following abnormal visual developmental trajectory. Before training, LG's basic visual functions such as visual acuity, crowding effects, and contour integration abilities were underdeveloped relative to normal adult vision, and similar to those of 5-6 year olds or younger children, resembling amblyopic vision (Gilaie-Dotan et al., 2009). LG also suffered from higher level visual perceptual impairments in face and object recognition (prosopagnosia and object agnosia). We monitored LG's visual improvements during and after training, as well as 4 years post training. Importantly, the training significantly improved many of LG's basic visual functions (including visual acuity, contour integration, and crowding effects), approaching close to age-level performance, and this improvement was found to be stable and sustained even 4 years post training. A mild improvement was also observed in LG's part integration and object recognition, although objective and subjective measurements indicate that

Visual training and perceptual changes

LG still has object and face recognition impairments (but see (Duchaine & Nakayama, 2006)).

When LG was 20 years old, upon commencing the training, his visual system's estimated biological age was approximated to be around 5-6 years old (Gilaie-Dotan et al., 2009) or younger (c.f. visual acuity performance). This estimate was based on the observation that in all the parameters that were tested (visual acuity, crowding, lateral interactions, and contour integration), LG's visual performance before training in either eye was similar to that of an amblyopic eye (Bonneh et al., 2004, 2007; Levi et al., 2002; Polat et al., 2004; Wong, Levi, & McGraw, 2005) and corresponded to the developmental level of children (Doron & Polat, 2011). Additional factors supported this estimate. First, before the training, LG's high degree of suppression in measures of lateral interactions, which was paralleled by an increased effect of crowding and a deficit in contour integration, was underdeveloped relative to normal adult vision and similar to that found in 5-6 year olds (Doron et al., 2007). Second, LG's perceptive field size (a psychophysical measurement of local integration fields) before the training was similar to the size of the perceptive field in the periphery, resembling effects observed in children when their fovea is not fully developed (Provis, Diaz, & Dreher, 1998), as well as in amblyopia (Lev & Polat, 2011; Levi, Klein, & Aitsebaomo, 1985). It has recently been shown that the human perceptive field in the fovea can be estimated from the collinear interaction function, at the cross-over point between suppression and facilitation (Lev & Polat, 2011, 2012). Based on that, our estimate of the size of LG's perceptive field in the fovea before training was 4λ for the right eye and 3λ for the left eye, an estimate that was larger than normal by 100% and 50% for the right and left eyes respectively, and resembled

Visual training and perceptual changes

the size of the perceptive field in the periphery. Taken together, we suggest that LG's vision prior to training was characterized by immature and undeveloped fovea relative to adult normal vision, similar to adult peripheral vision and in some aspects similar to vision of children about 5-6 years old.

Our results indicate that non-invasive intervention in the form of corrective visual training can be very effective in partially overcoming abnormal development of basic visual functions, even when such an intervention is applied years after the critical period. However, how influential can such a recovery of basic visual functions be to mid-level functions as contour integration and higher visual perceptual functions such as face and object recognition? Since normal development of perceptual functions probably relies on normal visual inputs, which were not present in LG, his perceptual functions did not develop normally. Could an improvement of perceptual functions take place after the recovery of basic visual functions due to corrected inputs that enter the visual system? Some support is evident from studies that tested individuals with congenital cataract (Maurer, Lewis, & Mondloch, 2005; Maurer, Mondloch, & Lewis, 2007; Ostrovsky, Andalman, & Sinha, 2006). These studies suggest that visual functions, and consequently, perceptual functions were impaired in adults after removing the obstacles that prevented normal visual input during the normal developmental period. However, some perceptual functions recovered a few years after the brain received visual input. With respect to LG, we believe he suffered from unknown and unusual binocular deprivation of normal visual input during his childhood. This obstacle was a dominant cause that arrested the development of normal visual functions and hence some of his mid- and high-level perceptual visual functions. Less than a year after training onset significant improvements in mid-level

Visual training and perceptual changes

functions as contour integration were already evident, and these were sustained for a long period. Additional mid-level functions tested years post-training appear normal. A possible mild improvement in LG's high-level shape recognition might be observed following training, when examining his possibly improved Hooper and Birmingham Object Recognition Battery overlapping figures test scores for letters, and possibly improvements in overcoming occlusion, yet the significance of these changes cannot be determined. LG also reported an improvement in his day-to-day life activities and felt more confident, partly due to his spectacles. However, LG still has significant impairments in object recognition and face recognition. This is evident by his significantly long reaction times in identifying objects, and his impaired face recognition. Furthermore, a recent study that was done 2-years post training found that some aspects of LG's ability to perform figure-ground segmentation, which is assumed to support object recognition processes, are still impaired. For instance, although he can clearly perform figure-ground organization based on local motion cues, he does not appear to use a contextual/non-local motion information to determine figure-ground organization (Brooks et al., 2012), something that control participants use very reliably (Brooks & Driver, 2010). LG also indicated that despite feeling more confident with his vision, he still does not feel a significant improvement in his recognition skills. Thus, further improvement in his high-level perceptual functions of object and face recognition in years to come, remains to be seen.

Recent studies by Grill-Spector and colleagues that investigated the developmental trajectory of face sensitivity with respect to face perception in the visual cortex (Golarai et al., 2007; Golarai, Liberman, Yoon, & Grill-Spector, 2010; Grill-Spector, Golarai, & Gabrieli, 2008) found that in normally developed individuals it takes more

Visual training and perceptual changes

than a decade from the age of 7 for face-sensitivity in visual cortex to mature (Golarai et al., 2007), and that face-selective cortex in adults is significantly different than that of adolescents (Golarai et al., 2007). If indeed LG's visual system was underdeveloped relative to adult normal vision before training, some functions at the biological age of 5-6 years old, then a decade could be a reasonable time window to examine significant improvements in his face perception. However, since we cannot be sure that from this point in time LG would follow a typical maturation process, it is hard to predict whether such a significant change will indeed take place and what its effective size would then be. fMRI examinations of LG's visual system (Gilaie-Dotan et al., 2009) suggest that LG's visual stream has not successively developed and that his intermediate visual areas may remain not fully developed. Intermediate visual areas, that are associated with fine resolution processing (Amedi, Malach, Hendler, Peled, & Zohary, 2001; Grill-Spector et al., 1999; Lerner et al., 2001; Lerner, Hendler, & Malach, 2002) are not normally developed in amblyopia (Lerner et al., 2006; Lerner et al., 2003). Thus, it is possible that the development of the visual stream might not be hierarchical and typically "leaves a gap" such that higher level perceptual areas develop before intermediate areas. Future examination of LG's high-level visual perceptual functions might assist in resolving this issue.

In summary, we found that before training, some of LG's visual functions were underdeveloped relative to adult typical vision and equivalent to those of children aged 5-6, due to a probable developmental cause that arrested the normal development of his visual functions in both eyes. This effect resulted in deficient functioning of those brain areas that process the perceptual functions. Here, we were able to train LG to achieve useful visual functions that have already resulted in mid-

Visual training and perceptual changes

level vision improvements and possible mild progress in his higher perceptual abilities. We expect that further improvement in his visual perceptual functions might follow, similar to our experience with trained amblyopes (Polat et al., 2004).

ACKNOWLEDGEMENTS

This research was supported by grants from the National Institute for Psychobiology in Israel, funded by the Charles E. Smith Family and the Israel Science Foundation (ISF, grant number 188/10). We thank LG and his family for their ongoing wholehearted participation in this study. We thank Ravid Doron for proving us with control data for some of the experiments, Yulia Lerner and Rafael Malach for providing the pretraining animal occlusion experimental paradigm and control data, and Bahador Bahrami for providing the motion coherence paradigm.

REFERENCES

- Amedi, A., Malach, R., Hendler, T., Peled, S., & Zohary, E. (2001). Visuo-haptic object-related activation in the ventral visual pathway. *Nat Neurosci*, *4*(3), 324-330. doi: 10.1038/85201
- Ariel, R., & Sadeh, M. (1996). Congenital visual agnosia and prosopagnosia in a child: a case report. *Cortex*, *32*(2), 221-240.
- Atkinson, J. (2000). *The developing visual brain*. New York: Oxford University Press.
- Benton, A. L. , Sivan, A. B. , Hamsher, K., Varney, N. R. , & Spreen, O. . (1994). *Contributions to Neuropsychological Assessment*. New York: Oxford University Press.
- Biran, I., & Coslett, H. B. (2003). Visual agnosia. *Curr Neurol Neurosci Rep*, *3*(6), 508-512.
- Birch, E., Williams, C., Drover, J., Fu, V., Cheng, C., Northstone, K., . . . Adams, R. (2008). Randot Preschool Stereoacuity Test: normative data and validity. *J AAPOS*, *12*(1), 23-26. doi: 10.1016/j.jaapos.2007.06.003
- Bonneh, YS., Sagi, D., & Polat, U. (2004). Local and non-local deficits in amblyopia: acuity and spatial interactions. *Vision Res*, *44*(27), 3099-3110.

- Bonneh, Y.S., Sagi, D., & Polat, U. (2007). Spatial and temporal crowding in amblyopia. *Vision Res*, 47(14), 1950-1962. doi: 10.1016/j.visres.2007.02.015
- Brooks, J. L., & Driver, J. (2010). Grouping puts figure-ground assignment in context by constraining propagation of edge assignment. *Atten Percept Psychophys*, 72(4), 1053-1069. doi: 10.3758/APP.72.4.1053
- Brooks, J. L., Gilaie-Dotan, S., Rees, G., Bentin, S., & Driver, J. (2012). Preserved local but disrupted contextual figure-ground influences in an individual with abnormal function of intermediate visual areas. *Neuropsychologia*, 50(7), 1393-1407. doi: 10.1016/j.neuropsychologia.2012.02.024
- Chandna, A., Pennefather, P. M., Kovacs, I., & Norcia, A. M. (2001). Contour integration deficits in anisometropic amblyopia. *Invest Ophthalmol Vis Sci*, 42(3), 875-878.
- Ciuffreda, K.J., Levi, D.M., & Selenow, A. (1991). *Amblyopia: Basic and Clinical Aspects*. Stoneham: Butterworth-Heinemann.
- Crawford, J. R., Garthwaite, P. H., & Slick, D. J. (2009). On percentile norms in neuropsychology: proposed reporting standards and methods for quantifying the uncertainty over the percentile ranks of test scores. *Clin Neuropsychol*, 23(7), 1173-1195. doi: 10.1080/13854040902795018
- Crawford, J. R., & Howell, D. C. (1998). Comparing an Individual's Test Score Against Norms Derived from Small Samples. *J Clin Exp Neuropsychol*, 12(4), 482-486. doi: <http://dx.doi.org/10.1076/clin.12.4.482.7241>
- Daw, N. W. (1998). Critical periods and amblyopia. *Arch Ophthalmol*, 116(4), 502-505.
- Doron, R., Meshulam, A., Mandel, Y., Rosner, M., Belkin, M., & Polat, U. (2007). Less is more: The perceptual advantage of being color blinded. *Neural Plasticity*, 1, 27.
- Doron, R., & Polat, U. (2011). A common basis for developing visual crowding, collinear facilitation and contour detection in young children. *J Molecular Neurosci*. doi: DOI: 10.1007/s12031-011-9682-4
- Duchaine, B., & Nakayama, K. (2006). The Cambridge Face Memory Test: results for neurologically intact individuals and an investigation of its validity using inverted face stimuli and prosopagnosic participants. *Neuropsychologia*, 44(4), 576-585. doi: 10.1016/j.neuropsychologia.2005.07.001
- Elleberg, D., Hess, R. F., & Arsenault, A. S. (2002). Lateral interactions in amblyopia. *Vision Res*, 42(21), 2471-2478.
- Elleberg, D., Lewis, T. L., Maurer, D., Brar, S., & Brent, H. P. (2002). Better perception of global motion after monocular than after binocular deprivation. *Vision Res*, 42(2), 169-179.
- Gilaie-Dotan, S., Bentin, S., Harel, M., Rees, G., & Saygin, A. P. (2011). Normal form from biological motion despite impaired ventral stream function. *Neuropsychologia*, 49(5), 1033-1043.
- Gilaie-Dotan, S., Kanai, R., Bahrami, B., Rees, G., & Saygin, A. P. (2013). Neuroanatomical correlates of biological motion detection. *Neuropsychologia*, 51(3), 457-463. doi: 10.1016/j.neuropsychologia.2012.11.027
- Gilaie-Dotan, S., Perry, A., Bonneh, Y., Malach, R., & Bentin, S. (2009). Seeing with profoundly deactivated mid-level visual areas: non-hierarchical functioning in the human visual cortex. *Cereb Cortex*, 19(7), 1687-1703.
- Gilaie-Dotan, S., Saygin, A. P., Lorenzi, L., Egan, R., Rees, G., & Behrmann, M. (In press). The role of ventral visual “what” stream in motion perception. *Brain*.

- Golarai, G., Ghahremani, D. G., Whitfield-Gabrieli, S., Reiss, A., Eberhardt, J. L., Gabrieli, J. D., & Grill-Spector, K. (2007). Differential development of high-level visual cortex correlates with category-specific recognition memory. *Nat Neurosci*, *10*(4), 512-522. doi: 10.1038/nn1865
- Golarai, G., Liberman, A., Yoon, J. M., & Grill-Spector, K. (2010). Differential development of the ventral visual cortex extends through adolescence. *Front Hum Neurosci*, *3*, 80. doi: 10.3389/neuro.09.080.2009
- Grill-Spector, K., Golarai, G., & Gabrieli, J. (2008). Developmental neuroimaging of the human ventral visual cortex. *Trends Cogn Sci*, *12*(4), 152-162. doi: 10.1016/j.tics.2008.01.009
- Grill-Spector, K., Kushnir, T., Edelman, S., Avidan, G., Itzchak, Y., & Malach, R. (1999). Differential processing of objects under various viewing conditions in the human lateral occipital complex. *Neuron*, *24*(1), 187-203.
- Hess, R. F., Field, D., & Watt, R. J. (1990). The puzzle of amblyopia. In C. Blakemore (Ed.), *Vision: Coding and Efficiency*. Cambridge: Cambridge University Press.
- Hess, R. F., McIlhagga, W., & Field, D. J. (1997). Contour integration in strabismic amblyopia: the sufficiency of an explanation based on positional uncertainty. *Vision Res*, *37*(22), 3145-3161.
- Hess, R. F., Thompson, B., Gole, G. A., & Mullen, K. T. (2010). The amblyopic deficit and its relationship to geniculo-cortical processing streams. *J Neurophysiol*, *104*(1), 475-483. doi: 10.1152/jn.01060.2009
- Ho, C. S., Paul, P. S., Asirvatham, A., Cavanagh, P., Cline, R., & Giaschi, D. E. (2006). Abnormal spatial selection and tracking in children with amblyopia. *Vision Res*, *46*(19), 3274-3283. doi: 10.1016/j.visres.2006.03.029
- Hooper, H.E. (1983). . *Hooper Visual Organisation Test (VOT)*. Los Angeles: Western Psychological Services.
- Horton, Jonathan C., & Hocking, Davina R. (1997). Timing of the Critical Period for Plasticity of Ocular Dominance Columns in Macaque Striate Cortex. *J Neurosci.*, *17*(10), 3684-3709.
- Hubel, D. H., & Wiesel, T. N. (1970). The period of susceptibility to the physiological effects of unilateral eye closure in kittens. *J Physiol*, *206*(2), 419-436.
- Jeon, S. T., Hamid, J., Maurer, D., & Lewis, T. L. (2010). Developmental changes during childhood in single-letter acuity and its crowding by surrounding contours. *J Exp Child Psychol*, *107*(4), 423-437. doi: 10.1016/j.jecp.2010.05.009
- Jeon, S. T., Maurer, D., & Lewis, T. L. (2012). The effect of video game training on the vision of adults with bilateral deprivation amblyopia. *Seeing Perceiving*, *25*(5), 493-520.
- Kapadia, M. K., Ito, M., Gilbert, C. D., & Westheimer, G. (1995). Improvement in visual sensitivity by changes in local context: parallel studies in human observers and in V1 of alert monkeys. *Neuron*, *15*(4), 843-856.
- Kasamatsu, T., Miller, R., Zhu, Z., Chang, M., & Ishida, Y. (2010). Collinear facilitation is independent of receptive-field expansion at low contrast. *Exp Brain Res*, *201*(3), 453-465. doi: 10.1007/s00221-009-2057-1
- Kasamatsu, T., Polat, U., Pettet, M. W., & Norcia, A. M. (2001). Colinear facilitation promotes reliability of single-cell responses in cat striate cortex. *Exp Brain Res*, *138*(2), 163-172.
- Kovacs, I., Kozma, P., Feher, A., & Benedek, G. (1999). Late maturation of visual spatial integration in humans. *Proc Natl Acad Sci U S A*, *96*(21), 12204-12209.

- Kovacs, I., Polat, U., Pennefather, P. M., Chandna, A., & Norcia, A. M. (2000). A new test of contour integration deficits in patients with a history of disrupted binocular experience during visual development. *Vision Res*, *40*(13), 1775-1783.
- Le Grand, R., Cooper, P. A., Mondloch, C. J., Lewis, T. L., Sagiv, N., de Gelder, B., & Maurer, D. (2006). What aspects of face processing are impaired in developmental prosopagnosia? *Brain Cogn*, *61*(2), 139-158. doi: 10.1016/j.bandc.2005.11.005
- Lerner, Y., Hendler, T., Ben-Bashat, D., Harel, M., & Malach, R. (2001). A hierarchical axis of object processing stages in the human visual cortex. *Cereb Cortex*, *11*(4), 287-297.
- Lerner, Y., Hendler, T., & Malach, R. (2002). Object-completion effects in the human lateral occipital complex. *Cereb Cortex*, *12*(2), 163-177.
- Lerner, Y., Hendler, T., Malach, R., Harel, M., Leiba, H., Stolovitch, C., & Pianka, P. (2006). Selective fovea-related deprived activation in retinotopic and high-order visual cortex of human amblyopes. *NeuroImage*, *33*(1), 169-179. doi: 10.1016/j.neuroimage.2006.06.026
- Lerner, Y., Pianka, P., Azmon, B., Leiba, H., Stolovitch, C., Loewenstein, A., . . . Malach, R. (2003). Area-specific amblyopic effects in human occipitotemporal object representations. *Neuron*, *40*(5), 1023-1029.
- Lev, M., & Polat, U. (2011). Collinear facilitation and suppression at the periphery. *Vision Res*, *51*(23-24), 2488-2498. doi: 10.1016/j.visres.2011.10.008
- Lev, M., & Polat, U. (2012). When masking is like crowding. *J Vis*, *12*(12). doi: 10.1167/11.11.1070
- Levi, D. M. (2008). Crowding--an essential bottleneck for object recognition: a mini-review. *Vision Res*, *48*(5), 635-654.
- Levi, D. M., Hariharan, S., & Klein, S. A. (2002). Suppressive and facilitatory spatial interactions in amblyopic vision. *Vision Res*, *42*(11), 1379-1394.
- Levi, D. M., Klein, S. A., & Aitsebaomo, A. P. (1985). Vernier acuity, crowding and cortical magnification. *Vision Res*, *25*(7), 963-977.
- Levi, D. M., & Li, R. W. (2009a). Improving the performance of the amblyopic visual system. *Philos Trans R Soc Lond B Biol Sci*, *364*(1515), 399-407.
- Levi, D. M., & Li, R. W. (2009b). Perceptual learning as a potential treatment for amblyopia: A mini-review. *Vision Res*.
- Levi, D. M., & Polat, U. (1996). Neural plasticity in adults with amblyopia. *Proc Natl Acad Sci U S A*, *93*(13), 6830-6834.
- Levi, D.M. (1991). Spatial vision in amblyopia. In D. M. Regan (Ed.), *Spatial Vision* (pp. 212-238). London: Macmillan.
- Levi, D.M., & Carkeet, A. (1993). Amblyopia: a consequence of abnormal visual development. In Kurt Simons (Ed.), *Early visual Development , Normal and Abnormal* (pp. 391-407). New York , Oxford: Oxford University Press.
- Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *J Acoust Soc Am*, *49*(2), Suppl 2:467+.
- Lewis, T. L., Ellemberg, D., Maurer, D., Wilkinson, F., Wilson, H. R., Dirks, M., & Brent, H. P. (2002). Sensitivity to global form in glass patterns after early visual deprivation in humans. *Vision Res*, *42*(8), 939-948.
- Li, R., Polat, U., Makous, W., & Bavelier, D. (2009). Enhancing the contrast sensitivity function through action video game training. *Nat Neurosci*, *12*(5), 549-551.

- Li, R., Polat, U., Scalzo, F., & Bavelier, D. (2010). Reducing backward masking through action game training. *J Vis*, *10*(14). doi: 10.1167/10.14.33
- Li, R. W., Klein, S. A., & Levi, D. M. (2008). Prolonged perceptual learning of positional acuity in adult amblyopia: perceptual template retuning dynamics. *J Neurosci*, *28*(52), 14223-14229. doi: 10.1523/JNEUROSCI.4271-08.2008
- Li, R. W., Ngo, C., Nguyen, J., & Levi, D. M. (2011). Video-game play induces plasticity in the visual system of adults with amblyopia. *PLoS Biol*, *9*(8), e1001135. doi: 10.1371/journal.pbio.1001135
- Maurer, D., Lewis, T. L., & Mondloch, C. J. (2005). Missing sights: consequences for visual cognitive development. *Trends Cogn Sci*, *9*(3), 144-151. doi: 10.1016/j.tics.2005.01.006
- Maurer, D., Mondloch, C. J., & Lewis, T. L. (2007). Effects of early visual deprivation on perceptual and cognitive development. *Prog Brain Res*, *164*, 87-104. doi: 10.1016/S0079-6123(07)64005-9
- Mizobe, K., Polat, U., Kasamatsu, T., & Norcia, A. M. (1996). Lateral masking reveals facilitation and suppression from the same single cells in cat area 17. *Investigative Ophthalmology & Visual Science*, *37*(3), S483.
- Ostrovsky, Y., Andalman, A., & Sinha, P. (2006). Vision following extended congenital blindness. *Psychol Sci*, *17*(12), 1009-1014. doi: 10.1111/j.1467-9280.2006.01827.x
- Pelli, D. G., & Tillman, K. A. (2008). The uncrowded window of object recognition. *Nat Neurosci*, *11*(10), 1129-1135.
- Polat, U. (2008). Restoration of underdeveloped cortical functions: evidence from treatment of adult amblyopia *Restorative Neurology and Neuroscience*, *26*, 1-12.
- Polat, U. (2009a). Making perceptual learning practical to improve visual functions. *Vision Res*, *49*(21), 2566-2573.
- Polat, U. (2009b). Perceptual learning induces neuroplasticity, enabling improvement of visual functions. *Expert Review of Ophthalmology*, *4*(6), 573-576. doi: doi:10.1586/eop.09.54
- Polat, U., Bonneh, Y., Ma-Naim, T., Belkin, M., & Sagi, D. (2005). Spatial interactions in amblyopia: effects of stimulus parameters and amblyopia type. *Vision Res*, *45*(11), 1471-1479. doi: 10.1016/j.visres.2004.12.014
- Polat, U., Ma-Naim, T., Belkin, M., & Sagi, D. (2004). Improving vision in adult amblyopia by perceptual learning. *Proc Natl Acad Sci U S A*, *101*(17), 6692-6697.
- Polat, U., Ma-Naim, T., & Spierer, A. (2009). Treatment of children with amblyopia by perceptual learning. *Vision Res*, *49*(21), 2599-2603.
- Polat, U., & Sagi, D. (1993). Lateral interactions between spatial channels: suppression and facilitation revealed by lateral masking experiments. *Vision Res*, *33*(7), 993-999.
- Polat, U., & Sagi, D. (1994a). The architecture of perceptual spatial interactions. *Vision Res*, *34*(1), 73-78.
- Polat, U., & Sagi, D. (1994b). Spatial interactions in human vision: from near to far via experience- dependent cascades of connections. *Proc Natl Acad Sci U S A*, *91*(4), 1206-1209.
- Polat, U., Schor, C., Tong, J. L., Zomet, A., Lev, M., Yehezkel, O., . . . Levi, D. M. (2012). Training the brain to overcome the effect of aging on the human eye. *Sci Rep*, *2*, 278. doi: 10.1038/srep00278

Visual training and perceptual changes

- Provis, J. M., Diaz, C. M., & Dreher, B. (1998). Ontogeny of the primate fovea: a central issue in retinal development. *Prog Neurobiol*, *54*(5), 549-580.
- Riddoch, M. J., & Humphreys, G. W. (1993). *The Birmingham Object Recognition Battery (BORB)*. London: Erlbaum.
- Sharma, V., Levi, D. M., & Klein, S. A. (2000). Undercounting features and missing features: evidence for a high-level deficit in strabismic amblyopia. *Nat Neurosci*, *3*(5), 496-501.
- Solomon, J. A., & Morgan, M. J. (2000). Facilitation from collinear flanks is cancelled by non-collinear flanks. *Vision Res*, *40*(3), 279-286.
- Sterkin, A., Yehezkel, O., Bonnef, Y., Norcia, AM, & Polat, U. (2007). Multi-component correlate for lateral collinear interaction in the human visual cortex as revealed by Visual Evoked Potentials. *Vision Sciences Society*.
- Sterkin, A., Yehezkel, O., & Polat, U. (2011). Learning to be fast: gain accuracy with speed. *Vision Res*, *in press*.
- Torfs, K. , Vancleef, K., Lafosse, C., Wagemans, J., & de-Wit, L. . The Leuven Perceptual Organizing Screening Test (L-POST), an online test to assess mid-level visual perception. *submitted*.
- Wong, E. H., Levi, D. M., & McGraw, P. V. (2005). Spatial interactions reveal inhibitory cortical networks in human amblyopia. *Vision Res*, *45*(21), 2810-2819.
- Woods, R. L., Nugent, A. K., & Peli, E. (2002). Lateral interactions: size does matter. *Vision Res*, *42*(6), 733-745.

FIGURE LEGENDS

Figure 1

LG's visual acuity (VA) improvements during training are long lasting. (A) Illustration of a visual acuity ETDRS chart. (B) LG's VA for distance (3 meters); (C) LG's VA for near (40 cm). The X axes show the time since the onset of training, the arrow below the X axes (0-9 months) indicates the duration and cessation of the training period, the Y axes denote visual acuity in LogMAR (on the right) or Snellen units (on the left), lower values indicate better VA. The red, green, and blue plots show the results for right (R), left (L), and both eyes, respectively. Both distance and near VA improved significantly and are enduring for more than 4 years post-training.

Figure 2

Visual crowding improvements during and following training. (A) Stimuli examples for measuring crowding effects and visual acuity by the "Tumbling-E patterns test" (Bonneh et al., 2004), which is a LogMAR chart equivalent. The minimal size for central pattern identification is measured under single (on left) and multiple (crowded, on right) pattern conditions to determine visual acuity; crowding effects are estimated from the acuity difference between the crowded and single conditions, smaller crowding effects indicate better vision. The X axis shows the time since the onset of training (arrow below the X axis indicates the duration of the training), and the Y axis denotes the crowding effects in LogMAR units. Visual crowding was measured pre-training (at X axis=0), during and at the end of the training (X axis = 9), and more than 4 years post-training (X=60 months). The red and green indicate right (R) and

Visual training and perceptual changes

left (L) eyes respectively. The gray shaded zone denotes normal crowding effects of the normal adult population (0 ± 0.05 (S.E.M.)).

Figure 3

Lateral interactions before and after LG's training. (A) Collinear lateral interactions stimuli examples, in which contrast detection threshold of a single flashed Gabor patch at fixation (on left) is measured against detection threshold of displays with lateral high contrast collinear flankers (appearing above and below target) at various distances (on right- three columnar examples of different distances). (B-D) The X axes denote target-flankers separation in wavelengths (λ), Y axes denotes the contrast detection threshold difference (single target vs. with flankers) in log units. (B) Before training LG's lateral interactions were dominated by suppression, especially for $\lambda = 2-3$ (LG's right (R) and left (L) eyes denoted in red and green respectively), similar to those found in typical adult amblyopia before training (dashed brick line), and not showing the typical facilitation effect found in normal adults (dashed gray line). (C) After 9 months of training, LG's lateral interactions for $\lambda \geq 2$ (typically showing facilitation in healthy adults controls), showed small but clear facilitation effects, similar to amblyopes following training (dashed brick line), and these effects in LG endured over 4 years post-training (D) for $\lambda = 2, 3$. The control data presented in panels B, C, and D are the same for all these panels; lateral interactions of typical amblyopes are presented in B, and interactions of amblyopes following training are presented in panels C and D. Error bars indicate SEM.

Figure 4

LG's contour integration threshold improved to age level performance. (A) Illustration of contour detection in noise stimulus, where a contour made of Gabor patches (circular shape) embedded in randomly oriented patches was measured as a function of background element density to target spacing ratio. See methods for more details. (B) LG's performance pre-training to more than 4 years post training. The X axis shows the time since the onset of training (arrow below X axis indicates the training duration), and the Y axis denotes the contour integration thresholds. Light and dark gray lines indicate performance of children aged 5-6 years, and normal adults. Error bars indicate SEM.

Figure 5

LG's normal performance on a wide range of mid-level visual functions. Top – LG's overall performance across all tests from the Leuven Perceptual Organization Screening Test (L-POST, see Methods), below – LG's scores for the specific subtests. LG scored above average on all subtests (in blue). Norms are based on performance of 1500 individuals. Permission to duplicate L-POST output results obtained from Johan Wagemans.

Figure 6

The error rates for object recognition and part integration before (in gray) and 4 years after the training ended (post training, in blue). (A) LG's error rates in the Birmingham Object Recognition Battery overlapping figures task (test 6) were reduced following training only for letters (N.B. LG's error rate on the pretest for simple geometric patterns was 0%). (B) LG's Hooper visual organization error rates

Visual training and perceptual changes

dropped to nearly half following training (from 58% pre-training to 33% post training). (C) LG's naming accuracy for intact or occluded line drawings of animals.

His performance on the occluded animals might indicate mild improvement.