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Making perceptual learning practical to improve visual functions

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ABSTRACT

Task-specific improvement in performance after training is well established. The finding that learning is stimulus-specific and does not transfer well between different stimuli, between stimulus locations in the visual field, or between the two eyes has been used to support the notion that neurons or assemblies of neurons are modified at the earliest stage of cortical processing. However, a debate regarding the proposed mechanism underlying perceptual learning is an ongoing issue. Nevertheless, generalization of a trained task to other functions is an important key, for both understanding the neural mechanisms and the practical value of the training. This manuscript describes a structured perceptual learning method that previously used (amblyopia, myopia) and a novel technique and results that were applied for presbyopia. In general, subjects were trained for contrast detection of Gabor targets under lateral masking conditions. Training improved contrast sensitivity and diminished the lateral suppression when it existed (amblyopia). The improvement was transferred to unrelated functions such as visual acuity. The new results of presbyopia show substantial improvement of the spatial and temporal contrast sensitivity, leading to improved processing speed of target detection as well as reaction time. Consequently, the subjects, who were able to eliminate the need for reading glasses, benefited. Thus, here we show that the transfer of functions indicates that the specificity of improvement in the trained task can be generalized by repetitive practice of target detection, covering a sufficient range of spatial frequencies and orientations, leading to an improvement in unrelated visual functions. Thus, perceptual learning can be a practical method to improve visual functions in people with impaired or blurred vision.

1. Background

Our vision is limited by two main factors: (a) the quality of the image that is transferred from the eye, and (b) the neural processing in the brain, which needs to integrate information between different neurons located at neighboring brain locations (space). Cortical cells (neurons) are highly specialized and optimized as image analyzers. Thus, to characterize an image, visual processing involves the cooperative activity of many neurons—those neuronal interactions contributing to both excitation and inhibition. The integration of image parts should be performed very quickly, since the time-window in which the first percept is formed is very short. Thus, visual information processing may be limited if the first percept representation is inefficient either due to slow neural processing or to the lack of effective interactions between the neurons.

1.1. Contrast sensitivity

Contrast sensitivity (CS), i.e., the ability to discriminate between shades of gray, is one of the main determinants of how well people see. It is assumed that the contrast sensitivity function (CSF) describes the combined response of the classical receptive fields of simple cells that have been selectively tuned for location, orientation, and spatial frequency and constitute the fundamental units of analysis. Models of spatial vision assume that the outputs of linear spatial filters produce a field of local signals that can be integrated at later stages of signal processing (Wilson, 1991; Wilson & Wilkinson, 1997). Thus, CSF describes the output of an early stage that provides the building blocks for the succeeding steps of visual processing. Thus, the fidelity of this output may determine how well higher visual areas process the information and hence their output including their feedback to the lower visual areas.

During the last decade, it was demonstrated that contrast response is also determined by lateral interactions in the visual cortex of humans (Bonneh & Sagi, 1999; Cass & Alais, 2006; Cass & Spehar, 2005; Ellenbogen, Polat, & Spitzer, 2006; Polat & Norcia, 1996; Polat & Sagi, 1993, 1994a, 1994b, 2006; Shani & Sagi, 2006; Solomon & Morgan, 2000; Tanaka & Sagi, 1998; Woods, Nugent, & Peli, 2002) and of animals (Crook, Engelmann, & Lowel, 2002; Kapadia, Ito, Gilbert, & Westheimer, 1995; Mizobe, Polat, Pettet, & Kasamatsu, 2001; Polat, Mizobe, Pettet, Kasamatsu, & Norcia, 1998; Polat & Norcia, 1996), suggesting that early stages of visual processing are involved in inducing this effect. Feedback (top shown) input to the early visual cortex may also modulate

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the CSF (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Carrasco, Williams, & Yeshurun, 2002).

Visual acuity (VA) is the most common clinical measurement of visual function and is considered as the gold standard measure of visual functions. VA measures the ability to identify black symbols on a white background at a standardized distance as the size of the symbols is varied. A person with standard (normal) VA can recognize a letter that subtends an angle of 5′ (i.e., each stroke subtends 1′). Clinically, this level of VA is specified as 6/6 (20/20).

1.2. Neural plasticity and perceptual learning

Visual plasticity is the ability of the visual system to change its responses in order to adapt to changes in the visual input. Evidence for plasticity in the adult visual system has been reported in human studies that have demonstrated that training in specific visual tasks leads to improvement in performance or sensitivity (for a review, see (Fahle & Poggio, 2002)). Perceptual learning has a major influence on our understanding of the development and plasticity of the visual system. Improvement after perceptual learning was demonstrated using a variety of visual tasks showing that the adult visual system can change according to behavioral demands (Fahle, 2005; Fiorentini & Berardi, 1980; Polat & Sagi, 1994b; Sagi & Tanne, 1994). (For a review, see Fahle (2002), Fahle and Poggio (2002), Gilbert, Sigman, and Crist (2001), Sagi and Tanne (1994)).

The improvement in performance after training is well established and is usually task specific but the underlying neural mechanisms are not fully understood. The finding that learning is task and stimulus-specific and that the visual gain is not transferred between different stimuli, between stimulus locations in the visual field, or between the two eyes, has supported the notion of the task-dependent response modifications of neurons or assemblies of neurons at the earliest stage of cortical processing (e.g., V1) (Fahle, 2005; Fahle & Skrandies, 1994; Hirsch & Gilbert, 1991; Polat & Sagi, 1994b, 1995; Sagi & Tanne, 1994).

1.3. Specificity vs. generalization

As previously mentioned, a prominent aspect of perceptual learning is the specificity of the improvement regarding stimulus features, whereas transferring to different stimulus features is rarely found. Thus, the specificity of the perceptual learning may pose a limitation on the technique when it is employed to improve anomalous visual functions such as amblyopia, age-related macular degeneration (AMD), loss of vision after stroke, or to improve visual functions such as visual acuity in people with normal vision (Polat, 2006, 2008; Polat, Ma-Naim, Belkin, & Sagi, 2004). On the other hand, it was noted that improvement achieved through perceptual learning generalizes more for complex tasks than for simpler ones (Fahle, 2005). Thus, the challenge seems to be to identify where the bottle-neck for generalization of basic visual functions is located. Addressing this question is important for two different reasons: understanding the mechanism underlying brain plasticity and for the practical purpose of improving visual functions within a reasonable time period. Here we propose that CS is a fundamental function that reflects the output of early visual processing. More specifically, it represents the performance of the neurons at the primary visual cortex. Improvement in CS may facilitate the performance of visual processing during the next stages of the visual cascade, which rely on the output of these neurons.

1.4. Plasticity in amblyopia

Amblyopia is a reduction of visual functions that cannot be directly attributed to the effect of any structural abnormality of the eye or the posterior visual pathway. It is caused by abnormal binocular visual experience early in life, during the 'critical period' that prevents normal development of the visual system. A generally practiced principle of treatment is that therapy can only be effective during the critical period, usually considered to end around the age of 8–9 (Greenwald & Parks, 1999; Prieto-Diaz, 2000; von Noorden, 1981), when the visual system is considered sufficiently plastic for cortical modifications to occur. The standard amblyopia therapy is thus traditionally directed toward children and consists of penalizing the preferred eye by using an eye patch or atropine, thus forcing the brain to use the visual input from the amblyopic eye. However, in adults, the visual deficiencies are thought to be irreparable after the first decade of life, once the developmental maturation window has been terminated; thus the standard treatment is usually not offered. However, recovery of visual functions in adults with amblyopia after occlusion therapy (Birnbaum, Koslowe, & Sanet, 1977; Simmers, Gray, McGraw, & Winn, 1999; Wick, Wingard, Cotter, & Scheiman, 1992) or after loss of vision in the good eye (El Mallah, Chakravarthy, & Hart, 2000) was reported.

The first step in a series of controlled studies that provided evidence for plasticity, after perceptual learning, in adults with amblyopia used training for the vernier acuity task (Levi & Polat, 1996; Levi, Polat, & Hu, 1997b). Repetitive practice led to a substantial improvement in vernier acuity in the amblyopic eyes of adults with amblyopia. In two observers, the improvement in vernier acuity was accompanied by a commensurate improvement in VA reaching up to normal vision. These studies provided an optimistic possibility for future treatment of amblyopia based on perceptual learning. However, in these studies CS was not measured. Recent studies have provided additional evidence for plasticity in adults with amblyopia (Chung, Li, & Levi, 2006; Fronius, Cirina, Cordey, & Ohrloff, 2005; Fronius, Cirina, Kuhli, Cordey, & Ohrloff, 2006; Levi, 2005; Li & Levi, 2004; Polat et al., 2004; Zhou et al., 2006). In some of these studies, there was transfer between categories such as training on contrast detection and improvement of visual acuity (Huang, Zhou, & Lu, 2008; Polat, 2008; Polat et al., 2004; Zhou et al., 2006). Thus, the question has been raised whether CS limits visual acuity and whether improvement in CS is essential and precedes improvement in letter recognition tasks (VA).

1.5. Abnormal spatial interactions in amblyopia

Early findings of abnormal spatial interactions in amblyopia were presented by Polat, Sagi, and Norcia (1997) and recently by other researchers (Ellemberg, Hess, & Arsenault, 2002; Levi, Hariharan, & Klein, 2002; Polat, 2006; Polat et al., 1997, 2004). In amblyopia, abnormal neuronal interactions resulted in reduced facilitation and increased suppression. It has also been shown that amblyopic observers failed in tasks that required integration of local features (Chandna, Pennefather, Kovacs, & Norcia, 2001; Hess, McIlhagga, & Field, 1997; Kovacs, Polat, Pennefather, Chandna, & Norcia, 2000; Liu, Wang, Liao, Xu, & Han, 2004; Popple & Levi, 2000; Simmers, Ledgeway, Hess, & McGraw, 2003; Wong & Levi, 2005; Wong, Levi, & McGraw, 2005). The main effect of abnormal spatial interactions is found in strabismic amblyopes (Bonneh, Sagi, & Polat, 2007; Levi et al., 2002; Polat, 2008; Polat, Bonneh, Ma-Naim, Belkin, & Sagi, 2005). Thus, the suggestion that there is a link between impaired lateral interactions and the typical reduced CS encountered in amblyopia (Polat, 1999, 2006; Polat et al., 2004) seems to be more pronounced in strabismic amblyopia.

1.6. Improving normal visual functions

Some insight into the mechanism underlying neural plasticity, which may improve the contrast sensitivity, comes from lateral masking experiments (Polat & Sagi, 1994b, 1995; Polat et al., 2004). Learning experiments showed that practice increases the range of the lateral interactions by a factor of six, but only along the collinear direction. Training on non-collinear configurations revealed no improvement. A range increase could not be obtained by practicing only at the large distances; rather, it required practicing with varied distances, including the small ones. The contrast threshold of the target improved, but only when it was embedded between the two collinear flankers and not when the subject was trained on a single target. The above studies show the importance of context in perceptual learning; however, this view is not supported by a recent study (Yu, Klein, & Levi, 2004). The training shows that the suppression from the short target-flanker separation (<2λ) can be reduced as well. These studies suggest that practice on lateral interactions increases the efficacy of the collinear interactions between neighboring neurons, an effect that enables connectivity with remote neurons via a cascade of local interactions. Thus, the results suggest a possible tool for the use of lateral interactions for improving CS in people with normal vision and in people with impaired lateral interactions such as amblyopia.

We have developed a perceptual learning procedure that was designed to improve the abnormal lateral interactions in amblyopia by stimulating the deficient neuronal populations and effectively promoting their collinear interactions (Polat, 2006, 2008; Polat et al., 2004). Since the amblyopic deficit is not identical among subjects (Bonneh, Sagi, & Polat, 2004; Bonneh et al., 2007; Polat, 2008; Polat et al., 2005), the treatment was tailored and specifically designed for each individual's deficiencies. The treatment and its results are summarized in the following sections.

1.7. Improvement of lateral interactions in amblyopia

Amblyopes exhibit abnormal lateral interactions (Bonneh et al., 2004, 2007; Ellemberg et al., 2002; Levi et al., 2002; Polat, 2006, 2008; Polat et al., 2004). The lateral interaction function of the amblyopes at the beginning of the treatment showed no facilitation and in fact, increased the amount of suppression. However, after the treatment, the amount of suppression was significantly reduced to a normal level (Polat, 2008; Polat et al., 2004). Thus, the results indicate that the trained tasks improved but an open question is whether this can be applied to other unrelated tasks.

1.8. Improvement of CSF in amblyopia

In the study of Polat et al. (2004), the amblyopic eyes exhibit the typical lower CS before treatment, as compared with normal sighted eyes, with the low spatial frequencies near the normal values and the high spatial frequencies showing a worse deficit. The treatment produced a significant improvement in sensitivity, by about a factor of two, in all spatial frequencies including the high spatial frequency range, raising the function to within the normal (lower) range. Most interesting is the result that after 12 months, CSF was not only retained, but it also increased toward an average range at the high spatial frequencies. This result suggests that the high spatial frequencies are used after the treatment in daily tasks and thus are naturally practiced. Recent studies have shown that training for contrast detection near the cutoff of the CS of anisometropic amblyopes improved CS near the trained spatial frequency (Huang et al., 2008; Zhou et al., 2006). The study of Huang et al. (2008) shows that the training on CS, near the cutoff, improved CS over a broad range of spatial frequencies, an effect that demonstrates the generalization idea.

1.9. Improvement of CSF in non-amblyopic groups

The procedure of Polat et al. (2004), when applied to people with normal vision or corrected to normal vision, improved their visual acuity to better than 6/6 (Polat et al., unpublished data). Therefore, it has been recently applied to improve the vision of people with low myopia (Tan & Fong, 2008). The vision of myopic (short sighted) subjects is blurred without optical correction. Therefore, the CSF is reduced, especially at the higher spatial frequencies, when compared with people with corrected vision. This reduction in CS is reminiscent of the CS of amblyopic subjects. This study used a protocol similar to the one used for the amblyopia (Polat et al., 2004); it showed that when subjects practiced with uncorrected moderate myopia it improved their CS. Thus, even in cases when the lateral interactions are normal (low myopia), training improves CS.

1.10. Improvement of VA

It was shown that letter recognition and contrast sensitivity are directly related (Chung, Legge, & Tjan, 2002; Chung, Mansfield, & Legge, 1998; Legge, Pelli, Rubin, & Schleske, 1985; Levi, Song, & Pelli, 2007; Majaj, Pelli, Kurshan, & Palomares, 2002; Patching & Jordan, 2005).

The VA was found to improve after training on contrast detection of amblyopes (Polat et al., 2004), anisometropic amblyopes (Huang et al., 2008; Zhou et al., 2006), and after training on verneir acuity (Levi & Polat, 1996; Levi, Polat, & Hu, 1997a). The training of low myopia on lateral interactions also shows improvement of VA (Tan & Fong, 2008). Thus, the training can be generalized to the letter recognition task (VA), an effect that supports the relationships between these perceptual tasks and letter recognition.

There are a few studies that directly targeted training and improvement of CSF to promote improvement of letter recognition (visual acuity). The mean improvement of CSF in Polat et al. (2004) was 0.34 log units. They found that the improvement was paralleled by an improvement of 0.25 log units (78%) in the visual acuity. Tan and Fong (2008) applied the technique of Polat et al. to improve the visual acuity of young people with low myopia who have normal vision when wearing their corrected glasses. After training, when measured without their corrected glasses, the mean improvement in CSF was 0.32 log units and the average improvement in VA was 0.21 log units (62%). Huang et al. (2008) trained anisometropic amblyopes and found an improvement of 0.35 log units in CS, but the improvement in VA was 0.136 log units (37.2%), probably because they trained in only one spatial frequency near the cutoff. Note that both studies, in which subjects were trained in the range of spatial frequencies (Polat et al., 2004; Tan & Fong, 2008), though consisting of different groups of subjects (amblyopes vs. low myopes), found a similar improvement in the average CSF before and after training (0.34 and 0.32 log units, respectively) and the improvement in visual acuity was also similar (0.25 vs. 0.21 log units). Interestingly, the maximal improvement in the study of Polat et al. (2004) was at 6 cpd (0.52 log units), which was correlated with reading abilities (Patching & Jordan, 2005). Thus, apparently improvement in the range of spatial frequencies leads to better improvement of letter recognition.

1.11. Transfer to improvement of binocular vision

In the studies of Polat and colleagues, during the treatment, the fellow eye was covered; thus the treatment was monocular, targeting the abnormal lateral interactions of the amblyopic eye. Very surprisingly, after treatment, the binocular functions improved, indicating that both the binocular fusion and the stereo acuity improved (Polat, 2006, 2008). An improvement in binocular functions was found in all groups (anisometripic, strabismic, and combined), though the average improvement was higher for the groups with anisometropia, but the differences did not reach significance. Thus, both sensory binocular functions and stereo acuity improved after treatment without directly practicing both eyes.

1.12. Persistence of the improved functions

The visual functions were tested 12 months after ceasing the treatment without any interventions. The patients were instructed to use their optical correction if needed. According to the results, most of the patients retained their improved visual functions 12 months after the treatment ceased. This result is consistent with the long-lasting improvements found in other studies using perceptual learning. Most interesting is the result that after 12 months, CSF was not only retained—it also increased toward an average range at the high spatial frequencies. This result may indicate that the high spatial frequencies are used after the treatment in daily tasks and thus are naturally practiced.

2. Improving visual functions in presbyopia

The following section presents new data concerning ongoing treatment of presbyopic subjects. Presbyopia, the Greek word for aging eye, is an age-related visual impairment. Presbyopia causes near vision to fade with age and results from the gradual decrease that comes with age; it can have multiple effects on the quality of vision and the quality of life. The highest incidence of presbyopia (i.e., first-reported effects) is in persons aged 42–44; most people are affected after this age and everyone is by age 51. Use of reading glasses is the standard solution to enable normal reading for presbyopic people.

In presbyopia, unlike amblyopia, the visual input to the cortex is limited by the optics of the eye. The high spatial frequencies are perceived as having low contrast even when their physical contrast is high. Thus, the CSF is lower than normal, reminiscent of the amblyopic CSF (see Fig. 1). Therefore, the lower contrast perception may cause the neuronal response in the visual cortex to be weaker and slower, leading to degraded letter identification and deficient reading abilities. Thus, in both cases, amblyopia and presbyopia, the initial contrast sensitivity is lower than normal. However, in presbyopia, the visual processing is normal but there is blurred visual input. Moreover, presbyopic subjects are older than the amblyopic group and are within the age range where plasticity is considered rare. Thus, improvement of visual functions in presbyopia is of scientific and practical importance.

2.1. Reading speed

As previously mentioned, there is a close relationship between CSF and letter recognition. However, although people have the strong impression of seeing a whole page of text simultaneously, it has long been known that only a few letters are recognized in each fixation span. Therefore, reading speed is limited by the visual span, which is the number of letters that can be recognized in parallel at a glance (O'Regan, 1990). It has been proposed that the size of the visual span imposes a fundamental limit on reading speed, and that shrinkage of the visual span accounts for slower reading (Legge, Mansfield, & Chung, 2001). It was also shown that the visual span increases with increasing presentation time (Legge et al., 2001). Levi et al. (2007) showed that in central, peripheral, and amblyopic vision, it is letter spacing (crowding of lateral masking) that limits reading speed. It was also shown that spatial and temporal crowding is correlated (Bonneh et al., 2007). Thus, reading abilities are increased by increasing the available processing time to sample the text.

2.2. Lateral masking and crowding

A pattern can be difficult to identify when surrounded by a "crowd" of flanking patterns, a phenomenon called "crowding" (Stuart & Burian, 1962). A closely related phenomenon, contour interaction, refers to the effect of proximal contours such as bars or edges on the resolution of a single letter (Flom, Weymouth, & Kahneman, 1963). The related phenomenon of "visual masking" refers to impaired performance regarding some judgment of a target stimulus when a mask stimulus is briefly presented before, during, or after the target, at the same or at flanking locations (for a review, see (Breitmeyer, 1984; Breitmeyer & Ogmen, 2000)).

The relation between ordinary masking and crowding is unclear. Studies in the spatial domain suggest that ordinary masking and crowding are related (Bonneh et al., 2007; Livne & Sagi, 2007; Petrov & McKee, 2006; Polat & Sagi, 1993), distinct (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Pelli, Palomares, & Majaj, 2004), or partially related (Bonneh et al., 2004; Chung, Levi, & Legge, 2001). Masking may be considered in terms of suppression or early alteration of the target signal. However, crowding is considered as "pooling" or over-integration of target and mask signals (Hariharan, Levi, & Klein, 2005; Pelli et al., 2004) or the inability to individuate a target among distracters (Tripathy & Cavanagh, 2002).

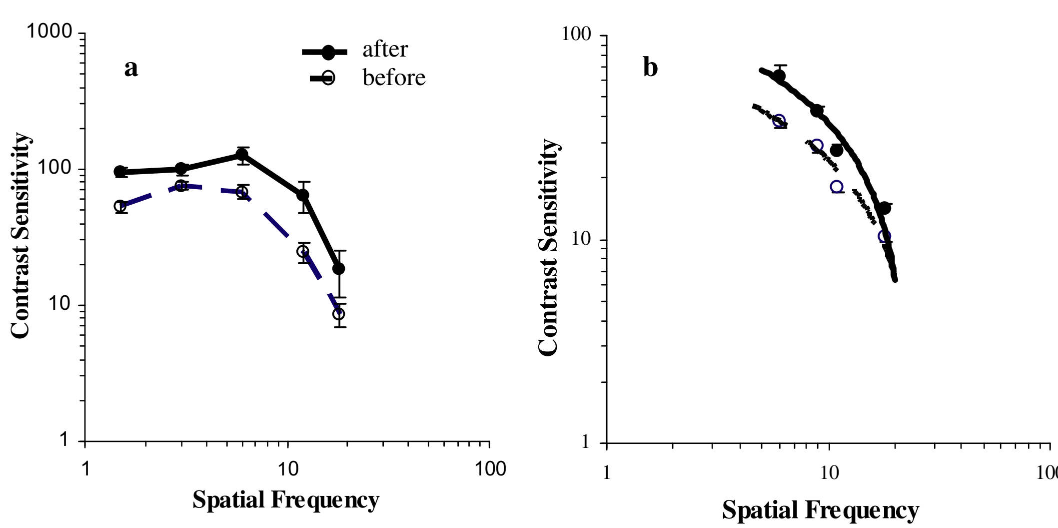

Fig. 1. Contrast sensitivity function of presbyopic subjects: CS before (dashed line, open circles) and after training (solid line, filled circles) is presented on the *y*-axis against spatial frequency on the *x*-axis. (a) CS for the first group ($n = 6$) measured with the clinical chart before and after an average of 30 sessions. (b) CS for the second group ($n = 14$) that is still undergoing training, measured using the computerized method, before and after 20 sessions. Error bars indicate ± se of the mean.

For the visual brain, it takes time to carry out operations necessary for building up sensory and perceptual representations of the impinging visual objects. People are able to derive the gist of the scene at a rate of ~100 ms per picture. When a mask is presented, typically less than 100 ms after the target, the target's visibility is reduced – an effect that is usually inferred as suppression (Breitmeyer, 1984; Breitmeyer & Ogmen, 2000; Polat & Sagi, 2006). However, if the image is processed fast enough, it is seen as presented without a mask and can be perceived distinctly and correctly.

In order to improve the visual abilities of presbyopic subjects, we designed a training procedure aimed at improving the spatial and temporal CS using perceptual learning.

2.3. Procedure and methods

A treatment procedure is currently being developed to train presbyopes, with the aim of improving their reduced reading abilities. The perceptual learning procedure targets the improvement of neural processing by promoting the spatial and temporal interactions of the neurons. Each session the subjects are trained on contrast detection of a Gabor target; this includes collinear lateral interactions (Polat & Sagi, 1994b) and backward masking on the target and on the lateral interactions (Polat & Sagi, 2006). The training covers a range of spatial frequencies and orientations that are modified in accordance with the progress and improvement of the subjects. The inter-stimulus-interval (ISI) is decreased from 240 to 60 ms according to the progress of the treatment. The subjects are trained from a distance of 40 cm with both eyes open. The visual acuity, spatial, and temporal contrast sensitivity, as well as reaction time are tested before and compared in the course of the treatment. The training is performed in a dark room, with the subjects having both eyes open; there are two sessions of about 30 min per week.

This study is still ongoing; here we show final data from the first group of 13 subjects (50 ± 1.1, mean ± se years old, initial VA 0.385 LogMar) that completed the training and a second group of 14 subjects (51.6 ± 0.05, mean ± se years old, initial VA 0.47 LogMar) that are still undergoing training. The other measurements were taken from subgroups of subjects from the second group, before and after 20 sessions of practice.

2.3.1. Spatial contrast sensitivity

A 3:1 staircase method was used to determine the contrast threshold level at 79% correct performance (Levitt, 1971). All staircases started with a high-contrast target that allowed error-free detection or discrimination. The contrast level of the target was increased by 0.1 log units after every incorrect response and was decreased by 0.1 log units after three consecutive correct responses. Each test block was terminated after eight reversals of the staircase procedure, and the geometric mean of the last six reversal reversed values in log units was used to estimate the contrast threshold.

2.3.2. Temporal contrast sensitivity

The contrast threshold of a single target with a fixed spatial frequency (either 6 or 11 cpd) was measured as described above. A few target durations were tested: 30, 60, 120, and 240 ms.

2.3.3. Reaction time

A simple reaction time (RT) for contrast detection of a single Gabor patch was tested for a few spatial frequencies (6, 9, 12, and 16 cpd). Three constant contrast levels of the target were used (5%, 10%, and 20%). The subjects were instructed to answer as fast as they can when they detect the target. A time jitter of 1000 ms was applied to avoid false responses.

2.4. Improvement of CSF

CS for near vision was measured using a clinical chart (Sine Wave Contrast Test, Stereo Optical, Inc.) from a distance of 40 cm before and after training. Eight subjects from the first group that had completed the training (an average of 30 sessions) participated. The average result is presented in Fig. 1a. The CSF improved 0.26 log units (an average of 95%), whereas the peak improvement was 164% at 12 cpd. This improvement is similar to the results found for amblyopia and low myopia (Polat, 2008; Polat et al., 2004; Tan & Fong, 2008) that were measured on clinical charts for distance (a distance of 3 m). CS is also measured using a computerized method. The average results, presented in Fig. 1b, after 20 sessions, for 14 other subjects who did not yet complete the training, shows an average improvement of 0.19 log units (54%), whereas the maximal improvement is 71% at 6 cpd. The CS after 20 sessions is significantly higher than at baseline ($p = 0.035$, paired t-test). The computerized results are slightly lower and the shape of the CSF of the figures is different, probably due to several differences: (1) the computerized method is measured only after 20 sessions before reaching saturation, whereas the CS on the clinical chart is measured after the subjects complete training (an average of 30 sessions). More sessions are expected to increase the improvement (see (Levi & Li, 2009; Polat, 2006)), especially considering that these subjects had not yet undergone training for the higher spatial frequencies. (2) The clinical charts measured static performance, allowing the subjects to scan the patches without a time limitation, whereas the computerized method is transient and was presented for only 80 ms. A longer presentation time is supposed to improve CSF (see below, Critical duration). (3) We used Gabor patches with $\sigma = \lambda$, meaning that the target size is reduced with increasing spatial frequency, whereas in the clinical chart, the size of the target is constant; thus the number of cycles increased with increasing spatial frequencies. Therefore, a sharp drop in CS with increasing spatial frequency is expected using our targets (Peli, Arend, Young, & Goldstein, 1993).

2.5. Improvement of minimal duration for best contrast sensitivity

To further confirm our hypothesis that the improvement in visual functions is due to improved temporal processing, we tested the integration time for contrast detection for two spatial frequencies (6 and 11 cpd), by measuring contrast detection as stimulus duration was varied (temporal CS). It was shown that contrast detection reached saturation after 120–200 ms in physiological experiments (Albrecht, 1995; Mizobe et al., 2001; Polat et al., 1998) and psychophysical experiments (Polat, Sterkin, & Yehezkel, 2007; Watson, Barlow, & Robson, 1983). Critical duration is usually defined as the exposure duration at which the contrast sensitivity reaches a criterion (80%) of its asymptotic value, and reflects the time constant for contrast sensitivity. A shorter critical duration indicates greater sensitivity, with less overall energy being necessary for detection to occur and an increased ability to escape from backward masking (Polat et al., 2007).

In our study, as predicted and shown in Fig. 2, training resulted in a remarkably shorter minimal duration that was needed in order to reach the level of maximal sensitivity before training. As expected, sensitivity increased with increasing presentation time. Before training, the subjects reached the maximal level of CS after 240 ms, whereas after training, they reached this level after 30 ms for 6 cpd (Fig. 2a). For targets of 11 cpd, the subjects reached the maximal level at 120 ms, whereas after 20 sessions they reached this level at 90 ms. Taken together, our results confirm our prediction that practice improves the temporal contrast sensitivity, hence the processing time.

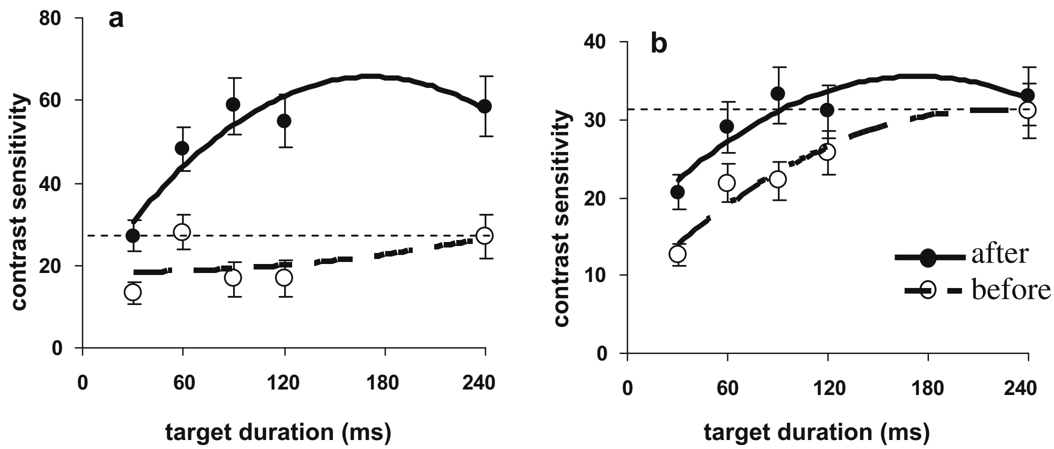

Fig. 2. Minimal duration for maximal contrast sensitivity of presbyopic subjects: CS before (dashed line, open circles) and after training (solid line, filled circles) is presented on the *y*-axis against spatial frequency on the *x*-axis. The horizontal dashed lines indicate the level of maximal contrast sensitivity before practice. CS measured using the computerized method, before and after 20 sessions. Error bars indicate ± se of the mean. (a) 6 cpd ($n = 9$), (b) 11 cpd ($n = 3$). The results indicate that the critical duration is remarkably faster after training.

2.6. Improvement of reaction time (RT)

An improvement in the reaction time per se may also be indicative of reading speed. Simple reaction time is measured as target detection (e.g., detection of targets at different contrasts) in a paradigm where the timing of the visual target varies randomly from trial to trial and detection rates and latency are quantified. It was shown that the reaction time improves linearly with increased contrast of the targets (Harwerth & Levi, 1978; Plainis & Murray, 2005). Since our treatment improves spatial and temporal contrast sensitivity, consequently, the improved RT may be due to the increased visibility of the targets after learning.

To further confirm our hypothesis that the improvement in spatial and temporal contrast sensitivity is paralleled by improvement of the temporal processing, we measured simple RT. The results, presented in Fig. 3 for 9 subjects, are for 20% contrast. The results for the other contrast levels (5% and 10%) are similar. As can be seen, RT is slower for increasing spatial frequencies. The subjects improve their RT dramatically after 20 sessions of practice, from 126 at 6 cpd to 231 ms at 16 cpd. In order to test whether the improvement in RT is due to general improvement of the performance owing to familiarity with the task or visual-motor learning, we normalized the RT of all spatial frequencies to the faster one, i.e., 6 cpd, before and after training. If true, the improvement should be homogenous over all spatial frequencies. The results, presented in Fig. 3b, show that there is a differential improvement in the RT, which increases with increasing spatial frequencies, an effect that rejects the possibility that general improvement underlies the improvement in RT. Thus, the results indicate a remarkable improvement in RT, an effect that was shown to be correlated with improved reading speed.

2.7. Improvement of visual functions for near vision

The improvement in the visual acuity of the first group of 13 subjects that completed the training was 0.26 and 0.22 log units in the right and left eyes, respectively. The initial VA was 0.39 and 0.38. This is an average improvement of 73% in the visual acuity for near and the magnitude is similar to the improvement in the amblyopia and low myopia study (Polat, 2008; Polat et al., 2004;

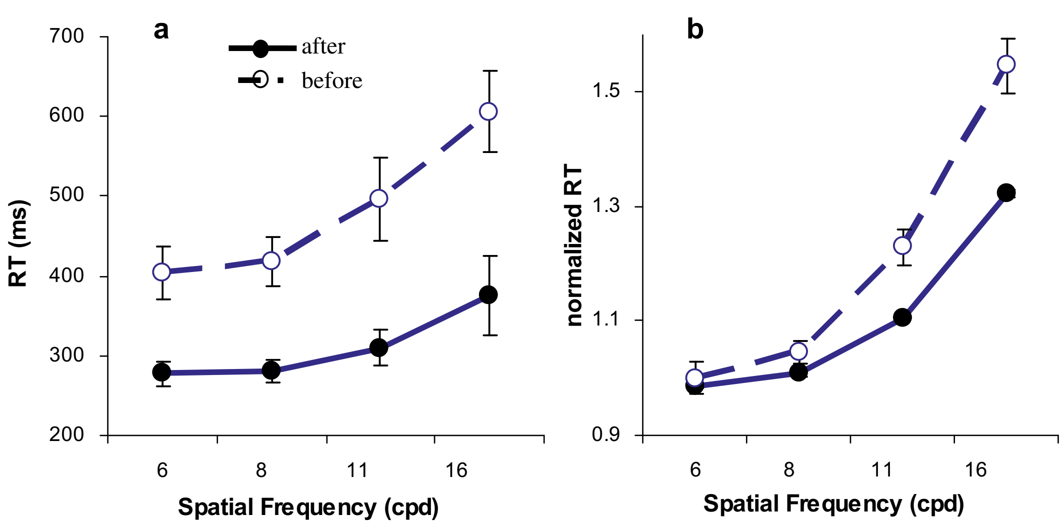

Fig. 3. Reaction time of presbyopic subjects: RT before (dashed line, open circles) and after training (solid line, filled circles) is presented on the *y*-axis against spatial frequency on the *x*-axis. CS measured using the computerized method, before and after 20 sessions. Error bars indicate ± se of the mean. (a) RT for a target contrast of 20% ($n = 9$); (b) normalized RT – each subject's results were normalized to the faster RT (6 cpd) before and after training. In both figures it is apparent that RT improved significantly and more for the high spatial frequencies.

Tan & Fong, 2008). After training, there was a real benefit for the subjects; based on our clinical observation, 11 out of 13 are now able to read, without the aid of reading glasses, from a distance of 40 cm, and the other 2 are able to do so from an arm's length, using reading glasses for extensive reading only. More importantly, the subjects reported a subjective feeling of improvement in their daily activities such as using cellular phones, digital watches, inspecting small texts during shopping, and choosing items from menus in restaurants.

In the second group of 14 subjects, after 20 sessions, the interim improvement of the near visual acuity was 0.21 and 0.14 log units for the right and left eyes, respectively, reflecting 64% and 37% improvement. The improvement in this group is slightly lower, but it is expected because this group did not complete the training sessions and performed fewer sessions than the first group (Levi & Li, 2009; Polat, 2006).

3. Summary

The aim of this manuscript was to show that perceptual learning is not restricted to a laboratory setting as a scientific tool to study visual processing, rather, it can be applied for practical purposes to improve visual functions of people with special needs. We showed, by describing results from unrelated studies including new results of an ongoing study of treatment of presbyopia, that improvement of the spatial and temporal contrast sensitivity is transferred to improvement of other visual functions. This suggestion is supported by the fact that improvement of contrast sensitivity is paralleled with a similar amount of visual acuity, although the studies were performed at different locations and with different types of patients (amblyopia, myopia, and presbyopia). We also provided a new set of data, collected from a study where presbyopic subjects were trained, showing that the temporal contrast sensitivity is also improved, an effect that probably led to the improvement found in the reaction time and the reading abilities.

The approach that is described here is based on the idea that visual functions are composed of a cascade of visual processing stages. We suggest that improvement of the spatial and temporal contrast sensitivity at early visual processing should be followed by improvement of other functions that are processed either at the same or at later stages.

In the course of treating presbyopia, which we previously described here, the subject is initially exposed to relatively long presentation times that become significantly shorter with improvement. Thus, owing to the improvement of the temporal contrast sensitivity, the time needed to grasp the same amount of information is shortened, allowing people to significantly increase their reading speed. Alternatively, the accuracy of reading is increased as more samplings are allowed during the same exposure time. We speculate that, within the limited time provided for recognition, improvement of the processing speed enables one to perform more iterations of processing the blurred image received from the eyes; this results in extracting a sharper and better recognized image.

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