# Perceptual learning induces neuroplasticity, enabling improvement of visual functions

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Uri Polat
*Goldschleger Eye Research Institute, Tel Aviv University, Sheba Medical Center, Ramat Gan, Tel Hashomer, 52621 Israel*
*urip@post.tau.ac.il*

**"Improvement following perceptual learning was demonstrated using a variety of visual tasks showing that the adult visual system could change according to behavioral demands."**

Our vision is limited by two main factors: the quality of the image that is transferred from the eye to the brain, and the quality of the neural processing in the visual cortex, which is needed to integrate the visual input from the retina. To interpret an image, the visual processing must have very quick cooperative activity involving many neurons. Thus, the quality of vision may be impaired, either when the operation of the eye is compromised and cannot be fixed by clinical aid, and/or when the central visual processing is abnormal or impaired.

The aim of this paper is to show that perceptual learning (PL) can be applied for practical and clinical purposes to improve visual functions of people with special needs. Recent results have shown that improvement of the spatial and temporal contrast sensitivity is associated with improvement of valuable visual functions and can be measured in terms of improved visual acuity (VA).

Visual acuity is the most common clinical measurement of visual function and is considered as the gold standard for measuring visual functions. However, it has also been shown that 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 CS function (CSF) describes the combined response of the neurons in the early visual cortex, which constitutes the building blocks for the succeeding steps of visual processing. Thus, the fidelity of this output may determine how well the visual information will be processed.

Visual plasticity is the ability of the visual system to change its responses in order to adapt to changes in the visual input. For decades, it was assumed that the ability to achieve neural plasticity is lost towards the end of the first decade of life [1–3]. However, evidence for plasticity in the adult visual system has been reported in humans with visual deficits [4] and in studies that have demonstrated that training based on PL leads to improved performance [5]. Improvement following PL was demonstrated using a variety of visual tasks showing that the adult visual system could change according to behavioral demands [5–11].

A prominent aspect of PL is the specificity of the improvement to the trained features, whereas transferring learning to other stimulus features is rarely found. This may restrict the use of this technique when it is used to improve anomalous visual functions. Moreover, the improvement usually requires a long period of training [12–14], which may limit its use in clinical settings. An attempt to use PL to improve vision for clinical use was first demonstrated in amblyopia [15,16].

Amblyopia is a reduction of visual functions that cannot be directly attributed to the effect of any structural abnormality of the eye or to the posterior visual pathway. It is caused by abnormal binocular visual experience early in life, when the visual system is considered sufficiently plastic for cortical modifications and, thus, normal development can occur. Therefore, a generally practiced principle of treatment is that therapy can only be effective up to the age of 8–9 years [1–3]. Standard amblyopia therapy is, thus, traditionally directed towards children, whereas in adults, this treatment is usually not prescribed.

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Training for the vernier acuity task was used in the first step in a series of controlled studies that provided evidence for plasticity following PL in adults with amblyopia [15,16]. The improvement in vernier acuity was accompanied by a commensurate improvement in VA, which approached normal vision in two observers. These studies provided an optimistic possibility for future treatment of amblyopia based on PL. A recent clinical and controlled study provided evidence for the potential use of PL for treating adults with amblyopia [17], and this is supported by other recent studies [18–23]. Therefore, the potential for treatment of adult amblyopia with PL is well demonstrated and established.

We have provided the first evidence that impaired visual integration (i.e., the spatial interactions between different neurons, an effect that may underlie impaired CSF, perceptual grouping and object recognition [24]) is a main deficit in amblyopia. Recent studies further supported this idea [17,25–35]. A pioneering PL procedure designed to improve the abnormal spatial interactions in amblyopia was recently developed [13,14,17]. Since the level of amblyopic deficit is not identical among subjects [36–38], the treatment was tailored and specifically designed for each individual's deficiencies. After the treatment, the impaired spatial interactions were significantly improved to the normal level [13,17]. Thus, these results show that PL improved the performance of the trained tasks, but an intriguing question was whether the training could be transferred to improve other visual tasks as well. Before treatment, the amblyopic eyes exhibited typically lowered CS, compared with normal-sighted eyes. Importantly, the treatment produced a significant improvement in sensitivity, by approximately a factor of two, in all spatial frequencies, including the high spatial frequency range, raising the CSF to within the normal (lower) range.

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Letter recognition (VA) and CS are directly related [39–44]; therefore, it is expected that improvement in CSF should lead to improvement in VA. Indeed, it was found that both VA and CS were improved by PL in adults with amblyopia. The mean improvement in CS in the study by Polat and colleagues was 0.34 log units and was paralleled by an improvement of 0.25 log units (78%) in VA [17], similar to the results reported later by Huang and colleagues for CS (0.35 log units) [45], although the improvement in VA was less pronounced (0.136 log units; 37.2%), probably because only one spatial frequency was used for training.

In the studies by Polat and colleagues, the other eye was covered during the treatment process; thus, the treatment was monocular, targeting the abnormal lateral interactions of the amblyopic eye [17]. However, very surprisingly, binocular functions improved in all groups (anisometripic, strabismic and combined) after treatment, indicating that both the binocular fusion and stereo acuity improved [13,27]. Thus, both sensory binocular functions and stereo acuity improved after treatment without directly interfering with both eyes.

The visual functions were retested 12 months after ceasing the treatment without any interventions. The patients were instructed to use their optical correction if needed. Most of the patients retained their improved visual functions 12 months after the treatment ceased. This result is consistent with the long-lasting improvement found in other studies using PL [17].

Recent studies have shown that when PL was applied to children, the outcome of the treatment was very successful [46–49]. Thus, the scientific evidence that PL may constitute an effective treatment for amblyopia seems to be compelling [12,14,22]. Unfortunately, despite the excellent results achieved by PL treatment showing that training of approximately 20 h is equivalent to approximately 500 h of patching [12], the availability of treatment based on PL is still very limited. A few reasons may underlie this: the slow natural adaptive process of such exceptional treatment by the clinical community; the technical limit requiring that the treatment be tailored individually for each patient; the high number of the treatment sessions; and the nature of the treatment being purely scientific and not entertaining. Therefore, the current challenge is to explore new avenues to develop a more accessible PL treatment for amblyopia. Since it has recently been shown that playing video games improves CS [50], it is possible that future applications will combine PL and video games to make the treatment more attractive.

> “...the current challenge is to explore new avenues to develop a more accessible perceptual learning treatment for amblyopia.”

Recently, PL has been applied to improve the vision of people with normal central neural processing but a deficient optical system, such as low myopia [50] and presbyopia [14]. The procedure used by Polat and colleagues [17] was applied to improve the blurred image without optical correction in patients with low myopia [51]. Practice with uncorrected moderate myopia improved patients' CS and VA by 0.32 and 0.21 log units, respectively.

Presbyopia is an age-related visual impairment, resulting in blurred vision for near distances, starting at ages 42–44 years. In presbyopia, the visual input to the cortex is limited by the optics of the eye, resulting in lower CS than normal and leading to degraded letter identification and deficient reading abilities. Presbyopic patients are older than typical amblyopic and myopic populations, and are within the age range where plasticity is considered rare. Thus, improved visual functions in presbyopia is of both scientific and practical importance.

A training procedure, based on PL and targeted to improve temporal processing, was designed and applied to improve the visual abilities of presbyopic subjects [14]. The average age of the subjects was older than 50 years. CS for near vision was measured from a distance of 40 cm before and after training. After training, CS improved by 0.26 log units (an average of 95%), similar to the results found for amblyopia and low myopia [13,17,51]. The improvement in the VA was approximately 0.24 log units (an average improvement of 73%), which is also similar to the improvement in the other two groups of patients. After training, real benefits were acquired, as subjects were able to read from a distance of 40 cm without the aid of reading glasses. These results suggest that the training improved the processing speed of the visual neurons. Furthermore, most importantly, improvement in the temporal processing resulted in improved reading abilities.

For the visual brain, it takes time to carry out processes necessary to build up sensory and perceptual representations of visual objects. In the course of training, the processing speed becomes faster with improvement. Thus, owing to the improvement of the temporal CS, the time needed to grasp the same amount of information is shortened, thereby allowing people to significantly increase their visual abilities and reading speed.

We believe that future PL techniques will be modified and adjusted as complementary or standalone, noninvasive procedures that will aid clinicians to treat and improve a variety of visual functions that are not currently addressed by conventional treatment.

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