Training on spatiotemporal masking improves crowded and uncrowded visual acuity

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Spatial crowding impairs conscious visual perception and object recognition in clutter. Short presentation times produce crowding in the normal fovea, in young participants and in uncorrected presbyopes ("aging eye"), measured as reduced visual acuity (VA). On the other hand, perceptual learning improves near VA in healthy young adults, in presbyopia, and in amblyopia. Here we aimed at exploring the effects of perceptual training on crowded VA in uncorrected presbyopes with naturally decreased VA, with two specific objectives: (a) to objectively measure crowded VA, taking advantage of the natural deterioration of near visual acuity from being normal or better than normal (i.e., 20/20 or better) in young participants to naturally decreasing in uncorrected presbyopes; and (b) to explore whether perceptual training previously shown to improve visual functions as complex as reading will affect crowded VA. Visual acuity was measured under crowded and uncrowded conditions by having subjects identify letters presented for short durations ranging from 34 to 116 msec. Training consisted of detecting brief Gabor stimuli under spatial and temporal masking conditions, using the GlassesOff mobile application (GlassesOff, Inc., New York, NY) on iOS devices from a distance of 40 cm. Before training, a robust reduction in crowded VA was found in the fovea of presbyopes. Training resulted in significant improvement of letter identification under both crowded and uncrowded VA conditions for all stimulus durations. After training, the crowded condition threshold reached the level of the uncrowded threshold measured before training. Thus, training enabled the subjects to overcome the effect of reduced VA under the crowded condition. We suggest that more efficient spatial and temporal processing induced by perceptual learning allows one to improve crowded VA, including that found on naturally reduced near VA, and that this effect may transfer to improve complex visual functions, such as reading and object recognition.

Introduction

Spatial crowding is the inability to recognize objects in clutter, which poses fundamental limits on conscious visual perception and object recognition (for reviews, see Chung, Levi, & Legge, 2001; Levi, 2008; Levi, Klein, & Hariharan, 2002; Pelli, Palomares, & Majaj, 2004; Strasburger, Harvey, & Rentschler, 1991; Whitney & Levi, 2011). When presented among other letters, the reduction in letter recognition is also termed "flanked acuity" (e.g., Song, Levi, & Pelli, 2014). It is most commonly found in the peripheral vision of normally sighted people or in the fovea of people with strabismic amblyopia (Bonneh, Sagi, & Polat, 2007; Flom, Weymouth, & Kahneman, 1963; Levi, 2008; Whitney & Levi, 2011). Over many years, the research

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on crowding has shown that it occurs in a wide variety of tasks, including letter identification (Bouma, 1970; Flom et al., 1963; Toet & Levi, 1992), vernier acuity (Levi, Klein, & Aitsebaomo, 1985; Westheimer & Hauske, 1975), orientation discrimination (Andriessen & Bouma, 1976; Livne & Sagi, 2007, 2010, 2011; Westheimer, Shimamura, & McKee, 1976), stereoacuity (Butler & Westheimer, 1978), contrast discrimination (Saarela, Sayim, Westheimer, & Herzog, 2009), the global effect and grouping (Manassi, Sayim, & Herzog, 2012, 2013; Saarela et al., 2009), and face recognition (Louie, Bressler, & Whitney, 2007; Martelli, Majaj, & Pelli, 2005).

Early research on crowding focused on the fovea (e.g., Flom et al., 1963). However, in the ensuing years, the vast majority of the studies presented stimuli at the periphery of the visual field, for which the rules originally defined for foveal crowding did not apply (for reviews, see Levi, 2008; Pelli et al., 2004; Pelli & Tillman, 2008; Whitney & Levi, 2011). Recent reviews of crowding or crowded conditions or flanked acuity attempted to generalize these findings into a unified model of crowding across eccentricities (Levi, 2008; Pelli et al., 2004; Whitney & Levi, 2011). In this study, we focused on foveal crowded VA.

Variability in the foveal crowding reports

Earlier estimates of the extent of foveal crowding vary from none (Strasburger et al., 1991) up to 0.5° (Chung et al., 2001). Strasburger et al. (1991) used low-contrast letters and, more importantly, low-contrast flankers, and reported little or no crowding in the fovea. The classical study of Flom et al. (1963), which used letters near the acuity limit, indicated that the extent of crowding was limited to only a few minutes of arc and was proportional to the minimum angle of resolution (MAR) in normal and amblyopic subjects. They found crowding in the fovea for target-flanker separations of less than 5 arcmin in the normal fovea, and to a much greater extent in the amblyopic fovea. Based on these findings, they concluded that the extent to which crowding occurs might be related to the size of the receptive field (and hence, the resolving capacity) associated with the retinal region used to fixate the target. On the other hand, in the normal periphery and in the central visual field of amblyopes larger receptive fields are engaged, resulting in reduced visual acuity or increased MAR. This putative shift from small to large receptive fields is commonly known as the scale shift hypothesis (Levi & Waugh, 1994; Levi, Waugh, & Beard, 1994). Chung et al. (2001) found a much larger extent of crowding (about 0.5°) using bandpass filtered letters. The results of Levi et al. (2002) suggest that the extent of spatial interactions in foveal vision should not be thought of as having a fixed retinal distance, but instead, as being proportional to the size of the target. However, although such scaling of crowding is currently under debate, the effect itself is measured using drastically different experimental paradigms in different studies, posing significant limitations on the overall consolidation of the findings. Some critically different experimental approaches that are particularly relevant for the current study, even when used in the fovea and using the same task are shown in the following paragraphs.

First, some studies used static presentations (e.g., Flom et al., 1963; Siderov, Waugh, & Bedell, 2013), whereas others used presentations limited to 500 msec (e.g., Danilova & Bondarko, 2007) and 250 msec (e.g., Levi & Carney, 2011), or brief presentations of 100 msec or shorter (e.g., Lev, Yehezkel, & Polat, 2014; Strasburger et al., 1991). In our studies we used incrementally decreasing presentation times in order to reveal the effects of a crowded presentation in the fovea, effects that are not evident when longer presentation times are used and when other parameters remained unchanged (Lev, Yehezkel et al., 2014). Moreover, by using shorter presentation times, foveal crowding was found to a much greater extent.

Second, some studies used large (one-letter) target–flanker spacing (e.g., Strasburger et al., 1991), whereas others used small (less than a half letter) spacing (e.g., Lev, Yehezkel et al., 2014; Simmers, Gray, McGraw, & Winn, 1999), resulting in different conclusions about crowding effects for otherwise similar parameters.

Third, some studies used center-to-center separation measurements (e.g., Levi et al., 2002; Pelli et al., 2004), whereas others used edge-to-edge spacing (e.g., Danilova & Bondarko, 2007). Consequently, when reanalyzed using a center-to-center separation, a specific target having a smaller interaction zone when using edge-to-edge spacing (Siderov et al., 2013), appears to have the largest interaction zone (Coates & Levi, 2014). Whereas target–flanker critical spacing appears to decrease for increasing target size based on edge-to-edge spacing measurements (e.g., Danilova & Bondarko, 2007), it remains consistent across target sizes with center-to-center spacing, an effect that has been shown in other studies (e.g., Levi & Carney, 2011; Pelli et al., 2004).

Fourth, some studies used stimuli consisting of a single letter target and flanking bars (e.g., Siderov et al., 2013), whereas others used letter targets (usually the letter E) surrounded by similar letters (e.g., Bonneh, Sagi, & Polat, 2004; Bonneh et al., 2007; Danilova & Bondarko, 2007; Lev, Yehezkel et al., 2014).

Fifth, there is a controversy regarding the impact of stimulus contrast. On one hand, as mentioned above, earlier studies on normal foveal vision suggested that crowding was limited to small high-contrast stimuli and vanished with low-contrast targets (Simmers et al., 1999; Strasburger et al., 1991). On the other hand, a recent study using three different contrast levels concluded that crowding for foveal targets indeed occurs within a fixed angular zone of a few minutes of arc, regardless of the size or the contrast of the acuity target (Siderov et al., 2013). This conclusion seems to contradict previous studies (Hariharan, Levi, & Klein, 2005; Levi et al., 2002) and a reanalysis of the same data (Coates & Levi, 2014; see also Siderov, Waugh, & Bedell, 2014; Strasburger & Malania, 2013). A saturation of these effects for contrasts above 20% was also reported (Coates, Chin, & Chung, 2013). The impact of contrast on crowding is especially relevant for better understanding of the effects of blurring on crowding, due to the contrast reduction accompanying natural blurring, such as in presbyopia (Polat, 2009; Polat et al., 2012) and anisometropic amblyopia (McKee, Levi, & Movshon, 2003; Polat, Ma-Naim, Belkin, & Sagi, 2004), which can be improved by training on contrast detection (Polat et al., 2004; Polat et al., 2012).

Crowding versus contour interaction

Whereas the classical studies applied the term *contour interaction* to describe the impaired perception of letters surrounded by different types of distractors (e.g., Flom et al., 1963), the term *crowding effect* was introduced as early as 1936 (Ehlers, 1936). This inconsistency in the terminology, which accumulated over the years, gave rise to a debate about the term *crowding* itself. It was suggested earlier that the term contour interaction be used when the acuity stimulus is flanked by simple distractors, such as bars, and that the term crowding be used when more complex surrounds are used, such as letters (Danilova & Bondarko, 2007; Siderov et al., 2013). For simplicity, since we use letter targets flanked by letters, here we will adopt this approach and will refer to our setup as *crowded acuity*. It is also important to clarify that, although many studies focus on the experimental question of the critical spacing dependency on acuity (Chung et al., 2001; Danilova & Bondarko, 2007; Hariharan et al., 2005; Pelli et al., 2004; Tripathy & Cavanagh, 2002), here we explored how crowded VA for a fixed spacing is related to acuity.

Uncorrected presbyopia under crowded conditions

Presbyopia results from the gradual decrease in accommodative (focusing) power with age (Koretz, Kaufman, Neider, & Goeckner, 1989). Uncorrected presbyopia (sometimes termed "aging eye") results in reduced near visual acuity, reduced contrast sensitivity, and slower processing speed (Holden et al., 2008; Polat, 2009; Polat et al., 2012). It has multiple negative effects on the quality of vision, mostly on reading. Since contrast is important for driving neural responses in the visual cortex, the consequence of blurred input may result in weaker and slower neuronal responses in the visual cortex, leading to degraded letter identification and reduced reading abilities (Polat, 2009). In our recent study, we presented robust evidence for reduced performance under crowded conditions presented in the fovea of presbyopic subjects, using letter stimuli (Lev, Yehezkel et al., 2014). Thus, here we used uncorrected presbyopia as a model for exploring the effects of blurring on crowded acuity.

Perceptual learning in vision

Performance on challenging perceptual tasks benefits from practice, and long-term improvements indicate perceptual learning. This was demonstrated using a variety of visual tasks and indicates that the adult visual system can change according to behavioral demands (for a review, see Fahle, 2002; Sagi, 2011; Sasaki, Nanez, & Watanabe, 2010). Perceptual learning using a paradigm that facilitates collinear lateral interactions between neurons in the primary visual cortex improves visual acuity in young normally sighted adults (Lev, Ludwig et al., 2014) and adults with amblyopia (Lev, Gilaie-Dotan et al., 2014; Polat, 2008, 2009; Polat et al., 2004). Similar training, combined with backward masking conditions, resulted in shorter processing times needed for target detection in young normally sighted adults, as indicated by a shorter latency of a specific neuronal marker (Sterkin, Yehezkel, & Polat, 2012). A similar training paradigm also robustly improved near VA in presbyopes, with no changes in the optics of the eye (Polat et al., 2012). Moreover, improvements following practice under crowded conditions were reported earlier in the periphery of normally sighted people (Bernard, Arunkumar, & Chung, 2012; Chung, 2007, 2011; Hussain, Webb, Astle, & McGraw, 2012; Maniglia et al., 2011), in the fovea of people with amblyopia (Hussain et al., 2012; Levi & Klein, 1985a; Li, Provost, & Levi, 2007; for review see Levi & Li, 2009) and, recently, in the fovea of normally sighted people (Lev, Ludwig et al., 2014). The specificity of the training effects was found to depend on the amount of training (Huckauf & Nazir, 2007), and the training gains were generalized to untrained spatial separations after numerous trials (Chung, Li, & Levi, 2007, 2012; for review see Levi, 2008). However, to the best of our knowledge, this is the first report on the effects of perceptual learning in the fovea, in large groups of participants at several initial acuity levels. We also report on generalization of the training gains, indicated by improved performance on letter stimuli following training on Gabor stimuli.

Rationale and key findings

We hypothesize that the blurred input to the visual cortex in uncorrected presbyopic observers, which comprises the lower spatial frequencies, creates a spatial frequency shift towards the nonoptimal range, meaning a shift towards larger perceptive fields (the basic processing unit, equivalent to the classical receptive field in visual perception); hence, it results in lower acuity for single targets. This, in turn, results in crowding at acuity levels that do not result in crowding in young participants, thus following the prediction of Flom et al.'s (1963) model. It was also suggested that flanked targets fall beyond the "critical" spatial frequency (Hess, Dakin, Kapoor, & Tewfik, 2000). Moreover, the improvements in reading, which is limited by crowding (Levi, 2008; Pelli et al., 2007), observed in our recent study (Polat et al., 2012) further motivated us to predict that a similar training paradigm will improve crowded acuity when measured directly. On the other hand, based on this potential mechanism, we suggest that the naturally induced blurring in uncorrected presbyopia, taking into account the wide range of acuity, may serve as a good model for researching the effects of blurring on crowding, like in anisometropic amblyopia. This is in agreement with a recent model of optical blurring for anisometropic amblyopia (Song et al., 2014). Anisometropic amblyopia was shown earlier to behave like blurred normal foveal vision, whereas strabismic amblyopia is similar to peripheral vision (Levi & Klein, 1985b; Polat, Bonneh, Ma-Naim, Belkin, & Sagi, 2005; Song et al., 2014) with an additional component of underdeveloped lateral interactions (Bonneh et al., 2004, 2007).

In people with uncorrected presbyopia, crowding in the fovea might result either from lower near visual acuity or from a deterioration in the processing speed with age (Owsley, 2011, 2013; Polat, 2009; Polat et al., 2012), or a combination of both options. Here we aimed at exploring the effects of perceptual training on crowded acuity in uncorrected presbyopes with naturally decreased VA, with two specific objectives: (a) to objectively measure crowded VA, taking advantage of the natural blurring by creating a continuum of visual acuity, ranging from normal or better-than-normal (i.e., 20/20 or better) in young participants, to low in uncorrected presbyopes, and (b) to explore whether perceptual training, previously shown to improve reading, will improve crowded VA. Before training, a robust crowding effect, measured as the difference in VA for large versus small spacing, was found in the fovea of presbyopes. Training resulted in a significant improvement in both uncrowded and crowded VA for all stimulus durations, though more markedly for shorter duration times, along with a substantial improvement in standard near VA Early Treatment Diabetic Retinopathy Study (ETDRS) chart measurements. After training, the crowded condition threshold reached the level of the uncrowded threshold measured before training. Thus, training enabled the subjects to overcome the effect of reduced VA under the crowded condition. Nevertheless, the crowded VA remained proportional to uncrowded VA after training. We suggest that more efficient temporal and spatial processing, induced by perceptual learning, allows one to compensate for the adverse effects of natural blurring on crowded acuity. Although improvements under crowded conditions were reported earlier in the periphery (Bernard et al., 2012; Chung, 2007, 2011; Maniglia et al., 2011), this is the first report on the fovea in nonamblyopic eyes, in large groups of participants, and at several initial acuity levels.

Methods

Participants

A total of 97 subjects participated in this study. Forty presbyopes aged 49.1 ± 0.8 years (mean ± *SE*) were divided into two groups according to their initial static VA measured with a standard near ETDRS chart from 40 cm: (a) 21 early presbyopes aged 46.4 ± 0.6 years (mean ± *SE*), whose near binocular VA was up to 0.2 logMAR; and (b) 19 advanced presbyopes aged 52.0 ± 1.02 years (mean ± *SE*), whose near VA was 0.21 logMAR and above. In addition, 17 young participants aged 24.6 ± 1.36 years (mean ± *SE*) with normal binocular near VA (–0.096 ± 0.02) performed a similar training protocol (see the Training Procedure section). Another 28 participants were divided into three control test–retest groups that performed only pretest and posttest measurements, on different days with no training in between (i.e., test and retest control groups): a group of 19 young controls aged 24.0 ± 5.00 years (mean ± *SE*) with normal near VA (–0.13 ± 0.016), and a group of nine presbyopic controls aged 53.9 ± 2.80 years (mean ± *SE*), divided into two subgroups of six with early presbyopia and three with advanced presbyopia. All participants had normal or corrected-to-normal distance vision. A group of 12 additional subjects aged 47.08 ± 2.36 years (age range 38–62; near VA 0.13 ± 0.04) participated in the control experiment with the reversed order of blocks.

Apparatus

Stimuli during both the brief VA measurements (eTest, see below) and during training sessions (see Training Procedure section) were displayed on mobile iOS devices having a color monitor (iPhone, iPad, and iPod). The effective screen resolution was 640 × 640 pixels (5 cm diameter), with a pixel size of 0.078 mm (Retina Display; Apple, Cupertino, CA) and a refresh rate of 60 Hz. The mean display luminance was set to the maximal level (120 cd/m^2) in an otherwise dark environment.

Visual acuity and procedures

Visual acuity, using both static chart and brief presentations combined with crowding, was tested before (pretest) and after (posttest) the training (see the Training Procedure section). All near acuity measurements were made without any optical correction for the near distance. Auditory and visual feedback was provided after each trial.

Objective measurements of accommodation: Fused cross cylinder

The fused cross cylinder (FCC) is one of the main clinical methods for determining the near addition (Yanoff & Duker, 2014). A cross composed of multiple horizontal and vertical lines was presented to the participants at a distance of 40 cm. A Jackson cross cylinder (JCC), with its minus axis vertical, was placed in front of the distance correction. The participant was asked to compare the boldness of the horizontal and vertical lines of the cross. If no addition was required, the lines were equally dark. However, if the horizontal lines were darker, plus power was added binocularly in 0.25 D increments until the lines were equally black or until the vertical lines became more prominent. This lens power is the refractive correction needed for compensating for the accommodation deficit in order to achieve sharp near vision.

Near ETDRS chart

Standard static near VA was measured with a near ETDRS chart (Precision Vision, La Salle, IL) from 40 cm, fixed onto a stand to maintain the exact distance. The ETDRS chart is composed of lines containing five letters each with size increments of 0.1 log units and spacing of one letter. The measurements were performed at a single seating session by the same experienced, certified optometrist in the same room under standardized fixed light conditions using two variations of the same chart to prevent participants from remembering the order of the letters. The termination rules were based on a forced-choice paradigm and testing continued until the participant made a complete line of errors, or read all the letters on the chart (Kaiser, 2009).

eTest

The paradigm used here is very similar to the one we used before (Bonneh et al., 2004, 2007; Lev, Ludwig et al., 2014; Lev, Yehezkel et al., 2014). Visual acuity was assessed using brief presentations under crowded conditions using eTest (GlassesOff, Inc., New York, NY; Lev, Yehezkel et al., 2014), from 40 cm. We recently showed that eTest measurements are highly correlated with the measurement of near visual acuity on an ETDRS chart (Yehezkel, Sterkin, Lev, & Polat, 2013).

The stimuli consisted of 5 × 5 "tumbling E" patterns (Figure 1a) presented at the fixation location in the center of the display, for brief durations of 34, 68, and 116, msec (two, four, and seven frames, respectively). Two different interletter spacing options were used: First, one-letter edge-to-edge spacing (top panels) was used. This option was shown in our earlier study to result in a pattern of results similar to isolated letter stimulation (hereafter referred to as "large spacing"). Second, 0.4 edge-to-edge letter spacing (bottom panels, hereafter referred to as "small spacing") was used. In earlier studies, this option was shown to produce maximal impairment of the target in both normal and amblyopic participants (Flom et al., 1963; Simmers et al., 1999), which produced crowding in our recent study with stimuli that were the same as those used here (Lev, Yehezkel et al., 2014). This is also the same spacing as the one recently shown to constitute a constant factor of 1.4 between the center-to-center spacing and the acuity of a single target (Song et al., 2014).

A four-alternative forced-choice paradigm was used in which the participants were asked to determine whether the open side of the central letter E faced right, left, up, or down. Participants responded by pressing the buttons on a touch screen placed in the corresponding locations (right, left, top, and bottom). The patterns were black on a gray background. A visible fixation circle appeared in the center of the screen before each trial, thus directing attention to the target's location in the fovea. It disappeared when the participants initiated the trial by pressing anywhere on the touch screen, after which a blank screen (i.e., only the gray background) appeared for 300 msec, followed by the stimulus presentation (Figure 1b).

Each block measured the minimal identification of the letter size for a single duration and measured spacing using an adaptive procedure in which the pattern size and spacing were modified, according to

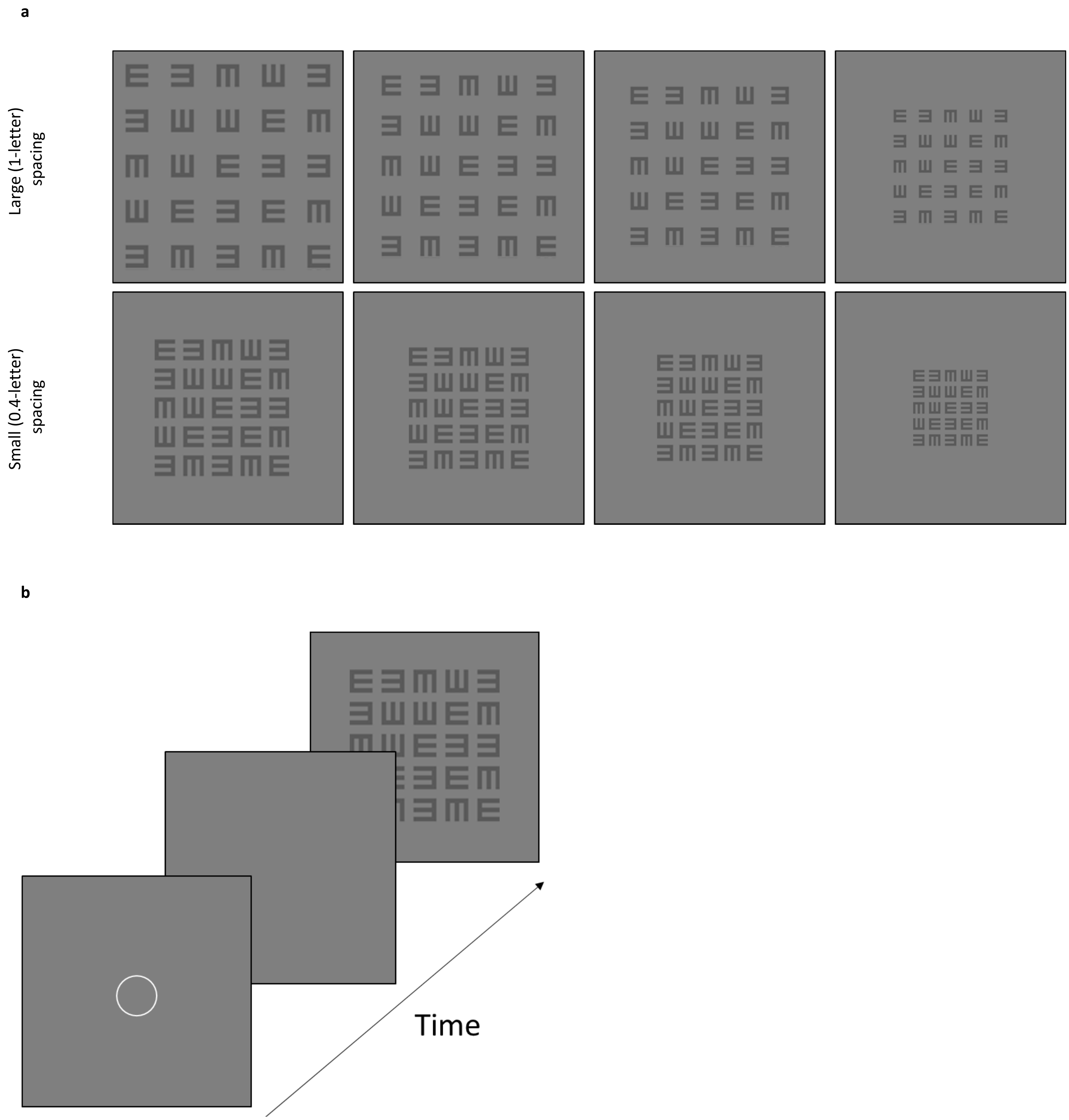

Figure 1. Stimuli and paradigm. (a) Tumbling E patterns with one-letter spacing (large, upper) and 0.4-letter spacing (small, bottom), in four representative stimulus sizes, with proportional spacing per letter size. (b) The timeline of a single trial. A fixation circle (enlarged for presentation) appeared in the center of the screen before each trial and disappeared when the participants initiated the trial by pressing anywhere on the touch screen, after which a blank screen appeared for 300 msec, followed by the stimulus presentation.

the performance (chance level of 25%), with the size increased for each mistake and decreased for two correct responses in a row. Spacing was always modified proportionally to the letter's size, as in the examples in Figure 1a. To determine crowding, we used separate blocks for the single space array and the crowded conditions for each presentation time. The order of the blocks was as follows: 238 msec large spacing (which served as practice), 116 msec small spacing, 116 msec large spacing, 68 msec small spacing, 68 msec large spacing, 34 msec small spacing, and 34 msec large spacing. The resulting minimal discriminable target size was converted to logMAR units for each block. The contrast was 29% (Weber contrast). The test lasted up to 15 min, including breaks that were allowed at any point.

Training procedure

The paradigm in this study is similar to the one used in our earlier studies involving young and presbyopic participants (Lev, Ludwig et al., 2014; Polat et al., 2012; Sterkin et al., 2012) in terms of behavioral tasks and temporal parameters. A perceptual learning method for improving visual functions using the GlassesOff application (GlassesOff, Inc., New York, NY) was adapted individually for each user by setting the training parameters according to the user's performance. Participants were trained on contrast detection and discrimination of Gabor targets under spatial masking, temporal masking, and spatial crowding conditions, while spatial and temporal constraints were posed on the visual processing. The training covered a wide range of spatial frequencies and orientations that were modified in accordance with the improved performance. Participants were instructed to train in a dark room from a distance of 40 cm with both eyes open. On average, participants practiced for 42.6 ± 3.9 sessions (mean ± *SE*) on different days, each lasting 12–15 min, with at least three sessions per week. Auditory and visual feedback was provided after each trial.

The stimuli consisted of localized gray-level gratings (Gabor stimuli) with equal luminance distributions, standard deviation (*SD* or σ), allowing a minimum of two cycles, $\sigma = \lambda$ (wavelengths), with spatial frequencies ranging between 1.33 and 8.00 cycles/°, subtending a visual angle ranging from 0.18° to 1.00°, at four possible orientations (0°, 45°, 90°, and 135°), which were modified in each session in accordance with the performance in the preceding session. Yes–no and temporal two-alternative forced choice (2AFC) paradigms were used. Training began with the yes–no paradigm for detection for several sessions (between five and seven), and then proceeded to the 2AFC paradigm, which was used for the remaining training sessions. Target detection or discrimination contrast threshold was determined for each condition, using a separate staircase for each block. The contrast of the Gabor was increased for each mistake and decreased for three correct responses in a row (with steps of 0.1 log units), which was used to estimate the stimulus strength at the 79% accuracy level. A fixation circle (subtending a visual angle of 0.7°) was presented in the center of the screen. Participants started each trial by touching the screen. Each target stimulus presentation interval duration was between 68 and 116 msec long, with an 800 msec gap between two intervals in the 2AFC paradigm. The first interval was preceded by a 300 msec blank period with a temporal jitter between 0 and 500 msec and had a uniform distribution. For the 2AFC contrast detection tasks, the target presentation was equally distributed between the two intervals across trials.

The experimental conditions were as follows: (a) the target alone: a single Gabor target with a spatial frequency; (b) lateral masking: a Gabor target masked by two high-contrast (60%) collinear Gabor flankers with a target–flanker distance of 0, 1.5, 2, 3, and 4 λ; (c) crowding: a Gabor patch masked by multiple collinear or noncollinear iso-oriented flankers, with a target–flanker distance of 1.5–4 λ; and (d) temporal masking: backward masking applied on the target alone, or lateral masking, composed of either flankers identical to those used in the lateral masking condition or those in the crowding condition, presented with varying time intervals (interstimulus intervals; ISI) of 68, 83, 116, or 150 msec. The duration of the mask was similar to the target stimulus presentation duration. Under the crowding condition, either four collinear flankers (above, below, on the right, and on the left) or a matrix of 11 × 11 Gabors surrounded the target. The target–flanker distance was kept constant throughout the trials of each staircase but varied between staircases within a session. Importantly, response facilitation to low-contrast Gabor targets by collinear Gabor flankers with target–flanker distances used for training was demonstrated using single-unit recording in the cat primary visual cortex (Mizobe, Polat, Pettet, & Kasamatsu, 2001; Polat, Mizobe, Pettet, Kasamatsu, & Norcia, 1998) and in monkeys (Kapadia, Ito, Gilbert, & Westheimer, 1995).

Each session included six blocks that included one block under the target alone condition, and five blocks under one of the previously described four conditions (contrast sensitivity, lateral masking, crowding, or temporal masking). The selection of the conditions used for each session was determined by an automated algorithm that advanced the conditions, the difficulty level (spatial frequency, orientation, and the initial target contrast in the staircase), and the ISI according to the participant's performance. ISI, the duration that the target and flanking Gabors were presented, their orientation, and spatial frequency were modified between sessions, one parameter at a time, according to the performance in the preceding session.

Control eTest with a reversed order of blocks

In order to explicitly verify that the effect of the presentation duration is stronger than the potentially confounding effect of fatigue, we performed a control eTest measurement for 12 new subjects with a reversed order of blocks. The order of the blocks was as follows: 238 msec large spacing (which served as practice), 34 msec large spacing, 34 msec small spacing, 68 msec large spacing, 68 msec small spacing, 116 msec large spacing, and 116 msec small spacing.

Data analysis

ANOVA was used for assessing the main effects and the interactions. For comparisons with degrees of freedom higher than 1, the Huynh-Feldt epsilon correction was applied (for any ANOVA). Pairwise comparisons included 12 a priori comparisons using paired t tests; thus, the threshold p value with an a priori Bonferroni correction is 0.0042 (0.05/12).

Results

Static ETDRS chart measurements for all groups

All acuity measurements and training sessions were conducted without near optical corrections. Objective measurements of accommodation obtained through the use of FCC show no change in prescription before versus after the training: 1.41 versus 1.41 D (paired t test, $p > 0.05$) measured on both groups together, 1.2 versus 1.24 D (paired t test, $p > 0.05$) for the early presbyopes, and 1.64 versus 1.60 D (paired t test, $p > 0.05$) for the advanced group. Visual acuity was measured before and after training. A two-factor ANOVA was performed, with the repeated measures design as follows: group (two levels, early and advanced presbyopia) and training (two levels, before and after perceptual learning). Consistent with our earlier findings (Polat et al., 2012), there was a significant improvement in the static VA measured using the ETDRS chart (Figure 2), the main effect of the group, $F(1, 76) = 80.9$, $p < 0.001$, and the main effect of training, $F(1, 76) = 61.5$, $p < 0.001$, paired t tests: $p < 0.001$ for both the early and advanced presbyopes. This is also consistent with the earlier notion of the magnitude of learning being a constant proportion of the initial performance, in concert with the Weber-like law suggested earlier (Astle, Li, Webb, Levi, & McGraw, 2013; Polat, 2008). The improvement in the advanced presbyopes (0.23 logMAR, or 70%) was significantly higher than in the early presbyopes (0.15 logMAR, or 41%), interaction: group $\times$ training, $F(1, 76) = 3.6$, $p = 0.05$. A separate ANOVA was performed with a similar repeated measures design, which included a test–retest control group that took the pretest and the posttest with no perceptual learning in between tests, including both the early and advanced stages of presbyopia and with a factor of the paradigm used (two levels: with perceptual learning and without). As Figure 2 shows, there was no difference in the measurements between the training and control group before training. There was, however, a

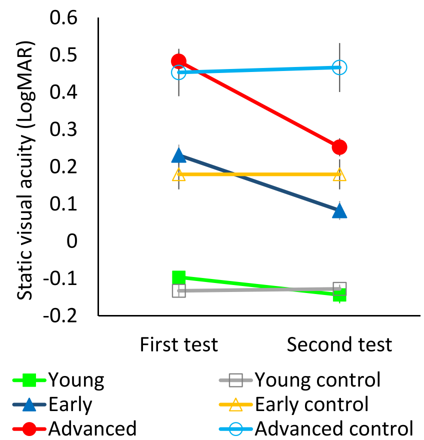

Figure 2. Static near VA improvement following training and test and retest control measurements. Standard near ETDRS measurements are presented for the early and advanced presbyopes before and after the training, for the young group before and after the training, and for the three corresponding control groups that were tested twice with no training in between (test and retest, open symbols). Error bars = *SE*.

significant effect of perceptual learning as opposed to a simple test–retest, which was evident from the significant interaction between training and the paradigm, $F(1, 46) = 25.8$, $p < 0.001$. Finally, for the young control group that was trained using the same protocol, there was a significant effect of training, evident from the significant interaction between training and the paradigm used, $F(1, 34) = 6.8$, $p = 0.13$ (paired t tests, $p = 0.016$), with no effect for the test–retest young group (paired t tests: $p > 0.05$), as we reported earlier (Lev, Ludwig et al., 2014).

Brief VA measurements in training presbyopic groups

Brief VA was measured using short letter stimuli presentations (eTest), with two interletter spacings: (a) one-letter spacing (large), which was shown in our earlier study to yield a pattern of results similar to single-letter stimulation (producing no crowding), and (b) 0.4-letter spacing (small), which was shown to produce maximal impairment of the target in both normal and amblyopic participants (Flom et al., 1963; Simmers et al., 1999), and which produced crowding in our recent research with stimuli that were the same as those used here (Lev, Yehezkel et al., 2014). This is also the spacing that was used recently to show a constant factor of 1.4 between the center-to-center spacing and the acuity of a single target (Song et al., 2014). ANOVA was performed, with the repeated measures designed as follows: training (two levels: before and after perceptual learning), spacing (two levels: large and small), duration (three levels: 34, 68, and 116 msec) with a factor of the group (two levels: early and advanced

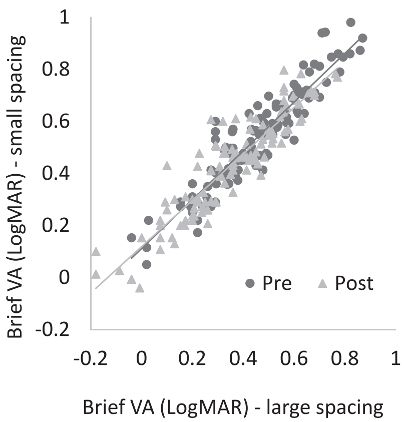

Figure 3. Correlation between brief VA measurements with large versus small spacing. Measurements by eTest before (circles) and after (triangles) the training, for the presbyopic participants (both early and advanced), across all presentation times, for small versus large spacing.

presbyopia). There were significant main effects of group, $F(1, 38) = 8.2$, $p = 0.007$; training, $F(1, 38) = 60.2$, $p < 0.001$; spacing, $F(1, 38) = 142.8$, $p < 0.001$; and duration, $F(2, 76) = 141.2$, $p < 0.001$.

Figure 3 summarizes the eTest measurements before and after training for the presbyopic participants (both early and advanced), across all presentation durations, for the small (x-axis) versus the large (y-axis) spacing, showing a high and significant correlation between the two measurements, $R = 0.93$, $p < 0.00001$, and slope = 0.939. This tight dependence between the two conditions of acuity measurements, which remains constant across a wide acuity range, supports our idea of using the naturally induced blurring in uncorrected presbyopia as a model for exploring crowding under the blurring conditions, in addition to a recently proposed model of artificial optical blurring for anisometropic amblyopia (Song et al., 2014). Moreover, uncorrected presbyopia allows one to explore the effects of crowding at different acuity levels presumably with no confounding cortical component.

Figure 4 presents measurements made using brief presentations (eTest), before and after training, for the experimental groups and for the first and second testing for the control groups. Before training (dotted lines), as expected, there was a significant decrease in the brief VA threshold with the shorter stimuli presentations, both for early (top panels) and advanced (bottom panels) presbyopes, for both large (left panels) and small (right) spacing (paired t test, $p < 0.001$ for all possible comparisons: 116 vs. 34 msec, 116 vs. 68 msec, and 68 vs. 34 msec). Moreover, there was a clear, highly significant crowding effect, measured as a significant decrease in VA values for smaller compared with larger spacing, for all stimulus durations, both for the early and the advanced presbyopes (paired t test, $p < 0.001$ for all presentations): early presbyopes, 0.09, 0.1, and 0.09 logMAR (23%, 27%, and 23%) for 34, 68, and 116 msec, respectively; advanced presbyopes: 0.06, 0.06, and 0.08 logMAR (16%, 16%, and 21%) for 34, 68, and 116 msec, respectively.

After training (solid lines), there was a significant improvement in brief VA both for early (top panels) and advanced (bottom panels) presbyopes, for both one-letter spacing (left panels) and 0.4-letter spacing (right panels), paired t test, $p < 0.001$ for all presentations. In the early presbyopes for the large spacing, there was an improvement of 0.14, 0.1, and 0.11 logMAR (37%, 27%, and 29%) for 34, 68, and 116 msec, respectively. In the early presbyopes for the small spacing, there was an improvement of 0.14, 0.12, and 0.1 logMAR (37%, 31%, and 26%) for 34, 68, and 116 msec, respectively. In the advanced presbyopes for the large spacing there was an improvement of 0.17, 0.09, and 0.1 logMAR (49%, 24%, and 25%) for 34, 68, and 116 msec, respectively. In the advanced presbyopes for the small spacing there was an improvement of 0.13, 0.11, and 0.09 logMAR (36%, 28%, and 22%) for 34, 68, and 116 msec, respectively. However, the difference between the acuity for the large and the small spacing remained for all stimulus durations, although relative to the new improved VA, as measured with large spacing after the training (paired t test, $p < 0.001$ for all presentations). In the early presbyopes, the difference was 0.09, 0.09, and 0.1 logMAR (23%, 23%, and 26%) for 34, 68, and 116 msec, respectively. In the advanced presbyopes, the difference was 0.1, 0.05, and 0.08 logMAR (27%, 12%, and 20%) for 34, 68, and 116 msec, respectively. The training effects varied for different stimulus durations: training × duration interaction, $F(2, 76) = 4.4$, $p = 0.027$. However, after training, a significant effect of presentation duration on brief VA remained, both for the early and advanced presbyopes, for both small and large spacing (paired t test, $p < 0.001$ for all possible comparisons: 116 vs. 34 msec, 116 vs. 68 msec, and 68 vs. 34 msec).

Most importantly, brief VA measured using small spacing after training became similar to the measurements made using large spacing before training, both in the early and in the advanced groups, for all stimulus durations (Figure 5)—a change toward achieving a lower level of presbyopia (Polat et al., 2012).

Brief VA measurements in control test–retest presbyopic groups

A separate ANOVA was performed with the same repeated measures design, which included a test–retest presbyopic control group that performed the pretest and the posttest with no perceptual learning in between tests, including both the early and advanced stages of

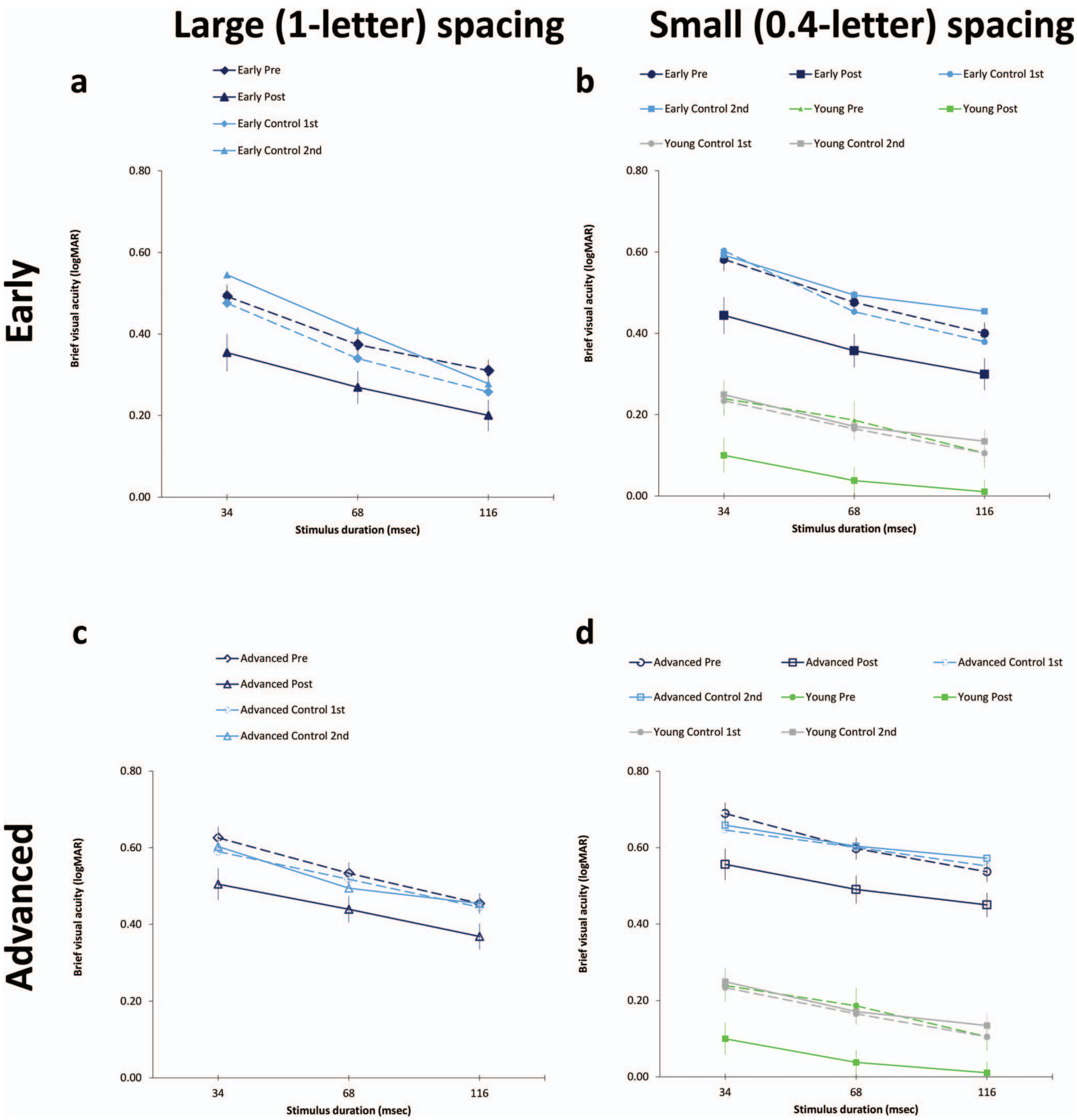

Figure 4. Improvement in brief VA under crowded conditions following training. Measurements by eTest using large one-letter spacing (left panels) and small 0.4-letter spacing (right panels) were measured before (dotted lines) and after (solid lines) training, for early (top panels) and advanced (bottom panels) presbyopes, and for the first (dotted lines) and second (solid lines) testing for the age-matched control groups. The measurements for the young control groups, either measured before (dotted lines) and after (solid lines) training or for the first (dotted lines) and second (solid lines) testing are shown in the right panels. Error bars = *SE*.

presbyopia (Figure 4), with a factor of paradigm (two levels: with perceptual learning and without). There was a significant effect of perceptual learning as opposed to the simple test–retest, $F(1, 46) = 12.9$, $p = 0.001$. Here there were also significant main effects of training, $F(1, 46) = 10.7$, $p = 0.002$; spacing, $F(1, 46) = 105.4$, $p < 0.001$; and duration, $F(1, 46) = 105.6$, $p < 0.001$. In both control groups, there was a clear, highly significant crowding effect for all stimulus durations (paired t test, $p < 0.001$ for all presentations): early presbyopes: 0.12, 0.11, and 0.12 logMAR (32%, 28%, and 32%) for 34, 68, and 116 msec, respectively;

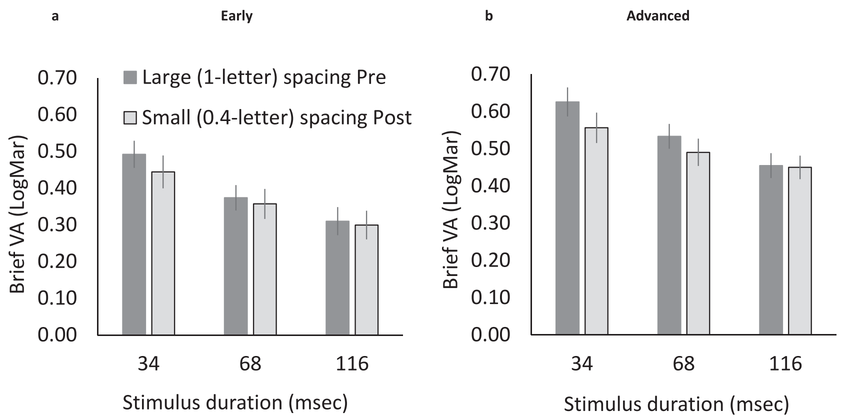

Figure 5. Training effects in the presbyopic groups. The threshold acuity before and after training, for the two spacing options are presented for (a) early presbyopic and (b) advanced presbyopic groups. The data of the presbyopic groups only are replotted from Figure 4 to emphasize the main training effect that brief VA measured using small spacing after training became similar to the measurements made using large spacing before training, both in the early and in the advanced groups, for all stimulus durations. Error bars = *SE*.

advanced presbyopes: 0.07, 0.08, and 0.08 logMAR (18%, 19%, or 19%) for 34, 68, and 116 msec, respectively. However, there were no significant changes in the brief VA after retesting in either of the groups, under any condition ($p > 0.05$), consistent with our previous training studies (Lev, Ludwig et al., 2014; Sterkin et al., 2014).

Brief VA measurements in training and control test–retesting of young groups

Finally, a separate ANOVA was performed with a similar repeated measures design that included a group of young participants who were trained using the same protocol, along with a test–retest young control group that performed the pretest and the posttest with no perceptual learning in between, with a factor of the paradigm (two levels: with perceptual learning and without). Figure 4 shows that there was no difference in the initial measurements between the trained and the control groups. However, there was a significant effect of perceptual learning as opposed to the simple test–retest, $F(1, 33) = 16.6$, $p < 0.001$. Here as well, significant main effects of training, $F(1, 33) = 8.5$, $p = 0.006$, and duration, $F(1, 33) = 37.5$, $p < 0.001$, were evident. After training, there was a significant improvement in the brief VA for each stimulus duration (paired t test, $p < 0.001$ for all presentations), with no significant changes in the control group (paired t test, $p > 0.05$ for all presentations). In contrast with the two presbyopic groups, however, both before and after training there were significant differences in the brief VA between the shortest and the longest durations (paired t test, $p < 0.001$ when comparing 116 vs. 34 msec), with no significant differences in the brief VA between consecutive stimulus durations (either for the 34 vs. 68 msec or the 68 vs. 116 msec comparisons, $p > 0.05$). This indicates that presbyopes are more sensitive to limitations in the presentation duration compared with the young participants, in concert with the critical duration measurements that we reported earlier (Polat, 2009; Polat, Sterkin, & Yehezkel, 2007).

The measurements using the large spacing in young participants were performed in our recent study of foveal crowding (Lev, Yehezkel et al., 2014) in a different group of 18 young participants aged 25.4 ± 0.77 years (mean ± *SE*). The results show a robust crowding effect of 0.16 logMAR (approximately 41%) for the small spacing, compared with the large spacing, for all presentation durations. However, because brief VA is below 6/6 for all durations, indicating a "floor" effect of the large spacing measurements, the large spacing conditions were omitted in the current study because they were redundant (the part of the study with young participants was performed at a later stage).

Control brief VA measurements with a reversed order of blocks

Although we have previous experience with a mixed block order design (e.g., Lev, Yehezkel et al., 2014), which results in an effect of presentation duration similar to the findings reported here, in order to explicitly verify that the effect of presentation duration is stronger than the potentially confounding effect of fatigue, we performed an experiment using 12 new subjects with a reversed order of blocks (Figure 6). ANOVA was performed, with the repeated measures designed as follows: spacing (two levels: large and small) and duration (three levels: 34, 68, and 116 msec).

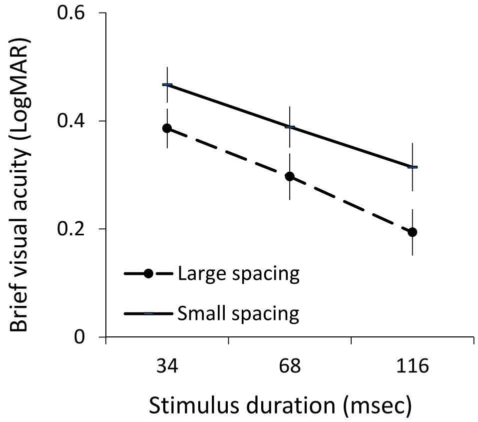

Figure 6. Control brief VA measurements with the reversed order of blocks. The threshold acuity before and after training, for the two spacing options are presented for 12 new subjects with a wide age and acuity range (age range 38–62 years, near VA 0.13 ± 0.04) who performed the eTest with a reversed order of blocks. Error bars = *SE*.

There was a significant effect of spacing, $F(1, 11) = 23.2$, $p = 0.001$, and duration, $F(2, 11) = 61.4$, $p < 0.001$, with no significant interaction. These results indicate that, despite the wide age and acuity range of the participants in this experiment (age range 38–62 years, near VA 0.13 ± 0.04), the main effect of presentation duration is not affected by the order of the blocks. The magnitude of the crowding effect is also unaffected by the order of the blocks. According to these results, we concluded that no significant fatigue confounded our experiments.

Discussion

Our aim was to explore how perceptual training affects crowded VA in the fovea under the conditions of different levels of blurring. To that end, brief VA was measured using very short presentations of crowded letter stimuli in people with different levels of natural blurring associated with uncorrected presbyopia—a potentially good model of blurred central vision, as in anisometropic amblyopia (Song et al., 2014).

Our results show that the crowding effect exists in the fovea. Improvements induced by perceptual learning regarding the detection of Gabor stimuli are transferred to the identification of crowded letters more pronouncedly for shorter presentation durations, along with a substantial improvement in the standard near VA measurements. In fact, crowded VA after training became similar to the uncrowded VA before training. We suggest that more efficient temporal and spatial processing following perceptual learning results in faster processing speed and in higher contrast sensitivity (Polat, 2009). These low-level changes compensate for the adverse effects of natural blurring on crowded acuity and the bottleneck it creates on the visual processing. Specifically, as suggested earlier, since crowding creates a bottleneck for the cortical processing during reading (Levi, 2008) and thus limits it (Pelli et al., 2007), we suggest that the resulting improvements provide the grounds for improving complex higher-level visual functions, such as reading and, possibly, object recognition in general. Contrasting amblyopia, in which the input is normal whereas the neural processing is deficient, this study was conducted under the assumption that in uncorrected presbyopia the processing is relatively normal, whereas the retinal input is blurred.

The observed pattern of results allowed us to propose that uncorrected presbyopia, with an acuity range that becomes very wide with brief presentations, may serve as a good model for exploring the effects of blurring on crowding, in addition to a recently proposed model of artificial optical blurring for anisometropic amblyopia (Song et al., 2014). Moreover, foveal crowded acuity in participants with uncorrected presbyopia is affected to a greater extent: up to 0.58° for 34 msec at the acuity threshold, but 0.21° in young people for the same presentation duration in the current study, consistent with our earlier measurements (Lev, Yehezkel et al., 2014), indicating a much larger angular zone in which detection is susceptible to interference from other stimuli. Importantly, there was no change in the objective measurements of the required optical correction through the use of FCC, supporting our earlier findings of no changes in optics accompanying improved visual functions in presbyopes trained using a similar paradigm, such as depth of focus, accommodation, and pupil diameter, measured for both near and far viewing distances (Polat et al., 2012). Nevertheless, because many parameters may interact with the effects of blurring at a given spacing, both external (such as lighting conditions and contrast), and internal (such as pupil size, contrast sensitivity, and age), there is a need for systematic exploration in future studies.

Crowding in the fovea under blurring conditions

Our results indicate that crowding effects exist in the fovea of presbyopes at all stages and in young participants, in agreement with our recent results (Lev, Ludwig et al., 2014; Lev, Yehezkel et al., 2014). It has been shown earlier that the range of crowding is wider for shorter presentation times (Chung & Mansfield, 2009; Tripathy & Cavanagh, 2002; Tripathy, Cavanagh, & Bedell, 2014), although Song et al. (2014) found only weak effects of duration. We showed that the presentation time significantly affects crowded acuity, in agreement with our recent results (Lev, Ludwig et al., 2014; Lev, Yehezkel et al., 2014). To induce crowded VA, we have used spacing equal to that recently shown to constitute a constant factor of 1.4 between center-to-center spacing and the acuity of a single target (Song et al., 2014). Indeed, we found a significant crowding effect with this spacing, across a wide range of acuity levels. Note, however, that Song et al. (2014) define this separation as a minimal spacing that nearly eliminates the effect of the flankers, whereas others (e.g., Siderov et al., 2013) found maximal crowding at about one stroke width with high contrast. Moreover, the stimuli we used (5×5 tumbling E patterns) are more challenging than most typical crowding stimuli, and are closest to the S target in Flom et al. (1963). Finally, the contrast of the stimuli used in the current study is considerably lower than the 100% contrast usually used in crowding research, which may have affected the amount of crowding. However, there are studies showing either no effects (Siderov et al., 2013) or only limited effects of contrast (Song et al., 2014) or a saturation of these effects for contrasts above 20% (Coates et al., 2013). We therefore believe that the use of short presentation times and contrast that is substantially lower than 100% may have affected the observed crowding effect in the fovea.

Most interestingly, every group improves according to its baseline value, with the magnitude of learning serving as a constant proportion of the initial performance, in concert with the Weber-like law suggested earlier (Astle et al., 2013; Polat, 2008). Improvement in crowding was reported earlier in the periphery (Bernard et al., 2012; Chung, 2007, 2011; Maniglia et al., 2011); however, this is the first time that improvement under crowded conditions was found in large groups of participants, at several initial acuity levels, in the fovea.

Contrast sensitivity and processing speed

It was shown earlier that training on low-contrast stimuli improved contrast sensitivity (Polat, 2009; Polat et al., 2004; Zhou et al., 2006). However, the differential effect of presentation duration indicates that the improvement is not only due to improved sensitivity. On one hand, increasing sensitivity may increase neural processing speed (McDonnell, Lee, Spritzer, Lindblad, & Hays, 2003). On the other hand, it is also possible that the training regimen, involving both very short presentations and backward masking, increases the processing speed directly. Support for this comes from earlier reports of training on backward masking, resulting in a reduction of 20 msec in the relevant event-related potentials (ERP) latency in the human visual cortex (Sterkin et al., 2012) and in shortened reaction times (Polat, 2009). Thus, taken together, training may improve both the sensitivity and processing speed (Lev, Ludwig et al., 2014; Polat et al., 2012) of the presbyopic visual system, either directly or as a secondary effect, in order to compensate for the blurred input.

Deblurring

It is known that presbyopes have lower contrast sensitivity (Polat, 2009; Polat et al., 2004). Watson and Ahumada (2011) concluded that blur detection and discrimination are instances of contrast detection, so it is not unreasonable to assume that, when we improve contrast detection through perceptual learning (Lev, Ludwig et al., 2014; Polat et al., 2004; Polat, Ma-Naim, & Spierer, 2009; Polat et al., 2012; Sterkin et al., 2012), we also improve the ability to detect and discriminate between blurred images. Our results show the remarkable ability of the brain to increase the efficiency of neural processing in order to perform deblurring of highly blurred images in order to retrieve the information. This could be achieved by increasing the sensitivity or gain of neurons by a factor that enables image processing at very low signal-to-noise levels with efficiency similar to processing at normal signal-to-noise levels. Support for this possibility was found in the improved contrast discrimination and sensitivity of presbyopes so that, following training, they approach the level of the young group (Polat et al., 2012). Here, the same increase in sensitivity, eventually resulting in improved acuity, is applicable as a possible mechanism for transferring the training effects to identify crowded letters. Importantly, an earlier study showed that the effect of crowding disappears when an artificial blur is applied (Simmers et al., 1999). This result may be due to (a) a different mechanism of processing an artificial versus a natural blur, (b) changes resulting in a different point spread function, or (c) a different adaptation time constant. It is still under debate, however, how the contrast reduction accompanying blurring can be accommodated (Watson & Ahumada, 2011), how crowding is affected by decreased contrast, and whether deblurring is related to a change in the perceived contrast. It is widely acknowledged that at or near the resolution threshold, a decrease in size, contrast, luminance, or viewing time usually alters the function of the visual system, which results in impaired resolution. Therefore, it is possible that the physical contrast of the letters used in the current study (which is considerably above the detection threshold though still lower than 100%, which is usually used in crowding research), may have affected the amount of crowding. We also noted a considerable difference in the magnitude of the resulting improvement in crowded acuity between groups. Across presentation durations, it is about 40% for the young participants, compatible with the reported ratio; however, it is nearly 20% for the early presbyopic group and even lower (although not significantly) for the advanced presbyopic group. This therefore suggests that natural blurring can account for these differences.

Uncertainty

As in any perceptual learning study, one can also raise the possibility that the effects of training may be accounted for by a reduction of uncertainty. However, we have supporting evidence from our previous studies and the current study, both showing that improved uncertainty alone cannot account for the improvements: (a) there was no improvement in the test–retest control groups, despite the fact that the training groups performed the eTest only before and after training, resulting in the same degree of familiarity with the task; (b) there were improvements in tasks that do not include preceding fixation, such as in static visual acuity measured using a standard ETDRS chart, shown both here and in our earlier study (Polat et al., 2012), and in the MNREAD chart (Subramanian & Pardhan, 2006), also shown in our earlier study (Polat et al., 2012); (c) there was no improvement following training on "irrelevant" tasks (i.e., noncollinear flankers), shown in control participants in our earlier amblyopia study with a similar training protocol (Polat et al., 2004).

Summary

In summary, our findings suggest that more efficient temporal and spatial processing following perceptual learning allows one to compensate for the adverse effects of natural blurring on crowded acuity in the fovea. We also suggest that the naturally induced blurring in uncorrected presbyopia with a wide range of acuity may serve as a good model for researching the effects of blurring on crowding. Moreover, the effects in the young participants suggest that perceptual learning may lead to improved vision despite the best measurable chart acuity observed using standard measurements. Consistent with a recent study (Lev & Polat, 2014) showing a high correlation between spatial and temporal masking and crowding, our current results show that the benefits of training under the conditions of spatiotemporal masking of Gabor targets are generalized into an improved crowded acuity. Finally, the observed improvements provide the grounds for improving complex visual functions, such as reading and, possibly, object recognition in general.

Keywords: crowding, crowded conditions, visual acuity, presbyopia, reading, perceptual learning

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