Crowding is proportional to visual acuity in young and aging eyes

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Spatial crowding decreases object recognition and conscious visual perception in clutter. In a previous study we used brief presentation times to reveal the effects of a crowded presentation in the fovea. Here we aimed to test the relationships between varying visual acuity (VA) and crowding in the fovea, under the assumption that in uncorrected presbyopia, the processing is relatively normal, whereas the retinal input is blurred. We tested whether normal participants whose near VA is gradually reduced due to age-related deterioration (presbyopia, or “aging eye”) will show an acuity-dependent increase in foveal crowding. We used brief presentations and acuity-threshold letter targets in order to magnify the crowding-effect amplitude in the fovea. A total of 195 participants with an age range of 20–68 years and an average of 44.3 ± 11.7 years (M ± SD) were divided into four age groups, all without any optical correction for the near distance. Our findings show that crowding is proportional to VA. This proportionality is affected by VA-age dependency, with a nonlinear S-shaped pattern: A steep VA reduction begins to develop, which is compatible with the normal onset age of presbyopia symptoms and a saturation in the VA-age dependency in the oldest age group, for which we propose a VA-eccentricity account. Finally, there is a high variance in the crowding amplitude in the young, even before the onset age of presbyopia symptoms, suggesting crowding conditions with limited presentation times as a highly sensitive measure of VA, which predicts visual performance in complex tasks, such as reading.

Introduction

Crowding effect in the fovea

Spatial crowding decreases object recognition and conscious visual perception in clutter (Levi, 2008; Pelli, Palomares, & Majaj, 2004; Whitney & Levi, 2011). It was widely acknowledged and demonstrated in a wide variety of tasks and stimulus types, and most commonly found in the periphery of normally sighted people or in the fovea of people with strabismic amblyopia (Bonneh, Sagi, & Polat, 2007; Flom, Weymouth, & Kahneman, 1963; Levi, Klein, & Chen, 2008; Whitney & Levi, 2011). Crowding occurs in a wide variety of tasks, including letter recognition (Bouma, 1971; Flom et al., 1963; Toet & Levi, 1992), Vernier acuity (Levi, Klein, & Aitsebaomo, 1985; Westheimer, 1975), orientation discrimination (Andriessen & Bouma, 1976; Livne & Sagi, 2007, 2010, 2011; Westheimer, 1976), stereoaucuity (Butler & Westheimer, 1978), contrast discrimination (Saarela, Sayim, Westheimer, & Herzog, 2009), face recognition (Louie, Bressler, & Whitney, 2007; Martelli, Majaj, & Pelli, 2005), and grouping (Manassi, Sayim, & Herzog, 2012, 2013), but mostly in the periphery (for a review, see Levi, 2008). The same phenomenon was also termed “contour interaction” in classical studies (e.g., Flom et al., 1963,
although the term “crowding effect” was originally introduced in Ehlers, 1936). A reduction in letter acuity, when presented among other letters, is also termed “flanked acuity” (e.g., Song, Levi, & Pelli, 2014). Here we use the term “crowded acuity” and explore how crowded visual acuity (VA) for a fixed spacing is related to acuity, as opposed to many studies that have focused on the experimental question of the critical spacing dependency on acuity (Chung, Levi, & Legge, 2001; Danilova & Bondarko, 2007; Hariharan, Levi, & Klein, 2005; Pelli et al., 2004; Tripathy & Cavanagh, 2002).

The classical study of Flom et al. (1963) found that the extent of crowding was limited to only a few minutes of arc and 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. However, in the periphery of normally sighted people and in the central visual field of amblyopes, larger receptive fields are engaged. This results in a higher minimal angle of resolution or lower VA. This assumed shift from small to large receptive fields is commonly known as the “scale shift” hypothesis (Levi & Waugh, 1994; Levi, Waugh, & Beard, 1994). The results of Levi, Klein, and Hariharan (2002) suggested that the extent of spatial interactions in fovea should be proportional to the size of the target, whereas Chung et al. (2011) found a much larger extent of crowding (about 0.5°). However, although scaling and the extent of crowding is currently controversial, due to the differences in paradigms in between studies, it became challenging to provide a unified framework for the crowding effect itself. For instance, one such difference is the use of static presentations (e.g., Flom et al., 1963; Siderov, Waugh, & Bedell, 2013), as opposed to limited presentations (e.g., Danilova & Bondarko, 2007; Lev, Yehezkel, & Polat, 2014; Levi & Carney, 2011; Strasburger, Harvey, & Rentschler, 1991). Another difference lies in using large (one-letter) target–flanker spacing (e.g., Strasburger et al., 1991), as opposed to small (less than a half-letter) spacing (e.g., Lev, Yehezkel et al., 2014; Simmers, Gray, McGraw, & Winn, 1999), resulting in different crowding effects for otherwise similar parameters. The flanking stimuli themselves are also not consistent between studies, that is, flanking bars (e.g., Siderov et al., 2013), as opposed to letters (e.g., Bonneh, Sagi, & Polat, 2004, 2007; Danilova & Bondarko, 2007; Lev, Yehezkel et al., 2014), as well as the spacing calculation, that is, center-to-center separation measurements (e.g., Levi & Carney, 2011; Pelli et al., 2004) as opposed to edge-to-edge spacing (e.g., Danilova & Bondarko, 2007). Consequently, conclusions regarding target–flanker critical spacing dependency on the target size are controversial.

Contrast has also been proposed to affect crowding (e.g., Coates & Levi, 2014; Hariharan et al., 2005; Levi et al., 2002; Simmers et al., 1999; Strasburger et al., 1991; but see Coates, Chin, & Chung, 2013; Siderov, Waugh, & Bedell, 2013, 2014; Strasburger & Malania, 2013). The effects of contrast on crowding provide the context for the effects of blurring on crowding, given a contrast reduction associated with natural blurring in presbyopia (Polat, 2009; Polat et al., 2012) and anisometropic amblyopia (McKee, Levi, & Movshon, 2003; Polat, Ma-Naim, Belkin, & Sagi, 2004).

Recently robust evidence for crowding in the fovea of normally sighted people was presented, both in young people and in people with presbyopia, using letter stimuli (Lev, Yehezkel et al., 2014). A classical study by Flom et al. (1963) suggested that crowding is scaled according to VA. In that study, participants with decreased VA due to anisometropic amblyopia showed proportionally more crowding in the fovea, an effect that was formulated as the scale shift hypothesis, and it extended to the fovea (Levi & Carney, 2011; Levi et al., 1985; Levi & Waugh, 1994; Levi et al., 1994). However, the crowding effect found in the fovea is low for targets larger than 0.2° (amplitude of 0.5), increasing substantially for smaller targets. This is much lower compared with the periphery and the amblyopic eyes of most strabismic amblyopes, showing a profound crowding-effect amplitude (>2; Levi & Carney, 2011).

Uncorrected presbyopia under crowded conditions

Presbyopia (“aging eye”) results mainly from the gradual decrease in focusing power during normal aging (Koretz, Kaufman, Neider, & Goeckner, 1989). Uncorrected presbyopia results in reduced near VA and reduced contrast sensitivity (Holden et al., 2008; Polat, 2009; Polat et al., 2012). Blurred input, and the associated reduction in contrast, may result in weaker and slower neuronal responses in the visual cortex, leading to reduced reading abilities (Polat, 2009). In our recent study, we showed reduced performance under crowded conditions in the uncorrected presbyopic fovea (Lev, Yehezkel et al., 2014). Thus, here we used uncorrected presbyopia as a model for exploring the effects of blurring on crowded acuity.

Aims and key findings

In our previous study 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.
Here, using a similar parameter manipulation, we aimed to test the relationships between varying VA and crowding in the fovea. In contrast to amblyopia, where 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. Our hypothesis was that age would affect crowding via an acuity-dependent mechanism.

Our findings show that crowding is proportional to VA. This proportionality is affected by VA-age dependency, which demonstrates a nonlinear S-shaped pattern: A steep VA reduction begins to develop, which is compatible with the normal onset age of presbyopia symptoms and a saturation in the VA-age dependency in the oldest age group, for which we propose a VA-eccentricity account. Finally, there is a high variance in the crowding amplitude in the young, even before the onset age of presbyopia symptoms, supporting our hypothesis that crowding conditions in combination with a limited exposure to a stimulus is a highly sensitive measure of VA, predictive of visual performance in complex tasks, such as reading.

**Methods**

**Participants**

A total of 195 participants with an age range of 20 to 68 years and an average of $44.3 \pm 11.7$ years ($M \pm SD$) were divided into four age groups (Table 1).

<table>
<thead>
<tr>
<th>Age group</th>
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<th>Age average and $SD$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20–30</td>
<td>34</td>
<td>$25.01 \pm 3.64$</td>
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<tr>
<td>31–40</td>
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<td>41–50</td>
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<td>51+</td>
<td>59</td>
<td>$56.35 \pm 4.60$</td>
</tr>
</tbody>
</table>

**Near ETDRS chart**

All near-acuity measurements were made without any optical correction for the near distance. Standard-static near VA was measured with a near-ETDRS chart (Precision Vision) from 40 cm, fixated 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).

**Brief VA: Apparatus**

Stimuli were displayed on color screens of mobile iOS devices (iPhone/iPod 4, iPhone/iPod 5) with a refresh rate of 60 Hz. The effective screen resolution was $640 \times 640$ pixels (5 cm in diameter), with a pixel size of 0.078 mm (retina display), which corresponds to VA of $-0.18$ logMAR.

**Brief VA: Stimuli**

The experiments were performed using a commercially available mobile software (GlassesOff™, New York, NY). All subjects were examined by a certified optometrist and their VA was measured using an ETDRS chart. Most of the subjects performed the experiment on lab devices; all of the subjects performed the experiment under supervised conditions, while the device was held by hand at a distance of 40 cm. The mean display luminance was set to the maximal level ($120$ cd/m$^2$) in an otherwise dark environment. All the iOS devices had the same pixel size to ensure that all VA measurements were made using the same screen resolution, regardless of the device type. The “E” shapes were created using high-precision graphics in a pixel-by-pixel manner, starting from the smallest stimulus size of $5 \times 5$ pixels and using a five-pixel step between each consecutive stimulus size (the minimal possible step for an E shape).

The stimuli consisted of $5 \times 5$ “Tumbling-E” patterns (Figure 1) presented at the fovea, at the fixation location in the center of the display, for brief durations of 34 (two frames), 68 (four frames), and 116 (seven frames) ms. VA was assessed using brief presentations under crowded conditions (eTest, provided by GlassesOff, Inc.; Lev, Yehezkel et al., 2014). Two different interletter spacing options were used: (a) one-letter edge-to-edge spacing (Figure 1a, top panels), which was shown in our earlier study to result in a pattern of results similar to isolated letter stimulation (hereafter referred to as “large spacing”), and (b) 0.4 edge-to-edge letter spacing (Figure 1a, bottom panels; hereafter referred to as “small spacing”), which was shown to produce maximal impairment of the target in both normally sighted and amblyopic participants (Flom et al., 1963; Simmers et al., 1999); this 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).

Figure 1. Stimuli and paradigm. (a) “Tumbling E” patterns with one-letter (large) spacing (upper panel) and 0.4-letter (small) spacing (bottom panel), 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, which disappeared when the participants initiated the trial by pressing anywhere on the touchscreen, after which a blank screen appeared for 300 ms, followed by the stimulus presentation. (c) The strong correlation ($R = 0.9$) between ETDRS chart measurement and the brief presentation (eTest) acuity measurements in the 238-ms presentation duration block with large spacing. Each data point is a subject. Line is a linear trendline. 0 logMAR is 20/20 vision.

**Brief VA: Paradigm**

A four forced-choice paradigm was used in which the subjects were asked to detect whether the open side of the central letter E faced right, left, up, or down; the subjects answered by pressing the touchscreen. The
patterns were black on a gray background. A visible fixation circle appeared in the center of the screen (thus directing the subject’s attention to the target’s location in the fovea) before each trial, which disappeared when the participants initiated the trial by pressing the touchscreen, after which a blank screen (i.e., only the gray background) appeared for 300 ms, followed by stimulus presentation (Figure 1b). Subjects were informed of wrong and correct answers by auditory feedback after each presentation throughout the experiment. The stimuli were viewed binocularly.

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). Each block measured the minimal detectable target size for a single duration and spacing using a staircase method, which is an adaptive procedure in which the pattern size and spacing were modified according to performance (chance level of 25%; the size increased for each mistake and decreased for two correct responses in a row). The number of size reversals (change from increase to decrease or vice versa) within each block was counted, and the block was terminated after eight such reversals. Threshold size of a block was the geometric average of the last six reversals (the first two were ignored). Staircase could be also terminated if performance appeared to asymptote (with a lower asymptote value of −0.18 logMAR for six correct responses in a row. A minimum of eight consecutive wrong responses from the beginning of the block is required to achieve the upper asymptote size, with an upper asymptote value of 1.06 logMAR that terminates the staircase after the first wrong response at this acuity level.

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-ms large spacing, 116-ms small spacing, 116-ms large spacing, 68-ms small spacing, 68-ms large spacing, 34-ms small spacing, and 34-ms large spacing. The resulting minimal discriminable target size was converted to logMAR units for each block. We used brief presentations because vision is limited by the temporal window created by the involuntary eye movements (saccades) occurring every 200–250 ms, even for static visual input. Moreover, in the younger people, our previous studies have shown a floor effect of VA for longer durations; therefore, brief durations were necessary to overcome this limitation. The contrast was 29% (Weber contrast). The test lasted up to 15 min, including breaks that were allowed at any point.

There is a high and significant correlation ($R = 0.9$, $p < 0.001$) between ETDRS chart measurements and the brief presentation (eTest) acuity measurements in the 238-ms presentation duration block. Each data point represents a subject. (Figure 1c).

### Control brief-VA measurement 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-ms large spacing (which served as practice), 34-ms large spacing, 34-ms small spacing, 68-ms large spacing, 68-ms small spacing, 116-ms large spacing, and 116-ms small spacing.

### Data analysis

An 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 are significant with an a priori Bonferroni correction. The $F$ test two sample for variances (Analysis tool pack, Excel 2013) was used to perform a two-sample $F$ test to compare two population variances in order to compare the effects of age and stimulus duration on data distribution. A two-tailed $p$ value is calculated to conclude whether the distributions are significantly affected. The acuity–age relationship was fitted using the cumulative distribution function (CDF):

$$f(x; \mu, \sigma) = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{x - \mu}{\sigma \sqrt{2}} \right) \right]$$

where $\mu$ is the mean and $\sigma$ is its standard deviation.

### Results

All acuity measurements and training sessions were conducted without near optical corrections. In addition the standard clinical near-VA measurements using the ETDRS chart, VA was measured using brief presentation under crowded conditions (eTest), with two interletter spacing: (a) one-letter (large) spacing, 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 (small) spacing, which was shown to produce maximal impairment of the target in both normally sighted 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). Figure 2 shows the eTest individual measurements for each presentation duration, for the small (y-axis) versus the large (x-axis) spacing, showing a high and significant correlation between the two measurements ($R = 0.96$, $p < 0.001$, and slope = 0.91 for 116-ms duration; $R = 0.96$, $p < 0.001$, and slope = 0.9 for 68-ms duration; $R = 0.96$, $p < 0.001$, and slope = 0.9 for 34-ms duration).

To test for the differential effects of spacing and presentation duration in different age groups, an ANOVA was performed, with the repeated measures designed as follows: spacing (two levels: large and small), duration (three levels: 34, 68, and 116 ms) with a factor of the group (four levels: 20–30, 31–40, 41–50, and 51 years and older). There were significant main effects of group, $F(3, 191) = 118.2$, $p < 0.001$, spacing, $F(1, 191) = 635.6$, $p < 0.001$, and duration, $F(2, 191) = 326.6$, $p < 0.001$, with a significant interaction between group and spacing, $F(3, 191) = 11.7$, $p < 0.001$, and between group and duration, $F(6, 191) = 2.3$, $p < 0.034$. There is a clear, highly significant crowding effect for all stimulus durations, measured as a significant decrease in VA values for small compared to larger spacing (for pairwise comparison $p$ values, see Table 2, first row). Moreover, VA is differently affected by increasing age (more profoundly for measurements with shorter stimulus presentation).

As expected, VA is reduced with age (McDonnell, Lee, Spritzer, Lindblad, & Hays, 2003). Figure 3 shows the eTest individual measurements for each presentation duration, as a function of age, with a nonlinear fit (see Data analysis for details). The results show an overall S-shaped pattern with a shallow slope for the youngest and the oldest age groups and a steep slope in the middle-aged participants. There is a change of about 0.1 logMAR in the VA with increasing age between the two younger groups. However, compatible with the normal onset age of presbyopia symptoms (41 years old; McDonnell et al., 2003), there is a much steeper reduction in VA of up to 0.3 logMAR as a function of age in the middle-aged participants (41–50 years old) compared to younger ones, for both spacings. Finally, there is a change of about 0.2 logMAR in the VA-age dependency between the oldest age group and the middle-aged. Figure 4a and b summarizes the averaged data per age group and illustrates the significant spacing-group and duration-group interactions (for $p$ values, see Tables 2 and 3).

The proportionality between the uncrowded and crowded acuity is evident at all ages, which remains constant in all age groups except from the oldest, perhaps due to a VA-eccentricity account suggested in the Discussion. A robust and significant decrease in the amplitude of the crowding effect is evident between the 30–40 and the 41–50 age group, consistent with the onset age of presbyopia (McDonnell et al., 2003; Figure 4c; for $p$ values, see Table 4). It is also clearly seen that within-group variance is higher under more challenging conditions (small spacing and shorter presentations).

The analysis of variances ($F$ test; see Methods for details) shows a significantly noisier distribution for the stimulus duration of 34 ms compared to 116 ms for small spacing, in the two youngest age groups ($p = 0.01$.)
and 0.03, for the 20–30 and the 31–40 age groups, respectively; *F* test), with no difference in the distribution in the older age group or for large spacing. This pattern of results suggests that before the common onset age of presbyopia, the larger variance in brief VA indicates that crowding conditions in combination with limited exposure to stimulus is a highly sensitive measure of functional VA.

Control brief-VA measurement 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 5). An ANOVA was performed, with the repeated measures designed as follows: spacing (two levels: large and small) and duration (three levels: 34, 68, and 116 ms). 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 test the relationships between varying VA and crowding in the fovea. To that end, we used incrementally decreasing presentation times and small targets that help reveal the effects of a crowded

<table>
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<tr>
<th>Age group</th>
<th>34 ms</th>
<th>68 ms</th>
<th>116 ms</th>
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<td>20–30</td>
<td>7E-08</td>
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<tr>
<td>31–40</td>
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<tr>
<td>41–50</td>
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<td>51+</td>
<td>8E-15</td>
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</tr>
</tbody>
</table>

Table 2. The *p* values of the paired *t* test for the effect of letter spacing on VA for different stimulus durations. Notes: VA was compared for large (one-letter) versus small (0.4-letter) spacing, using three stimulus durations: 34, 68, and 116 ms within each of the four age groups.

Figure 3. VA-age dependency and crowding effect. The decrease in VA as a function of age is plotted for uncrowded (using one-letter large spacing) and crowded (using 0.4-letter small spacing) acuity for the presentation durations of (a) 34, (b) 68, and (c) 116 ms. Each data point is a subject. Lines are nonlinear fit resulting in the overall S-shaped pattern (see Data analysis for details). *R*² for the fits are (a) 0.47 and 0.69, for uncrowded and crowded acuity, respectfully; (b) 0.55 and 0.49, for uncrowded and crowded acuity, respectfully; (c) 0.54 and 0.48, for uncrowded and crowded acuity, respectfully.
presentation in the fovea, effects that are not evident for longer presentation times and larger targets. The data support the study’s predictions. Our findings clearly show that crowding is proportional to VA. This proportionality is affected by VA-age dependency, which demonstrates a nonlinear S-shaped pattern: A steep VA reduction begins to develop, which is compatible with the normal onset age of presbyopia symptoms and a saturation in the VA-age dependency in the oldest age group, for which we propose a VA-eccentricity account. Finally, there is a high variance in the crowding amplitude in the young, even before the onset age of presbyopia symptoms, showing already profound VA reductions in some of them, yet affecting their age peers to a much lesser extent. This supports our hypothesis that crowding conditions in combination with limited exposure to a stimulus is a highly sensitive measure of VA, which can predict visual performance in complex tasks, such as reading.

Reading is the best example of a complex task that is central to everyday life and is limited by crowding (Legge, Mansfield, & Chung, 2001; Levi, 2008; Pelli & Tillman, 2008; Pelli et al., 2007). According to our VA measurements, using brief stimuli and crowded conditions, one ETDRS chart letter (0.02 logMAR) per year (or one chart line in 5 years) is lost from as early as the age of 30, due to normal aging. It has been shown earlier in a study of far VA with a compatible number of young participants (Elliot, Yang, & Whitaker, 1995) that logMAR measurements reveal acuities better than 0 logMAR. It is also noteworthy that previous studies reported that near VA is slightly worse than far visual acuity (Dong, Hawkins, & Marsh, 2002; Giese, 1946; Lev, Ludwig et al., 2014). Still, in concert with the findings of Elliot and his colleagues (1995), our eTest measurements also achieve VA better than 0 logMAR in the young participants, with only one of the 34 participants of the youngest age group reaching the lower asymptote level of −0.18 logMAR, thus supporting the reliability of our measurements.

**VA-eccentricity account**

The proportionality between the uncrowded and crowded acuity remains constant in all age groups except from the oldest. We suggest that the size of the target at detection threshold itself acts as the limiting factor. Figure 6 illustrates the VA-eccentricity rela-

<table>
<thead>
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<th>Age groups</th>
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<th>68 ms</th>
<th>116 ms</th>
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<tbody>
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<td>41–50 vs. 51+</td>
<td>0.510</td>
<td>0.300</td>
<td>0.820</td>
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</table>

Table 4. The p values of the t test for the crowding effect between age groups for different stimulus durations. Notes: The crowding effect was compared for pairs of consecutive age groups, using three stimulus durations: 34, 68, and 116 ms.
tionship for four sample acuities. For the acuity corresponding to the age range of 20 to 40 (before the onset of presbyopia), both the target stimulus and the flankers fall inside the foveola (corresponding to approximately 1/8 of the center of the visual field), which is responsible for the highest VA (Bishop, 1987; Curcio, Sloan, Kalina, & Hendrickson, 1990; McDonnell, 1989). However, for the acuity corresponding to the age above 51 (0.6 log units), the flankers with the small 0.4-letter spacing are already at its border, whereas for the large one-letter spacing, the flankers fall outside the foveola. It is widely acknowledged that there is a different scaling factor and range of spatial interactions for stimuli within the foveola as opposed to outside the foveola, with an expected difference in the crowding effect for fixed spacing (Levi, 2008; Pelli & Tillman, 2008). For instance, the VA is halved at 1° eccentricity (Levi et al., 1985; Oyster, 1999), whereas a reduced collinear facilitation at eccentricities as small as 1°–2° was shown (Shani & Sagi, 2005). Therefore, for the acuity of 0.6 logMAR, the one-letter spacing that does not produce crowding in the younger subjects and therefore was termed here “uncrowded” acuity, may not be valid for the older subjects because even the large spacing may already produce a significant crowding effect compared to a single target presentation. This point therefore needs further systematic exploration. Moreover, interestingly, 0.6 logMar is the acuity of a normally sighted young subject at an eccentricity of 1°–2°, depending on the stimulus contrast (1° for 10% contrast and 2° for 45% contrast; Abdelnour & Kalloniatis, 2001). The same rules are applicable when relating to foveal acuity of anisometropic amblyopes (Bonneh et al., 2004). It is important that in presbyopia, in addition to the larger size of the target’s detection threshold, there is an additional significant factor of blurring that merits extensive systematic investigation, with combined controlled manipulation of artificial blurring and several different spacings.

Log units versus minimal visual angle

The important but largely untested principle—that acuity chart design should have letter spacing proportional to letter size in order to keep the effect of spatial interaction consistent across acuity levels (Levi & Carney, 2011)—actually interferes here with addressing the study question, which is the interaction of acuity and crowding. Figure 7 shows that there is an opposite pattern of the age effect on the difference between the threshold stimulus size under the crowded as compared with uncrowded conditions, when plotted proportionally to the actual stimulus size, in terms of visual angle. This is similar to the usual calculation used for stimuli other than log-based reading charts and is more relevant for analyzing the results in the context of the magnification factor associated with eccentricity. This analysis shows a 2.5-fold increase in crowding in the...
oldest age group compared with the age group 20–30 for longer stimulus durations and a two-fold increase for the shortest duration. These findings are also consistent with the classical study of Flom et al. (1963), suggesting that crowding is rescaled according to VA, an effect that was formulated as the scale shift hypothesis and was extended to the fovea of normally sighted people (Levi & Carney, 2011; Levi et al., 1985; Levi & Waugh, 1994; Levi et al., 1994). Although the ability to test this dependency on VA in the fovea of normally sighted participants was limited by the floor effect of VA in nonamblyopia participants, here, using small foveal targets and naturally varying VA in normally sighted (not amblyopic) participants due to normal aging, we have shown that the crowding effect measured in absolute values as opposed to log units is much more pronounced for larger letters (lower acuities), probably due to the engagement of scale factors and spatial interaction ranges that are different from those within the foveola.

Keywords: crowding, visual acuity, presbyopia, reading

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References


Training improves visual processing speed and generalizes to untrained functions. Scientific Reports, 4, 7251, doi:10.1038/srep07251.

Uncovering foveal crowding? Scientific Reports, 4, 4067, doi:10.1038/srep04067.


