Perceptual Learning in Children With Infantile Nystagmus: Effects on Reading Performance

Bianca Huurneman,1 F. Nienke Boonstra,1,2 and Jeroen Goossens1

1Radboud University Medical Centre, Donders Institute for Brain, Cognition and Behaviour, Cognitive Neuroscience Department, Nijmegen, The Netherlands
2Bartiméus, Institute for the Visually Impaired, Zeist, The Netherlands

Citation: Huurneman B, Boonstra FN, Goossens J. Perceptual learning in children with infantile nystagmus: effects on reading performance. Invest Ophthalmol Vis Sci. 2016;57:18; albinism: n = 8; idiopathic IN: n = 10) and an uncrowded training group (n = 17; albinism: n = 9; idiopathic IN: n = 8). Also 11 children with normal vision participated. Outcome measures were: reading acuity (the smallest readable font size), maximum reading speed, critical print size (font size below which reading is suboptimal), and acuity reserve (difference between reading acuity and critical print size). We used multiple regression analyses to test if these reading parameters were related to the children’s uncrowded distance acuity and/or crowding scores.

RESULTS. Reading acuity and critical print size were 0.65 ± 0.04 and 0.69 ± 0.08 log units larger for children with IN than for children with normal vision. Maximum reading speed and acuity reserve did not differ between these groups. After training, reading acuity improved by 0.12 ± 0.02 logMAR and critical print size improved by 0.11 ± 0.04 logMAR in both IN training groups. The changes in reading acuity, critical print size, and acuity reserve of children with IN were tightly related to changes in their uncrowded distance acuity and the changes in magnitude and extent of crowding.

CONCLUSIONS. Our findings are the first to show that visual acuity is not the only factor that restricts reading in children with IN, but that crowding also limits their reading performance. By targeting both of these spatial bottlenecks in children with IN, our perceptual learning paradigms significantly improved their reading acuity and critical print size. This shows that perceptual learning can effectively transfer to reading.

Keywords: reading, visual acuity, children’s vision, congenital nystagmus

Infantile nystagmus (IN) is characterized by involuntary, bilateral oscillations of the eyes that are present from birth or the first 6 months of life.1 Visual acuity is approximately 0.3 logMAR or better in most subjects with IN without an afferent visual defect (also called idiopathic IN), and varies from 0 to 1.3 logMAR in subjects with albinism, a condition that is almost invariably linked to IN.2–4 Little is known about reading in children with IN. In adults with IN, reading acuity, the smallest readable font size and critical print size (the font size below which reading speed is suboptimal) are poorer than in normal controls.5–7 Nonetheless, maximum reading speed can be near normal in adults with IN if font size is not restricting reading speed.5,8 The difference between reading acuity and critical print size (acuity reserve) is often larger in adults with IN than in normal controls, indicating that adults with IN require font sizes much larger than their reading acuity to achieve optimum reading speeds.5,6,8 One explanation for the need for large fonts, might be that adults with IN have to rely on nonfoveating periods of their nystagmus waveform to read.7 Another explanation might be that crowding, the inability to identify objects in clutter, impairs reading of small print and peripheral reading by interfering with individual letter recognition and interfering with word identification.9–11 Increased crowding and contour interaction have been reported in subjects with IN.12–16

Recently, we developed a training paradigm that improves visual acuity and reduces crowding in children with IN.17 The 2-fold aim of the present study was to compare baseline reading performance of those children with the age-matched controls with normal vision, and to assess training-induced changes in their reading performance. Our participant group of children with IN consisted of children with idiopathic IN and children with albinism accompanied by IN.

Previous studies have demonstrated that reading performance can be improved by perceptual learning,18–20 which refers to a long-term performance increase resulting from perceptual experience.21 The reading measure that is improved by perceptual learning depends on the paradigm used. Visual span training, which aims to increase the number of letters that can be read without moving the eyes (visual span) by training several locations in the visual field, can increase maximum reading speed by an impressive 41%.18 Reading training also
seems effective at improving maximum reading speed and reading acuity, but not critical print size in adults with central vision loss. By contrast, crowded letter training does not improve maximum reading speed, but does improve critical print size, indicating that adult observers can read smaller print with higher reading speed after training. To evoke more generalized learning, we designed a training task that combines two approaches: identifying a letter at the acuity threshold, and execution of a goal-directed saccade toward the crowded letter under time constraints. Children performed the training with either a crowded near-threshold acuity letter (crowded training), or an uncrowded near-acuity threshold letter (uncrowded training). Although training did not alter the nystagmus characteristics of children with IN, both the crowded and uncrowded training-induced improvements in crowded acuity are evident.

To evoked more generalized learning, we designed a training task that combines two approaches: identifying a letter at the acuity threshold, and execution of a goal-directed saccade toward the crowded letter under time constraints. Children performed the training with either a crowded near-threshold acuity letter (crowded training), or an uncrowded near-acuity threshold letter (uncrowded training). Although training did not alter the nystagmus characteristics of children with IN, both the crowded and uncrowded training-induced improvements in crowded acuity are evident.

**Methods**

**Participants**

The present study presents reading data from 35 from a total of 36 children with IN that were included in a companion paper, which quantifies the effects of perceptual learning on visual performance in children with IN. The children were divided into two training groups (based on age and diagnosis): a crowded training group ($n = 18$; albinism: $n = 8$, idiopathic IN: $n = 10$; age: $111 \pm 20$ months), and an uncrowded training group ($n = 18$; albinism: $n = 9$, idiopathic IN: $n = 8$; age $111 \pm 16$ months). Inclusion criteria for both training groups were age between 6 and 11 years, normal birth weight (>3000 g), birth at term (>36 weeks), no perinatal complications and normal development, no additional impairments, distance visual acuity (DVA) between 1.3 logMAR and 0.2 logMAR, and IN (for clinical characteristics of the subjects, see Ref. 17). One 6-year-old child with albinism had to be excluded here because he could not yet read the sentences. Reference data were collected from an age-matched group of 11 untrained children with normal vision (age 100 $\pm$ 16 months). Children with prescription glasses wore them during the measurements and training sessions.

Informed consent was obtained from the parents of all participating children. The study was approved by the local ethics committee and conducted according to the principles of the Declaration of Helsinki.

**Ophthalmological Examination**

At the start of the study, all children underwent an ophthalmological examination that included a distance and a near visual acuity measurement (see Ref. 17 for methodological details). In short, DVA was measured mono- and binocularly at 40 cm for all children, the pixel pitch of our monitor was too coarse to guarantee sufficient image quality at this distance for fine resolution measurements in crowded and uncrowded visual acuity. Only the crowded training induced a decrease of the crowding intensity at near, whereas the uncrowded training did not affect crowding intensity. Based on the relation between visual acuity and reading acuity, we therefore expected that the training would also improve their reading acuity. We also hypothesized that, besides visual acuity, crowding might be an important bottleneck in their reading performance. Because it has been suggested that crowding may limit reading, we expected that children in the crowded training group would show larger improvements in reading performance than children in the uncrowded group.

**Reading Task**

Sentences of the Dutch reading chart LEOntientje were presented on a computer screen to assess reading performance (LE = Leestest Experimentelle Oogheelkunde Groningen). Sentences were composed of high-contrast black letters (0.3 cd/m²) presented on a white background (193.8 cd/m²; 99.7% Michelson contrast). Before sentences were presented, crowed DVA was entered as an initial estimation of reading acuity. A total of 10 words were presented in five font sizes ranging from 0 to 0.5 logMAR above the child’s crowded DVA. The minimum font size that was read correctly was identified as the reading acuity. Children then read 30 sentences out loud (typically seven words per sentence). Font size ranged from 0 to 0.75 logMAR above the children’s reading acuity with steps of 0.15 logMAR (five sentences for each size x six font sizes = 30 trials). A new trial was always preceded by the presence of a fixation cross that was presented at the center of the screen for 500 ms (Fig. 1A).

Four reading measures were extracted from our recordings. The first was reading acuity, which is the smallest font size (in logMAR) that children could read without making errors. The second measure was maximum reading speed, which was calculated by taking the average of the three fastest reading speeds (in words per minute). The third measure was critical print size, which refers to the smallest font size in logMAR that could be read at 80% of the maximum reading speed. Critical print size was estimated by linear interpolation between data points. The fourth measure was acuity reserve, which is the amount of enlargement above reading acuity that is needed to reach 80% of the maximum reading speed (i.e., the difference between reading acuity and critical print size).

Reading distance was 130 cm for children with crowded DVA of $\leq 0.7$ logMAR and 50 cm for children with crowded DVA poorer than 0.7 logMAR. Although we would have preferred a more typical reading distance of approximately 40 cm for all children, the pixel pitch of our monitor was too coarse to guarantee sufficient image quality at this distance for children with crowded DVA $< 0.7$ logMAR. A viewing distance of 50 cm was needed for children with poorer acuities, because the number of words on a line was restricted by the screen dimensions and font size. The focus of this study was on quantitative rather than qualitative aspects of reading. If children had difficulty reading the sentences, this resulted in poorer reading speed.

**Crowded Letter Task**

A crowded letter discrimination task was used to determine the crowding extent; that is, the spacing between target and flanker that a child needed to identify the target that was placed in the middle of a group of seven Landolt Cs rings at the left or right side of the screen (Fig. 1B, right). Crowding extent was expressed in logMAR. Stimuli were high-contrast black Landolt Cs (0.3 cd/m²) with four possible orientations on a white background (193.8 cd/m²). Children performed this task at the same distance as the reading task. Letter size was kept fixed at 0.15 log units above the subject’s uncrowded letter acuity. Center-to-center spacing of the target and flankers was varied to determine the 62.5% correct discrimination threshold (see Ref. 17 for details).

**Training**

The crowded training was similar to the crowded letter task except that target size and target-to-flanker spacing were
gradually reduced according to the child’s performance improvement (Fig. 1B, right). In the uncrowded training group, children worked with single Landolt Cs instead of letter groups, and letter size was the only variable that was adapted based on performance improvements (Fig. 1B, left). Each training session consisted of 350 trials. Children were trained two times per week during 5 consecutive weeks, making a grand total of 3500 trials per training. See Reference 17 for further details about the training protocol.

**Procedure**

At pretest, crowding extent was determined for all children and ophthalmological examinations were performed. In addition, the reading measures were collected. Subsequently, children with IN were trained for 5 weeks. Training started within 2 weeks after the pretest. Posttest performance measures were collected within 2 weeks after the last training session.

**Equipment**

Experimental measures were taken on a Dell M4700 laptop connected to a 32-inch ultrahigh density monitor (Dell UP3214Q, 3840 × 2160 pixels, pixel pitch: 0.18 mm²; Dell Inc., Round Rock, TX, USA). Training was executed on a Dell M3800 laptop (3200 × 1800 pixels; pixel pitch: 0.11 mm²). Stimulus software was written in MATLAB (version 2014b; MathWorks, Natick, MA, USA), using the Psychophysics Toolbox extension (version 3.0.12). 17

**Statistical Analysis**

Statistical analysis was done with SPSS (version 21.0; IBM SPSS Statistics, IBM Corporation, Chicago, IL, USA). Baseline reading measures were compared for children with albinism, children with idiopathic IN, and children with normal vision. Baseline equality of training groups was verified with an independent samples t-test. Training effects were evaluated with a repeated measures ANOVA with training group entered as the between subjects variable and pre- and posttest as the within subjects variable. Unless diagnosis (albinism with IN or idiopathic IN) was a significant factor, data from children with albinism and idiopathic IN were pooled. If not stated otherwise, PREPOST × training group interactions were absent.

A multiple linear regression analysis (enter-method) was used to test if the variability in baseline reading performance (reading acuity, maximum reading speed, critical print size, or acuity reserve) of children with IN could be explained by their uncrowded DVA (uDVA; determined from the C-test), crowding...
Perceptual Learning and Reading in Children With IN

IOVS | August 2016 | Vol. 57 | No. 10 | 4242

**Table 1.** Overview of Baseline Measures of Children With Albinism (Alb), Children With Idiopathic IN (IIN), and Children With Normal Vision (NV)

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>F</th>
<th>P</th>
<th>Post Hoc Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alb, n = 17</td>
<td>IIN, n = 18</td>
<td>NV, n = 11</td>
<td></td>
</tr>
<tr>
<td>Uncrowded DVA, logMAR</td>
<td>0.48 ± 0.31</td>
<td>0.25 ± 0.17</td>
<td>-0.23 ± 0.06</td>
<td>35.21</td>
</tr>
<tr>
<td>Crowded DVA, logMAR</td>
<td>0.67 ± 0.31</td>
<td>0.46 ± 0.16</td>
<td>-0.15 ± 0.07</td>
<td>48.95</td>
</tr>
<tr>
<td>Uncrowded NVA, logMAR</td>
<td>0.47 ± 0.30</td>
<td>0.17 ± 0.14</td>
<td>-0.20 ± 0.08</td>
<td>34.87</td>
</tr>
<tr>
<td>Crowded NVA, logMAR</td>
<td>0.60 ± 0.34</td>
<td>0.45 ± 0.15</td>
<td>-0.09 ± 0.07</td>
<td>37.71</td>
</tr>
<tr>
<td>Distance crowding intensity, logMAR</td>
<td>0.19 ± 0.08</td>
<td>0.21 ± 0.08</td>
<td>0.07 ± 0.03</td>
<td>12.34</td>
</tr>
<tr>
<td>Crowding extent, logMAR</td>
<td>1.17 ± 0.35</td>
<td>0.88 ± 0.23</td>
<td>0.44 ± 0.18</td>
<td>23.43</td>
</tr>
<tr>
<td>Reading Acuity, logMAR</td>
<td>0.71 ± 0.30</td>
<td>0.52 ± 0.17</td>
<td>-0.04 ± 0.07</td>
<td>42.25</td>
</tr>
<tr>
<td>Maximum reading speed, wpm</td>
<td>110 ± 36</td>
<td>101 ± 38</td>
<td>129 ± 19</td>
<td>2.31</td>
</tr>
<tr>
<td>Critical print size, logMAR</td>
<td>1.05 ± 0.27</td>
<td>0.90 ± 0.27</td>
<td>0.28 ± 0.21</td>
<td>31.23</td>
</tr>
<tr>
<td>Acuity reserve, logMAR</td>
<td>0.34 ± 0.22</td>
<td>0.39 ± 0.22</td>
<td>0.52 ± 0.16</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Children with albinism all had IN. Top rows list acuity and crowding measures. Bottom rows list reading measures. Analyses of variance were conducted to evaluate differences between groups (F-value, P-value, and post hoc pairwise comparisons between groups). n.s., not significant. * P < 0.05; ** P < 0.010; *** P < 0.001.

Both uncrowded DVA (partial \( r = 0.86, t = 9.55, P < 0.001 \)) and distance crowding intensity (partial \( r = 0.71, t = 5.68, P < 0.001 \)) made a unique contribution to the reading acuity variability in children with IN. Poorer DVA and higher distance crowding intensity were associated with poorer reading acuity.

**Maximum Reading Speed.** Consistent with research in adults,8 baseline maximum reading speed did not differ

---

**RESULTS**

**Baseline Reading Performance**

Table 1 presents the baseline differences among children with albinism, idiopathic IN, and normal vision. Figure 2 displays their mean reading speed as a function of font size. Table 2 compares the outcome measures for the two IN training groups. There were no significant baseline differences between the two training groups, but there were clear differences in reading performance of children with normal vision and children with IN. In children with IN, only reading acuity differed between children with idiopathic IN and children with albinism.

**Reading Acuity.** Reading acuity differed among the three groups (\( F_{3,45} = 42.25, P < 0.001 \), partial \( \eta^2 = 0.66 \); Table 1). Pairwise comparisons showed that children with albinism and idiopathic IN both had significantly poorer reading acuity than children with normal vision (\( P < 0.001 \)). Moreover, children with albinism had \( 0.20 \pm 0.07 \) log units poorer reading acuities than children with idiopathic IN (\( P < 0.05 \)). An impressive 89% of the variability in reading acuity in children with IN was accounted for by visual acuity, crowding intensity, and crowding extent (\( F_{5,31} = 86.61, P < 0.001 \)).

---

**Figure 2.** Baseline reading speed as a function of font size. Maximum reading speed of children with normal vision (NV) did not differ from those observed in children with idiopathic IN and albinism at baseline. Note the shape-resemblance of reading curves across groups. Error bars: ± 1 SEM.
between children with IN and children with normal vision \((F_{2,43} = 2.31, P = 0.111, \text{partial } \eta^2 = 0.10; \text{Fig. 2})\). Maximum reading speed was 129 ± 10 wpm in children with normal vision, 110 ± 8 in children with albinism, and 101 ± 8 wpm in children with idiopathic IN. The variability in maximum reading speed in children with IN could not be explained by our model \((P > 0.1)\), but note that maximum reading speed in children with IN was practically normal.

### Critical Print Size

Critical print size was 0.69 ± 0.09 logMAR larger in children with IN than in children with normal vision \((F_{2,43} = 31.23, P < 0.001, \text{partial } \eta^2 = 0.59; \text{Table 1})\). Critical print size did not differ between children with albinism and children with idiopathic IN \((P > 0.2)\). Forty-seven percent of the critical print size variability in children with IN was accounted for by our model \((F_{3,51} = 8.90, P < 0.001)\). Only crowding extent was a significant predictor of critical print size in children with IN \((\text{partial } r = 0.40, t = 2.41, P < 0.05)\). Children with a larger crowding extent typically needed a larger critical print size.

### Acuity Reserve

Acuity reserve did not differ among children with albinism, idiopathic IN, and normal vision \((F_{2,43} = 0.38, P = 0.688, \text{partial } \eta^2 = 0.02; \text{Table 1})\). The acuity reserve was 0.35 ± 0.06 log units for children with normal vision, 0.34 ± 0.05 log units for children with albinism, and 0.39 ± 0.04 log units for children with IN. Our regression model explained 31% of the variability in acuity reserve in children with IN \((F_{3,51} = 4.55, P = 0.010)\). Uncrowded DVA \((\text{partial } r = -0.54, t = -3.60, P = 0.001)\) and crowding extent \((\text{partial } r = 0.45, t = 2.80, P = 0.009)\) were both significant predictors of the acuity reserve. Children with poorer DVA and larger crowding extent needed more enlargement to reach 80% of their maximum reading speed.

### Reading Performance After Training

Figure 3 displays the pre- and posttraining reading speed as a function of font size for children with idiopathic IN (A) and albinism (B) in the crowded training group, and for children with idiopathic IN (C) and albinism in the uncrowded training group (D). Note that both the crowded and uncrowded training caused a significant shift of the reading-rate curves toward the left while the shape of the curves remained the same. This leftward shift indicates that training enabled children to read with smaller fonts at higher reading speed.

Training effects on all four reading performance measures were the same for children with albinism and idiopathic IN (all \(P < 0.3; \text{Fig. 3})\). We therefore pooled the results from children with albinism and idiopathic IN in the analyses below.

### Reading Acuity

Training improved the reading acuity in both the uncrowded and crowded training groups by 0.12 ± 0.02 logMAR \((F_{3,51} = 41.89, P < 0.001, \text{partial } \eta^2 = 0.58)\). Reading acuity changed from 0.62 ± 0.06 logMAR before to 0.48 ± 0.06 logMAR after training in the crowded training group, and from 0.61 ± 0.06 logMAR to 0.50 ± 0.06 logMAR in the uncrowded training group. There were two children without a posttest crowding extent value \((ID = 5 \text{ and ID} = 7)\). Our regression model with acuity and crowding predictors accounted for 46% of the variability in training-induced reading acuity changes \((F_{3,29} = 8.07, P < 0.001)\). Both improvements in uncrowded DVA \((\text{partial } r = 0.44, t = 2.64, P = 0.013)\) and decreases in distance crowding intensity \((\text{partial } r = 0.66, t = 4.67, P < 0.001)\) significantly accounted for improvements in reading acuity.

### Maximum Reading Speed

Training did not change maximum reading speed \((F_{3,51} = 0.2, P = 0.902, \text{partial } \eta^2 = 0.00; \text{Fig. 3})\). In the crowded training group, maximum reading speed was 100 ± 9 wpm before training and 111 ± 9 wpm after training under crowded conditions. In the uncrowded training group, children had a maximum reading speed of 112 ± 9 wpm before training and 111 ± 9 wpm after training. Variability in maximum reading speed changes could not be explained by our predictors \((P s > 0.9)\), but note that the average change in maximum reading speed was not significant to begin with.

### Critical Print Size

Critical print size was reduced by 0.11 ± 0.04 logMAR after training \((F_{3,51} = 7.13, P = 0.012, \text{partial } \eta^2 = 0.19)\). Children in the crowded training group showed an average critical print size of 0.98 ± 0.07 logMAR before training and 0.83 ± 0.07 logMAR after training. The critical print size of children in the uncrowded group changed from 0.98 ± 0.07 logMAR before to 0.92 ± 0.07 logMAR after training. Our model predicted 34% of the variability in critical print size changes \((F_{3,29} = 4.99, P = 0.007)\). Both improvements in uncrowded DVA \((\text{partial } r = -0.51, t = -3.22, P = 0.003)\) and decreases in crowding extent \((\text{partial } r = 0.42, t = 2.49, P = 0.019)\) were significant predictors of training-induced decreases in critical print size.

### Acuity Reserve

On average, training did not change the acuity reserve \((F_{3,51} = 0.19, P = 0.669, \text{partial } \eta^2 = 0.01)\). Even so, the variability in acuity reserve changes was significantly related to our model predictors \((F_{3,29} = 6.22, P = 0.002)\). A total of 39% of the variability in acuity reserve changes was accounted for by changes in uncrowded DVA \((\text{partial } r = -0.47, t = -4.24, P < 0.001)\), changes in distance crowding intensity \((\text{partial } r = -0.38, t = -2.21, P = 0.055)\), and changes in crowding extent \((\text{partial } r = 0.36, t = 2.09, P = 0.046)\). Note that a decrease in crowding extent was associated with a decrease in acuity reserve, while improvements in uncrowded

---

**Table 2. Overview of Pre-Post Measures in the Crowded and Uncrowded Training Groups**

<table>
<thead>
<tr>
<th></th>
<th>Crowded Training, ( n = 18 )</th>
<th>Uncrowded Training, ( n = 17 )</th>
<th>Baseline and Training Differences Crowded Versus Uncrowded Training</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td></td>
</tr>
<tr>
<td>Crowded DVA, logMAR</td>
<td>0.54 ± 0.28</td>
<td>0.44 ± 0.26</td>
<td>0.58 ± 0.26</td>
</tr>
<tr>
<td>Distance crowding intensity, logMAR</td>
<td>0.19 ± 0.07</td>
<td>0.17 ± 0.10</td>
<td>0.21 ± 0.09</td>
</tr>
<tr>
<td>Crowding extent, logMAR</td>
<td>0.96 ± 0.31</td>
<td>0.66 ± 0.32</td>
<td>1.08 ± 0.34</td>
</tr>
<tr>
<td>Reading acuity, logMAR</td>
<td>0.61 ± 0.28</td>
<td>0.47 ± 0.24</td>
<td>0.62 ± 0.24</td>
</tr>
<tr>
<td>Maximum reading speed, wpm</td>
<td>99 ± 43</td>
<td>100 ± 41</td>
<td>112 ± 30</td>
</tr>
<tr>
<td>Critical print size, logMAR</td>
<td>0.97 ± 0.29</td>
<td>0.82 ± 0.28</td>
<td>0.98 ± 0.27</td>
</tr>
<tr>
<td>Acuity reserve, logMAR</td>
<td>0.36 ± 0.22</td>
<td>0.36 ± 0.18</td>
<td>0.36 ± 0.22</td>
</tr>
</tbody>
</table>

n.s., not significant.
DVA and distance crowding intensity were associated with an increase in acuity reserve.

**DISCUSSION**

In this study, we report baseline differences in reading performance between children with IN and children with normal vision, and we demonstrate that the magnitude of the baseline reading impairment in children with IN is related to the magnitude of their visual acuity and crowding deficits. In addition, we show that a short period of perceptual learning improves two spatial aspects of reading performance, reading acuity and critical print size, in children with IN. We also find that these improvements are linked to acuity improvements and training-induced reductions of crowding.

**Baseline Differences in Reading Performance**

Only reading acuity and critical print size differed between children with IN and normal controls. This was to be expected, considering the poorer visual acuities in children with IN. Both reading acuity and critical print size are limited by the size of the area (of the visual field) in which stimulation leads to a response of a particular sensory neuron (i.e., the receptive field size). Receptive field sizes in the visual cortex can be restricted at the level of the retina, but can also be modulated at a cortical level by phenomena such as sensory suppression, which depends strongly on attention. In line with the logic that visual perception can be severely affected by competition between stimuli caused by the presence of distractors, uncrowded DVA was not the only predictor of reading acuity in children with IN (partial $r = 0.86$), but crowding intensity also accounted for part of the variability in reading acuity (partial $r = 0.71$). In adults with normal vision, crowding affects small print reading by interfering with both letter and word recognition. Crowding intensity predicted only reading acuity (partial $r = 0.71$), whereas crowding extent was a better predictor of critical print size (partial $r = 0.40$) and acuity reserve (partial $r = 0.45$) in children with IN. In sum, our findings suggest that crowding, in addition to visual acuity, is a significant factor degrading reading performance in children with IN.

We found no significant differences in maximum reading speed between children with IN and children with normal vision. This finding concurs with an earlier study that reported no differences in reading speed between adults with IN and healthy controls at a reading distance of 120 cm.8 Reading speed was lower in adults with IN than in adults with normal vision when viewing distance was 33 cm (see Ref. 8) or 40 cm (see Ref. 5), but we did not look at reading speeds for such near reading distances (see Methods). Nystagmus dampening at near has been reported in individuals with idiopathic IN when performing simple fixation stability or acuity tasks, but this dampening does not facilitate better task performance or better reading.8 Together, these findings suggest that dampening the nystagmus would probably not lead to better reading performance in children with IN, but that reducing crowding, a factor that predicts reading performance, does facilitate better reading performance.

**Training-Induced Improvements in Reading Performance**

As expected, our training resulted in improved reading acuity. In addition, improvements of critical print size were observed. Training-induced changes in uncrowded DVA, crowding intensity, and crowding extent were predictive of changes in

**FIGURE 3.** Effect of training on reading speed. After training, reading-speed curves shifted to the left in both the crowded training group (A, C) and the uncrowded training group (B, D), indicating that children with albinism and idiopathic IN in both training groups were able to read with smaller fonts and reached their optimum reading speed with smaller fonts. Error bars: ± 1 SEM.
three of four reading measures, suggesting that training-induced improvements in acuity and crowding effectively transferred to improvements in reading. Both uncrowded and crowded training improved reading performance, and our regression analyses suggest that this is not only due to the improvements in visual acuity, but also the result of reductions in crowding extent and intensity. Our results concur with those of a recent study that demonstrate that near-acuity letter training, either with or without flankers, results in improved visual acuity and reduced crowding in adults with amblyopia.30

Ten training sessions produced considerable improvements in spatial aspects of reading performance, indicating that children could read smaller print and do this at a higher reading speed than before training. Typical newsmprint size is approximately 0.5 logMAR and baseline critical print size was 0.90 to 1.05 logMAR for children with IN. Therefore, it should be said that for most children in this study, magnification of text is still needed after training to comfortably read newsmprint size. Longer training might result in more pronounced learning. Improvements of 0.2 to 0.4 logMAR lines have been reported in adults with amblyopia after 30 to 40 training sessions.30 It is unlikely that the improvements in reading acuity and critical print size are caused by experimenter bias or test-retest learning. For example, critical print size was determined by finding the font size at which children were reading at 80% of their maximum reading speed by interpolation. The experimenter could not have influenced this measure. Test-retest learning is also not likely to explain our results, because different sentences were used for pre- and posttest sessions. Although test-retest variability of the reading test we used is not known, test-retest variability for other comparable standardized reading tests is good.31,32

The successful transfer of perceptual learning to improvements in reading acuity and critical print size might be caused by the use of a combined training approach that involved learning to identify near-threshold acuity targets and, in addition, focused at improving visual processing speed. A well-documented restriction of perceptual learning is that training effects are often highly task-specific, and combined approaches should be used to evoke more generalized learning.33 Previously, a combined training approach proved to be successful at improving reading speed and reading acuity of adults with presbyopia, who show poorer baseline reading acuity at near and slower reading speed than healthy age-matched controls.34 Enhanced oculomotor control is probably not responsible for the reading acuity and critical print size improvements, because nystagmus parameters are poor predictors of reading performance3 and dampening the nystagmus does not facilitate better performance.29 In another article, we evaluated the oculomotor changes of our subjects after our training and did not find changes in their fixational eye movements and nystagmus characteristics, but did find faster saccade initiation.35 A probable candidate for the improvements of reading acuity and critical print size is better letter recognition due to enhanced sensory and/or attentional processing. Crowding is associated with enlarged responses in cortical areas V2 to V4,36,37 and perceptual learning can reduce the size of visual receptive fields.38 Our results support the hypothesis that enhanced sensory processing and attention are responsible for improved reading and vision in IN, because improvements in acuity and reductions in crowding were predictive of improvements in reading performance. Whether the training effects are long-lasting or not remains to be seen, but retention of perceptual learning is typically 80% to 90% after 12 months.30,39,40 Considering the positive impact of our training on reading performance and the probability of good retention, the training is likely to benefit the children in daily life.

**Conclusions**

We present evidence that spatial aspects of reading performance can be improved by crowded and uncrowded training in children with IN. Both our crowded and uncrowded training paradigm combined two approaches: near-acuity letter training and a visuomotor training. Multiple regression analysis showed that training-induced changes in uncrowded DVA and decreases in crowding intensity and extent were significant predictors of changes in spatial aspects of reading performance. Our findings thus demonstrate successful transfer of perceptual learning to improved reading acuity and critical print size, and show that our training ameliorates reading impairment in children with IN by improving visual acuity and reducing crowding.

**Acknowledgments**

The authors are grateful to the parents and children for their participation.

Supported by the ODAS Foundation and Landelijke Stichting voor Blinden en Slechtzienden (LSBS), which contributed through UitZicht, and Bartimeus Sonnenheerdt. The funding organizations had no role in the design or conduct of this research.

Disclosure: B. Huurneman, None; F.N. Boonstra, None; J. Goossens, None

**References**


7. Woo S, Bedell HE. Beating the beat: reading can be faster than the frequency of eye movements in persons with congenital nystagmus. *Optom Vis Sci.* 2006;83:559–571.


12. Huurneman B, Boonstra FN, Cox RF, Cillessen AH, van Rens G. A systematic review on ‘Foveal Crowding’ in visually impaired


