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Perceptual Learning in Children With Visual Impairment Improves Near Visual Acuity

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Purpose. This study investigated whether visual perceptual learning can improve near visual acuity and reduce foveal crowding effects in four- to nine-year-old children with visual impairment.

Methods. Participants were 45 children with visual impairment and 29 children with normal vision. Children with visual impairment were divided into three groups: a magnifier group ($n = 12$), a crowded perceptual learning group ($n = 18$), and an uncrowded perceptual learning group ($n = 15$). Children with normal vision also were divided in three groups, but were measured only at baseline. Dependent variables were single near visual acuity (NVA), crowded NVA, LH line 50% crowding NVA, number of trials, accuracy, performance time, amount of small errors, and amount of large errors. Children with visual impairment trained during six weeks, two times per week, for 30 minutes (12 training sessions).

Results. After training, children showed significant improvement of NVA in addition to specific improvements on the training task. The crowded perceptual learning group showed the largest acuity improvements (1.7 logMAR lines on the crowded chart, $P < 0.001$). Only the children in the crowded perceptual learning group showed improvements on all NVA charts.

Conclusions. Children with visual impairment benefit from perceptual training. While task-specific improvements were observed in all training groups, transfer to crowded NVA was largest in the crowded perceptual learning group. To our knowledge, this is the first study to provide evidence for the improvement of NVA by perceptual learning in children with visual impairment. (http://www.trialregister.nl number, NTR2537.)

Keywords: visual impairment, children's vision, perceptual learning, near visual acuity

Perceptual learning (PL) is considered to be any relatively permanent and consistent change in the perception of a stimulus array, following practice or experience with this array.[1,2] The first evidence that perceptual abilities can be improved by practice date back to the middle of the 19th century.[3] PL can improve a range of visual functions, including spatial resolution,[2] stereo acuity,[4] orientation discrimination,[5,6] motion direction,[7] contrast sensitivity,[8] texture perception,[9] and depth perception.[10] From a neuroscience perspective, it has been suggested that PL illustrates the remarkable capacity of early sensory cortex plasticity.[11] However, training effects also can transfer to untrained locations and orientations, suggesting a rule-based learning model in which higher-order processing areas learn the rules of reweighting V1 inputs through training.[12] Attention, mediated by higher-level visual areas, is thought to determine which representations in lower-level areas undergo plasticity and gates learning.[13] There are three general principles of PL for clinical application: practice must occur under conditions where performance is severely impaired with trial by trial feedback, a stopping rule must be

incorporated (at plateau performance), and stimuli and tasks must be interesting and engaging.[14] Finally, accurate refractive correction is essential before the commencement of PL, and the refraction should be reviewed regularly and refined during training.[14,15]

Techniques of PL have been evaluated in different patient populations, including those with amblyopia,[8,14] age-related macular degeneration (visual search,[16] reading speed[17–19]), visuospatial disorders after stroke (line orientation discrimination[20]), bilateral cortical blindness (visual field stimulation[21,22]), schizophrenia (motion perception[23]), low myopia and early presbyopia (visual acuity[24]), patients with hippocampal damage (face recognition[25]), and Parkinson's disease (artificial grammar and category learning[26]).

To our knowledge, PL has not yet been applied as a rehabilitation method for children with visual impairment (VI).[27] A VI during childhood obviously causes impoverished visual acuity and/or reduced contrast sensitivity. Recent research indicates that abnormal lower level visual processing influences mid-to-high level visual processes, such as visual

TABLE. Average Characteristics of Children With NV and VI

	NV						VI					
	4–6 y			7–9 y			4–6 y			7–9 y		
	M	PLc	PLu	M	PLc	PLu	M	PLc	PLu	M	PLc	PLu
N	5	6	4	4	4	6	7	11	7	5	7	8
Mean age	64.2	71.2	68.0	96.0	97.3	94.5	69.9	68.5	67.0	91.4	102.0	99.5
(SD)	(6.7)	(10.8)	(12.7)	(8.0)	(7.9)	(8.7)	(6.8)	(6.4)	(9.6)	(3.6)	(8.3)	(7.9)
Mean DVA	0.14	0.05	0.02	−0.08	−0.08	−0.07	0.84	0.80	0.70	0.66	0.66	0.63
(SD)	(0.16)	(0.11)	(0.10)	(0.05)	(0.05)	(0.05)	(0.18)	(0.23)	(0.37)	(0.13)	(0.30)	(0.18)

Age is presented in months and DVA is presented in logMAR notation for the crowded version of the C-test. Children with NV were not trained, but were measured with the training material at baseline. M, magnifier group.

search speed and accuracy,[16,28,29] peripheral crowding and motion processing,[28,30] and foveal crowding effects.[30] Explanations for slower visual search in children with VI are reduced foveal acuity, and the demands for attentional resources to attend to foveal information and reduced attention for peripheral stimuli,[28] or visuo-attentional impairments.[31] Little is known about rehabilitation outcomes in children with VI.[32] To fill this gap, we examined whether the development of (crowded) near visual acuity (NVA) can be stimulated and whether crowding effects can be reduced by PL, which seems to be an effective method to reduce foveal crowding in subjects with amblyopia.[27]

Three interventions were compared: a magnifier task in which children searched for a unique optotype in a row with distracters (experimental/crowded task), a PL task where crowding effects were evoked (experimental/crowded task, PLc), and a PL task in which optotypes were separated at such a distance that no contour interaction occurred (control/uncrowded task, PLu). Based on previous research by our group,[27,30,33] and by others, four hypotheses were formulated: children with VI have higher crowding ratios and poorer baseline performance on the training task than children with normal vision (NV); the PLc task is most effective in reducing crowding effects and improving NVA; task-specific learning effects and transfer to untrained visual functions, such as NVA, occur in all training groups; and improvements are larger for seven- to nine-year-old children than four- to six-year-old children, because focused attention is weaker in young children and functions as a gateway to ensure that PL occurs only in response to features to which attention is directed.[11]

METHODS

Participants

Participants were 45 children with VI and 29 children with NV. Inclusion criteria for both groups were age between four and nine years, and normal developmental level. Inclusion criteria for children with VI were distance visual acuity (DVA) between 20/400 and 20/40, normal birth weight (at least 3000 g), birth at term (at least 36 weeks), no perinatal complications, no additional impairments, and intact visual field. The Table presents the average age and DVA of the children with VI and with NV. Supplementary Material SA presents clinical diagnosis and characteristics of all children with VI.

Informed consent was obtained from the parents of all children after explanation of the nature and possible consequences of the study. The local ethics committee approved the study before the assessments were conducted (CMO Arnhem-Nijmegen, The Netherlands). The study was conducted in accordance with the tenets of the Declaration of Helsinki.

Ophthalmologic Examination

All children participated in an ophthalmologic exam before the start of the experiment. Visual acuity was measured mono- and binocularly on 5 meters (m) with the C-test[34,35] and at 6 m binocularly with the tumbling E-chart[36] under controlled lighting conditions. NVA was determined binocularly with the LH-version of the C-test[30] and the LH line 50% crowding chart[37] at 40 cm (distance was monitored carefully with a ruler). The LH-version of the C-test contains two chart versions with absolute spacing.[30] The crowded chart had an interoptotype spacing of 2.6 minutes of arc (′), and the single chart had an interoptotype spacing of $\geq 30'$ at 40 cm. The LH line 50% crowding chart contains interoptotype spacing that is 50% of the size of the optotype (therefore, 50% crowding chart). Children were asked to identify the first five symbols in a row, which were pointed out with a pencil, and could progress to the next line if they identified correctly three or more of the five symbols. If there were fewer than five symbols in a row, children could progress if they could identify correctly at least half of the symbols.

A gross estimation of the visual field was obtained by confrontational techniques. In case of retinal disease, children were tested on central or peripheral scotomas with dynamic perimetry (Goldmann). Of the 10 children with retinal diseases, nine had an intact visual field and one six-year-old girl with retinal dystrophy had a small concentric limitation of the left eye. No central scotomas were found and, therefore, we decided to include her in the study.

Objective refraction was obtained after cycloplegia and, if necessary, spectacle correction was prescribed or changed before the experiment and training period started.

Training Paradigms

Two experimental training paradigms and one control training were developed. The training paradigms were inspired by the Eriksen flanker task.[38] The training groups were matched with respect to age and DVA (see Table).

The first experimental training was a visual search training in which the child had to follow the trail of inversed E's in a 145×145 mm grid (Fig. 1A). At baseline, this grid consisted of symbols of 7.0 mm. Edge-to-edge optotype spacing was fixed at 0.3 mm (0.04° at 40 cm; consistent with spacing of the crowded chart of the C-test). A smiley was placed at the beginning of the trail. To make the training easier for the children, we let the children draw the trail. The children had to start and end at the smiley, and by doing this they drew a figure. All children started working with optotypes sized 4 M (1.0 logMAR at 40 cm/7.0 mm) at the first training session and could progress to 2 M (0.5 logMAR at 40 cm/3.5 mm), and subsequently 1 M (0.25 logMAR at 40 cm/1.75 mm) if they
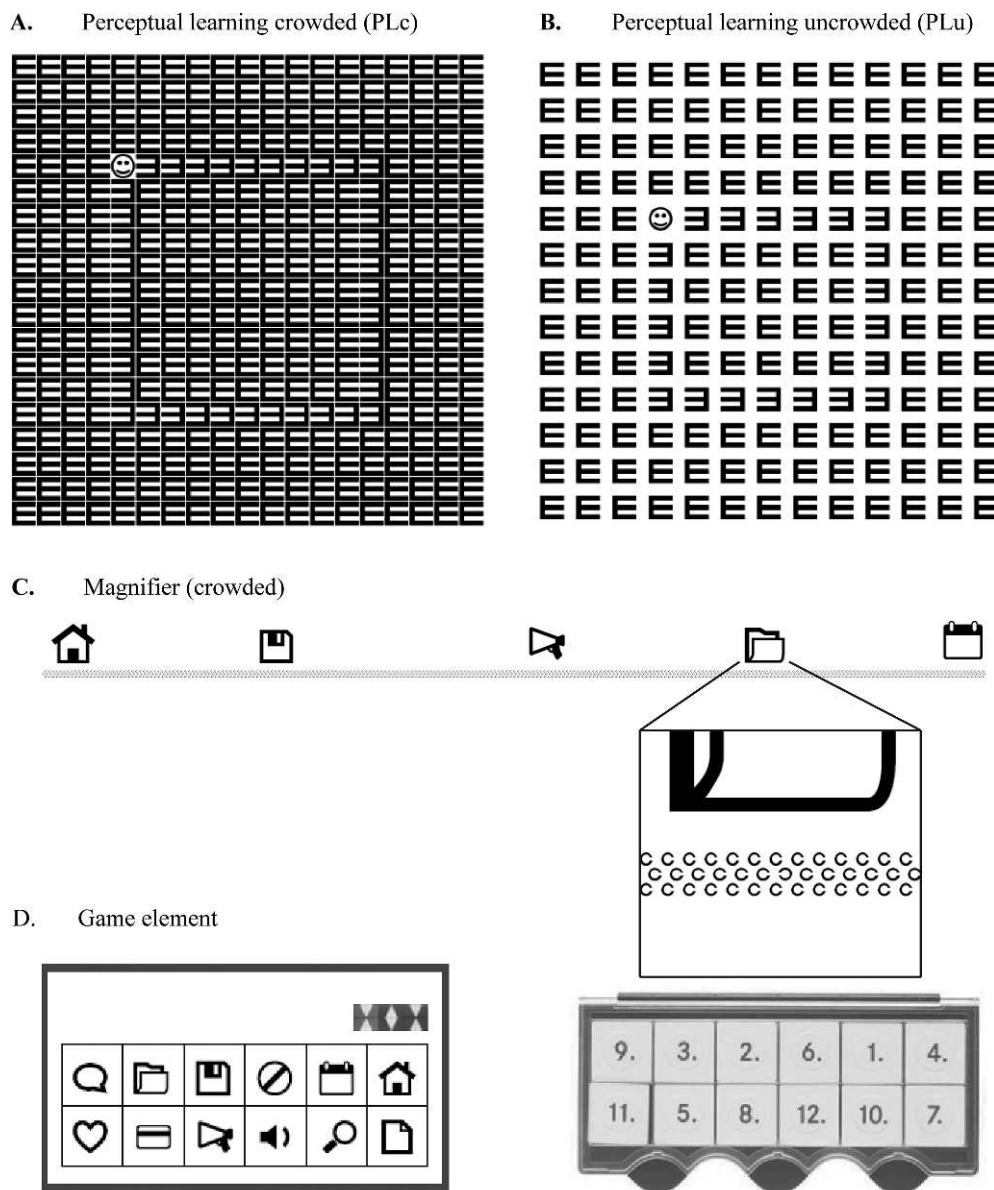
A. Perceptual learning crowded (PLc)

B. Perceptual learning uncrowded (PLu)

C. Magnifier (crowded)

D. Game element

FIGURE 1. (**A**) An example of a stimulus used for the PLc training. The child must search the smiley first and draw a line over the trail of the inversed Es. Consequently, a figure is drawn and this is the answer (*square*). (**B**) Represents the uncrowded version of this task (serving as a control task by not inducing contour interaction). (**C**) Presents an example of stimulus in the magnifier task. The child must search for the inversed Landolt C in a crowded search strip and uses an electronic magnifier while searching for the inversed optotype. (**D**) Presents an example of the game element. The correct answer is the paper map.

could draw a figure without making errors and could complete 12 trials in a 30-minute training session (see Supplementary Material SB). The control training consisted of exactly the same game, but with a fixed edge-to-edge spacing of 3.6 mm (0.52° at 40 cm, consistent with spacing of the single chart of the C-test, Fig. 1B). On average, children started to work with 2 M optotypes after three weeks and with 1 M optotypes after four weeks of training (progress was the same for the PLc and PLu training groups).

The second experimental training paradigm was a crowded magnifier training. This training was developed, because recent studies have demonstrated that children profit from a magnifier training.[39] The magnifier group trained with different material due to practical issues that disabled us from using the same design as the PL groups: the stimulus would be highly unattractive and children could not

draw a line while using the magnifier. We created a 191 mm array containing three rows with Landolt C's sized 0.32 M (−0.1 logMAR at 40 cm/0.5 mm) with an edge-to-edge element spacing of 0.3 mm. Children had to search for the inversed Landolt C in this row with an electronic handheld magnifier, with a display size of 3.5 inches, providing ×8 magnification (Fig. 1C).

A game element was incorporated for each of these training paradigms to provide feedback and to make the training engaging. Each training session consisted of 12 trials. Answer options were combined with tiles that the child could place on one of 12 answer boxes. If all tiles were placed correctly, they formed a pattern matching the pattern in the upper right corner of the page (Fig. 1D). During the training sessions, children could adopt a self-chosen distance.
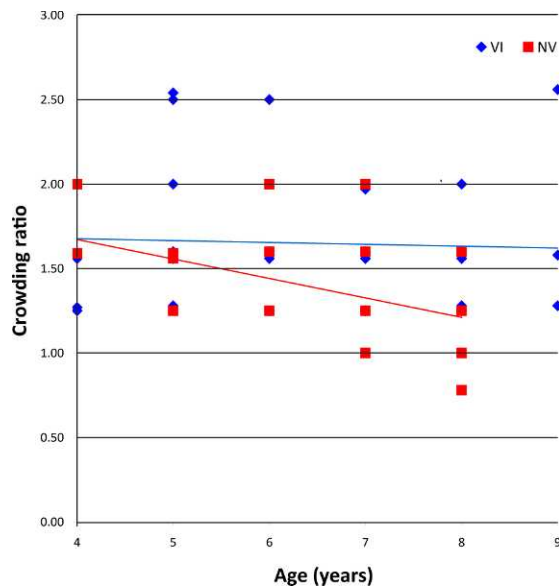
FIGURE 2. Crowding ratios for the children with NV and with VI as a function of age. Children with VI show higher crowding ratios than children with NV at baseline.

Procedure

At baseline, NVA and performance on the training task were measured. Children with NV were seen once as a reference group at baseline. For children with VI, this baseline performance counted as their pretest score.

Training started within two weeks after the pretest. During the training period, children with VI were seen twice a week for a period of six weeks (12 training sessions). Each training session consisted of 30 minutes of practice on the training task. Trainers visited children at their schools.

Within two weeks after the last training session, children performed the posttest. The posttest measurement consisted of the same measures as the pretest.

Statistical Analysis

There were seven main outcome measures. With regards to visual functions, there were two outcome measures: binocular NVA with the LH-version of the C-test (single and crowded NVA)[28] and the LH line 50% crowding chart,[35] and the crowding ratio (single NVA/crowded NVA).[30] Performance on the training task was captured in five parameters: the number of trials (no time limit), accuracy (number of correct trials [tiles placed correctly]/total number of trials), performance time, and (only for the PL tasks), number of small errors (incorrectly drawing one noninversed E), and number of large errors (incorrectly drawing >1 noninversed E).

First, baseline performance for crowding ratios and training task measures were compared between children with NV and children with VI with a univariate ANOVA. Age category (4-6 vs. 7-9 years), group (NV or VI), and training group (magnifier, PLc, and PLu) were the independent variables.

The differences between pretest and posttest performance of children with VI was measured with a repeated measures ANOVA. Age category and training group were the independent variables. Separate post hoc ANOVAs were run using Bonferroni statistics to disentangle interaction effects (significance level, $\alpha = 0.05$).

RESULTS

Group Differences at Baseline

There were six children with VI and one child with NV who were unable to perform the training task at baseline. As a result, we had a smaller sample size for four training task measures: accuracy, performance time, and small and large errors for these children.

Crowding Ratio. Children with NV had a lower crowding ratio (1.42) than children with VI (1.66); $F(1, 62) = 7.81$, $P = 0.007$, partial $\eta^2 = 0.11$ (Fig. 2). Age categories and training groups did not differ ($P > 0.07$). No interaction effects were found.

Number of Trials. There were no group or training group differences ($P > 0.07$). Age categories differed in the number of trials: four- to six-year-olds executed less trials (7.1) than seven- to nine-year-olds (11.8); $F(1, 62) = 33.68$, $P < 0.001$, $\eta^2 = 0.35$. No interaction effects were found.

Accuracy. There were no group differences in accuracy; $F(1, 55) = 0.29$, $P = 0.595$, partial $\eta^2 = 0.01$. Age categories differed: four- to six-year-old children were less accurate (76.4%) than seven- to nine-year-old children (90.6%); $F(1, 55) = 6.19$, $P = 0.016$, partial $\eta^2 = 0.10$. Training groups also differed: Children were more accurate in the magnifier group (98.3%) than in the PLc and PLu group (74.7% and 77.6%, respectively); $F(2, 55) = 6.37$, $P = 0.003$, partial $\eta^2 = 0.19$. No interaction effects were found.

Performance Time. There were no differences between the NV and VI group or training group differences ($P > 0.27$). Age categories differed: four- to six-year-olds were slower (72.1 s) than seven- to nine-year-olds (52.6 s); $F(1, 55) = 7.32$, $P = 0.009$, $\eta^2 = 0.12$. No interaction effects were found.

Small Errors. Groups, age categories, and training groups did not differ ($P > 0.55$). No interaction effects were found.

Large Errors. Groups differed: Children with VI made more large errors (0.66) than children with NV (0.28 errors); $F(1, 39) = 5.26$, $P = 0.027$, partial $\eta^2 = 0.12$. Age categories and training groups did not differ (P values > 0.37). No interaction effects were found.

Crowding Training: Children With VI

Preliminary linear regression analysis showed that the improvement in single and crowded NVA after training could not be predicted by the child characteristics of age (months), single NVA at baseline, sex, or pathology (retinal, iris, nystagmus, or lens); $F(4, 40) = 0.08$, $P = 0.989$, and $F(4, 40) = 0.99$, $P = 0.425$, respectively. There was no difference in NVA improvement between children with and without nystagmus (single NVA, $P = 0.91$; crowded NVA, $P = 0.57$; LH line 50% crowding, $P = 0.34$; crowding ratio, $P = 0.60$).

Single NVA. Children showed improved single NVA after training; $F(1, 39) = 31.43$, $P < 0.001$, partial $\eta^2 = 0.45$ (Fig. 3A). Average acuity was 0.54 logMAR (SE = 0.04) at pretest and 0.41 logMAR (SE = 0.05) at posttest. Training groups showed no difference in the amount of improvement; $F(2, 39) = 0.63$, $P = 0.536$, partial $\eta^2 = 0.03$, nor did age categories; $F(1, 39) = 0.38$, $P = 0.539$, partial $\eta^2 = 0.01$. Thus, single NVA improved for both age categories and all training groups. No interaction effects were found.

Crowded NVA. There was a pre-post × training group interaction effect; $F(2, 39) = 3.93$, $P = 0.028$, partial $\eta^2 = 0.17$. In the magnifier group, crowded NVA did not improve; $F(1, 10) = 1.89$, $P = 0.200$, partial $\eta^2 = 0.16$. There was no pre-post × age interaction; $F(1, 10) = 3.53$, $P = 0.090$, partial $\eta^2 = 0.26$. Crowded NVA did not improve for children in the magnifier group (Figs. 3B, 3C).
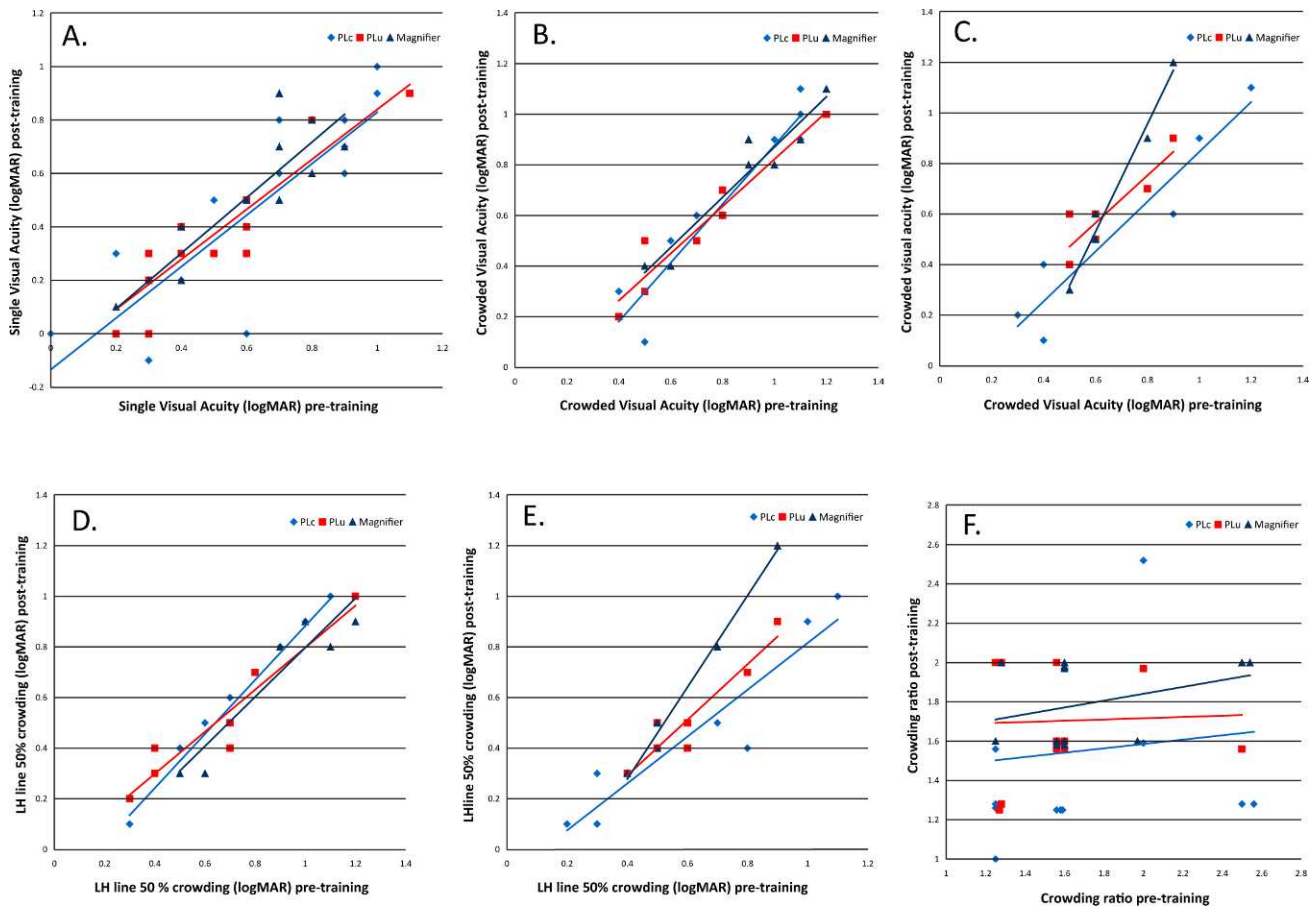
FIGURE 3. (A) Presents the single NVA chart pre- and posttraining. (B) Pretraining and posttraining crowded NVA for four- to six-year-olds. (C) Pretraining and posttraining crowded NVA for the seven- to nine-year-olds. (D) Pretraining and posttraining LH line 50% crowding NVA for the four- to six-year-olds. (E) Pretraining and posttraining LH line 50% crowding NVA for the seven- to nine-year-olds. (F) The crowding ratios pre- and posttraining.

In the PLc group, there was an improvement of crowded NVA in both age categories; $F(1, 16) = 33.60$, $P < 0.001$, partial $\eta^2 = 0.68$. Crowded NVA was 0.76 logMAR (SE = 0.07) at pretest and 0.59 logMAR at posttest (SE = 0.08). There was no pre–post × age interaction; $F(1, 16) = 0.28$, $P = 0.603$, partial $\eta^2 = 0.02$ (Figs. 3B, 3C).

In the PLu group, there was a pre–post × age interaction; $F(1, 13) = 9.15$, $P = 0.010$, partial $\eta^2 = 0.41$. For the four- to six-year-old children, crowded NVA improved; $F(1, 6) = 27.92$, $P = 0.002$, partial $\eta^2 = 0.82$ (Fig. 3B). Crowded NVA was 0.70 logMAR (SE = 0.10) at pretest and 0.54 logMAR (SE = 0.10) at the posttest. For the seven- to nine-year-olds, crowded NVA did not improve; $F(1, 7) = 2.03$, $P = 0.197$, partial $\eta^2 = 0.23$ (Fig. 3C). Thus, the PLc group was the only training group that showed a significant improvement in crowded NVA for both age categories. The magnifier group showed no progress in crowded NVA and only the four- to six-year-olds in de PLu group showed improved crowded NVA.

LH Line 50% Crowding. There was a three-way pre–post × age category × training interaction; $F(2, 39) = 5.85$, $P = 0.006$, partial $\eta^2 = 0.23$. In the magnifier group, there was a pre–post × age interaction; $F(1, 10) = 9.77$, $P = 0.011$, partial $\eta^2 = 0.49$. The LH line 50% crowding NVA of four- to six-year-olds improved; $F(1, 6) = 28.00$, $P = 0.002$, partial $\eta^2 = 0.82$ (Fig. 3D). LH line 50% crowding NVA was 0.89 logMAR at pretest and 0.69 logMAR at posttest. The seven- to nine-year-olds showed no improvement; $F(1, 4) = 0.286$, $P = 0.621$, partial $\eta^2 = 0.07$

(Fig. 3E), indicating an age-specific effect of the magnifier training.

In the PLc group, LH line 50% crowding NVA improved; $F(1, 16) = 41.35$, $P < 0.001$, partial $\eta^2 = 0.72$. LH line 50% crowding NVA was 0.67 logMAR ($SE = 0.07$) at pretest and 0.53 logMAR ($SE = 0.07$) at posttest. There was no pretest × age interaction; $F(1, 16) = 0.21$, $P = 0.655$, partial $\eta^2 = 0.01$ (Figs. 3D, 3E). Similar to the crowded NVA, both age categories benefitted from the PLc training.

In the PLu group, LH line 50% crowding NVA also improved; $F(1, 13) = 29.98$, $P < 0.001$, partial $\eta^2 = 0.70$. There was no pretest × age interaction; $F(1, 13) = 1.73$, $P = 0.211$, partial $\eta^2 = 0.12$. LH line 50% crowding NVA was 0.63 logMAR (SE = 0.06) at pretest and 0.51 logMAR (SE = 0.06) at posttest (Figs. 3D, 3E). LH line 50% crowding NVA improved for both age categories. The two PL groups showed improved LH line 50% crowding NVA for both age categories, and the magnifier group showed improvements for the four- to six-year-olds.

Crowding Ratio. Crowding ratios did not change after training; $F(1, 39) = 0.04$, $P = 0.835$, partial $\eta^2 = 0.00$. Training groups did not differ; $F(2, 39) = 1.05$, $P = 0.359$, partial $\eta^2 = 0.05$, nor did age categories; $F(1, 39) = 0.76$, $P = 0.389$, partial $\eta^2 = 0.02$ (Fig. 3F). No interaction effects were found. Although crowding ratios did not change at group level, eight of 18 children in the PLc group showed a reduction of the crowding ratio, as did two of 12 children in the magnifier group, and only
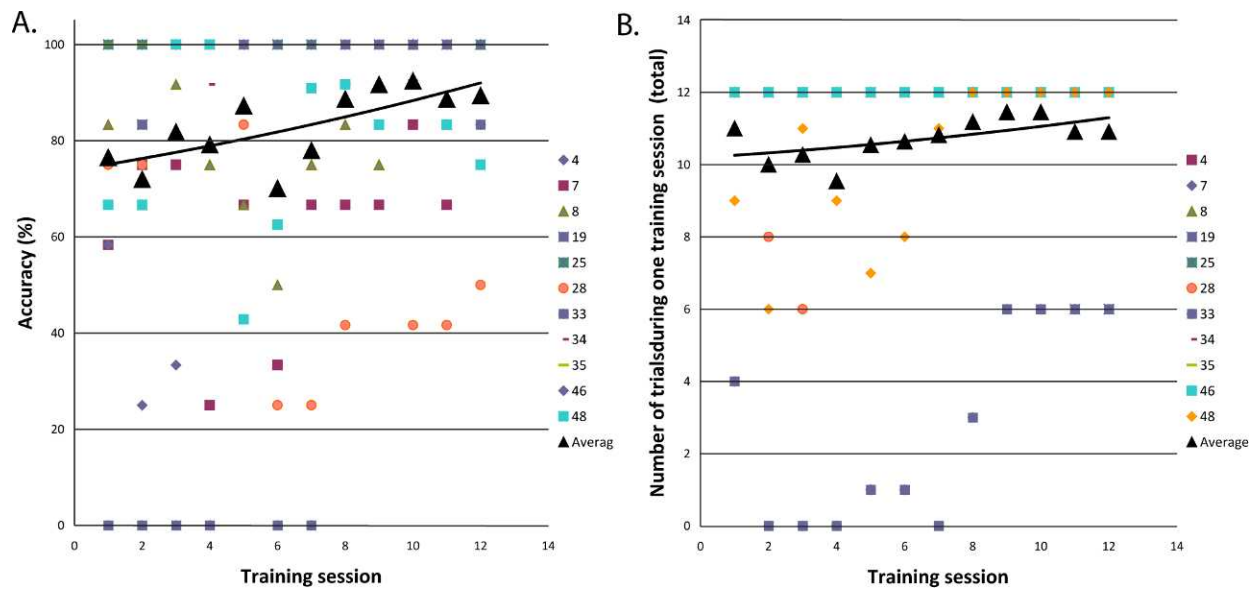
FIGURE 4. (A) Presents accuracy and (B) presents number of trials for four- to six-year-old children in the PLc group as a function of training session.

one of 15 children in the PLu group. Thus, crowding ratios did not change after training.

Performance on Training Task

Number of Trials. There was a pre–post × age interaction; $F(2, 39) = 25.66$, $P < 0.001$, partial $\eta^2 = 0.40$. The four- to six-year-olds completed more trials at posttest; $F(1, 22) = 37.32$, $P < 0.001$, partial $\eta^2 = 0.63$. Children completed 5.8 trials (SE = 1.00) at pretest and 11.7 (SE = 0.20) at the posttest (for examples of progress during training, see Figs. 4A, 4B). There was no pre–post × training interaction; $F(2, 22) = 0.57$, $P = 0.571$, partial $\eta^2 = 0.05$. All four- to six-year-olds showed an increase of the number of trials performed. The seven- to nine-year-old children did not perform more trials during the posttest; $F(1, 17) = 1.74$, $P = 0.204$, partial $\eta^2 = 0.09$. Children completed 11.7 trials (SE = 0.2) at pretest and 12.0 trials (SE = 0.0) at posttest. There was no pre–post × training interaction; $F(2, 17) = 0.61$, $P = 0.554$, partial $\eta^2 = 0.07$. Thus, only the four- to six-year-olds completed significantly more trials after training.

Accuracy. Accuracy improved after training; $F(1, 33) = 15.60$, $P < 0.001$, partial $\eta^2 = 0.32$. Accuracy was 85.1% (SE = 3.4%) at pretest and 98.7% (SE = 0.7%) at posttest. There were no differences in amount of improvement between training groups; $F(2, 33) = 2.40$, $P = 0.107$, partial $\eta^2 = 0.13$, or between age groups; $F(2, 33) = 2.50$, $P = 0.123$, partial $\eta^2 = 0.07$. No interaction effects were found.

Performance Time. Performance time decreased after training; $F(1, 33) = 119.58$, $P < 0.001$, partial $\eta^2 = 0.78$. Performance time was 65.2 seconds (SE = 4.7 seconds) at pretest and 17.9 seconds (SE = 1.6 seconds) at posttest. There was no difference between training groups; $F(2, 33) = 0.13$, $P = 0.878$, partial $\eta^2 = 0.01$, or age; $F(1, 33) = 2.82$, $P = 0.103$, partial $\eta^2 = 0.08$. No interaction effects were found. All training groups showed a shorter performance time after training.

Small Errors. Small errors decreased after training; $F(1, 24) = 5.85$, $P = 0.023$, partial $\eta^2 = 0.20$. Children made 0.45 errors (SE = 0.08) at pretest and 0.25 errors (SE = 0.05) at posttest (Fig. 5A). There was no difference between training groups; $F(1, 24) = 0.06$, $P = 0.812$, partial $\eta^2 = 0.00$, or age categories; $F(1, 24) = 0.02$, $P = 0.894$, partial $\eta^2 = 0.00$. No

interaction effects were found. All training groups showed a decrease of small errors after training.

Large Errors. Large errors also decreased after training; $F(1, 24) = 14.22$, $P = 0.001$, partial $\eta^2 = 0.37$. Children made 0.66 (SE = 0.13) large errors at pretest and 0.16 (SE = 0.03) errors at posttest (Fig. 5B). There was no difference between training groups; $F(1, 24) = 0.86$, $P = 0.362$, partial $\eta^2 = 0.04$, or age categories; $F(1, 24) = 1.43$, $P = 0.243$, partial $\eta^2 = 0.06$. No interaction effects were found. As for the number of small errors, all training groups showed a decrease of large errors after training.

DISCUSSION

Our study compared the effectiveness of three training paradigms to reduce crowding effects and improve NVA in children with VI. Four hypotheses were evaluated: Children with VI show a higher crowding ratio and poorer baseline performance on the training task than children with NV; the experimental PL task is most effective in reducing crowding effects and improving NVA; task-specific learning effects and transfer to untrained visual functions, such as NVA, occur in all training groups (generalization of learning effect); and improvements are larger for seven- to nine-year-old children than four- to six-year-old children.

Baseline Group Differences

Our first hypothesis was confirmed. Children with VI showed a higher baseline crowding ratio than children with NV. This replicated our earlier study with comparable children.[30] The children with VI also showed poorer performance on the training task in terms of the number of large errors. Children were wandering more and often "lost track." This is in line with an earlier study, showing selective attention impairments in children with VI.[31] This behavior cannot be explained by poor acuity, because children could approach the material and optotypes were large enough to guarantee visibility (1.0 logMAR at 40 cm/7.0 mm). No group differences were found in number of trials performed, accuracy, performance time, and small errors. The baseline group differences in crowding
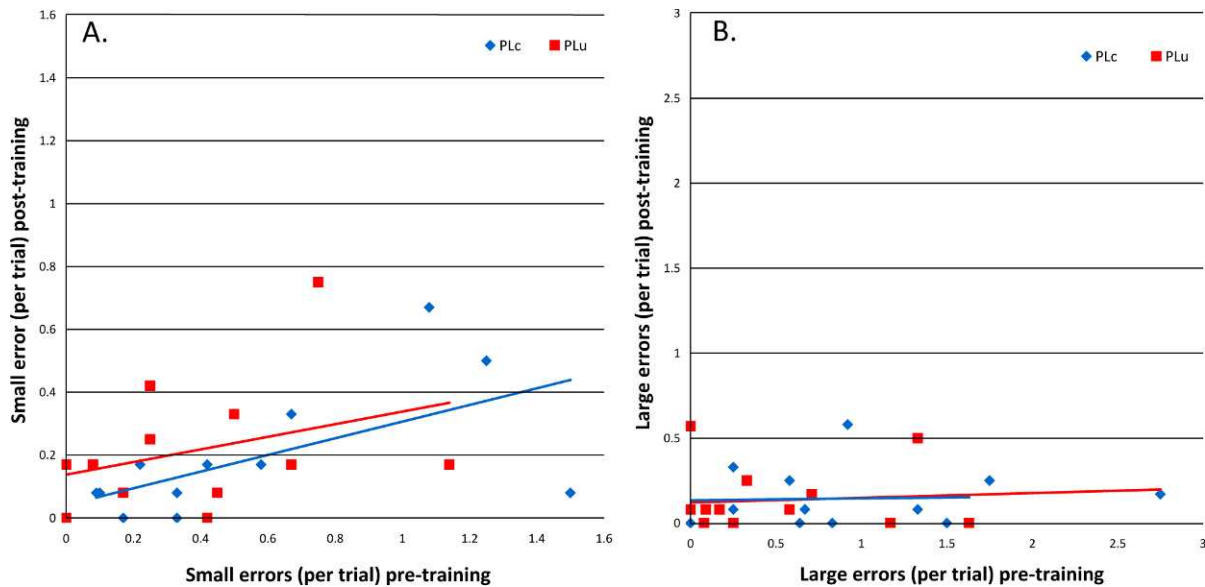
FIGURE 5. (**A**) Presents small errors and (**B**) presents large errors pre- and posttraining.

ratios and large errors indicated that the material addressed those skills that are impaired in children with VI.

Effectiveness of Experimental Crowding Training

Our second hypothesis was partially confirmed. We observed a striking improvement of single NVA for all training groups. The PLc training was the only training to induce an improvement of crowded NVA in both age categories (1.7 logMAR lines). Single NVA showed an average improvement of 1.3 logMAR lines in all training groups. When tested with the LH line 50% crowding chart, only the four- to six-year-olds in the magnifier group showed an improvement (2.0 logMAR lines). In the PL training groups LH line 50% crowding NVA improved in both categories (1.4 logMAR lines in the PLc group and 1.2 lines in the PLu group). It is a remarkable finding that 12 training sessions can induce such a general improvement of NVA.

An explanation for the larger improvement in the PLc group is that learning effects are specific to the physical features of the stimuli in PL paradigms.[40,41] In the PLc group, children trained with optotypes with an edge-to-edge spacing that is similar to the spacing on the crowded chart that we used.[30,35] Our paradigm did not train at threshold NVA, nor did we use LH-optotypes (the optotypes we used to measure NVA), so the improvement in NVA can be seen as a transfer of the training on NVA. Generalization can occur if a double-training paradigm is used that combines feature learning (e.g., contrast, size) and location learning (e.g., stimulus-nonspecific factors, like local noise at the stimulus location).[42] Our PL tasks used both mechanisms (manipulating letter size and local noise at the stimulus location).

A third component of the training tasks was the search element. The instruction of the magnifier task was to find the inversed Landolt C. The instruction of the PL tasks was to follow the trail of the inversed Es. In the two experimental training tasks, this meant disentangling small, closely-spaced symbols, an ability that relies on accurate eye movements.[43–45] Our paradigm, therefore, was not a purely visual PL paradigm, because multiple modalities were addressed; the visual modality (visual perception, i.e., sensory processing), and motor modality (oculomotor control and fine motor skills). It is possible that the training paradigms induced task-specific improvements in the motor domain, and the calibration

between visual and motor skills. This would be worth studying, because motor skills of children with VI often are impaired and training could induce coupled improvements in both modalities.[46,47]

Several possible explanations could be given for the improvements of NVA reported here. Firstly, studies show that PL does not only improve visual functions in patients with neural deficits, but also improves visual functions of patients with optical deficits (e.g., myopia[24] and presbyopia[24,48]). This has led researchers to suggest that improved NVA is the result of increased efficiency of neural processing.[48] The concept of neuroplasticity, that is, the capacity to adapt and modify neural circuitry to the environment and experience,[49] can be seen as the underlying mechanism. Following this reasoning, the improvements found here might be associated with neuroplasticity, certainly, since this capacity is considered to be substantial in childhood compared to adulthood.[50]

Secondly, improved NVA might be caused by a reduction of the retinal image velocity in subjects with nystagmus, due to discovering the gaze direction entailing minimal nystagmus, also known as the null-point.[51] An increase in ocular torticollis, the compensatory head turn fixating the eyes at this null-point, has been reported in children with VI after only six weeks of visual training.[46] Although we did not monitor ocular torticollis, and there was no difference in the amount of improvement between children with and without nystagmus, we cannot rule out this explanation at this point.

Thirdly, as mentioned in the introduction, PL consists of the process of increased correspondence or fidelity of perception to dimensions of stimulation.[1] In other words, PL pertains to an increased sensitivity for the available information from a stimulus array, more specifically, here, the relevant features of the test and training material (e.g., see the data of Gibson and Pick[52]). It is not unlikely that the training made children more effective in detecting and exploiting the symbols specifying those relevant features. This improvement of attention, which may be defined as "better knowing what to look for," is reflected by the increased NVA. This explanation is backed up partially by the additional decrease in large and small errors after training.

On a final note, it very well is possible that these mechanisms are interrelated and influence each other. For example, a reduction in retinal image velocity enables a child

to benefit from the training more, as it increases the opportunities for learning and becoming more sensitive to relevant information, as well as by increasing the efficiency of neural processing.

Crowding ratios did not decrease on a group level in any of the training conditions. However, when looking at individual data, eight of 18 children in the PLc group, two of 12 in the magnifier group, and one of 15 in the PLu group showed a decrease of the crowding ratio. The lack of a decrease of the crowding ratio can be explained by delayed visual maturation of single acuity in children with VI. In a previous study,[53] a stronger correlation was found between binocular single acuity and age for four- to eight-year-old children with albinism and infantile nystagmus syndrome ($r = -0.7$) than for children with NV ($r = -0.3$), while crowded acuities in all groups still were maturing at the same rate. These data indicated slower maturation of the visual system in children with VI. It is conceivable that more training sessions would lead to larger improvements and a subsequent reduction of the crowding ratio. This question warrants further research.

Generalization of Learning Effects

Our third hypothesis was confirmed. Transfer of learning effects appeared on an untrained visual function: near visual acuity. In PL protocols that specifically focus at repeated practice at threshold sized symbols, it is to be expected that visual acuity improves.[54] Improving contrast sensitivity in the amblyopic eye also transfers to visual acuity.[8,55] Transfer of functions indicates that the specificity of improvement in the training task can be generalized by repetitive practice of target detection, covering a sufficient range of spatial frequencies and orientations, leading to an improvement in unrelated visual functions. In children with amblyopia, contrast sensitivity training with Gabor patches led to an improvement of 1.5 Snellen lines on the acuity chart.[8] It is a novel finding that NVA can be improved after PL in children with VI.

Age Differences in Learning Effect

Our fourth hypothesis was not confirmed. Both age groups showed an improvement in NVA on all vision charts after the PLc training. Our training task was quite a challenge for the younger children, because it demanded them to focus and sustain attention. Our tasks resemble the Eriksen flanker task.[38] Adults with amblyopia also show impaired visual decision-making on Eriksen flanker tasks compared to adults with NV; these adults show significantly delayed responses.[56] In our training tasks, children had to filter out relevant (inversed Es/inversed Landolt C) from irrelevant (noninversed Es/noninversed Landolt Cs) optotypes. This basically makes it a "conflicting" task, because distractors also undergo perceptual analysis along with the target due to imperfect selection, and they might produce additional identity-specific interference effects if they signify a response other than that designated to the target stimulus.[57] At baseline, six of the four- to six-year-old children with VI were unable to work with the training material. The seven- to nine-year-olds were all able to work with the material at baseline.

An explanation for the improvement in NVA of seven- to nine-year-old children could be that more older children worked with smaller M-values (or print) than younger children did. This may have resulted in an equally challenging training for this group. While 14 of the 15 seven- to nine-year-olds worked with the smallest print (1 M), only nine of the four- to six-year-olds did so, while five worked with intermediate print (2 M), and four with the largest print (4M). Thus, the task itself may have been the greatest challenge for the younger children.

For the older children, gain may have been related to working with the smallest optotypes, which made the task challenging for them.

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