Symbol Discrimination Speed in Children With Visual Impairments

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PURPOSE. We measured visual acuity and visual discrimination speed simultaneously in children with visual impairments to determine whether they are slower than children with normal vision.

METHODS. Five- to twelve-year-old children with visual impairments due to ocular dysfunction (VIo; n = 30) or cerebral visual impairment (CVI; n = 17) performed a speed-acuity test in which they indicated the orientation of Landolt-C symbols as quickly and accurately as possible. The reaction times for symbols ranging between −0.3 and 1.2 logMAR relative to acuity threshold were compared with normative data. To test whether children were already slow in merely detecting symbols, we also compared their reaction times on a simple visual detection task (VDT) to normative data. An auditory detection task (ADT) was used to probe for other, more general deficits.

RESULTS. Of the children with visual impairments, 88% had abnormally long reaction times in the speed-acuity test. This deficit was partly explained by their reduced acuity, but 40% still needed more time to discriminate acuity-matched optotypes. Children responded late in the VDT too, especially those with CVI, but this impairment could not fully account for their slow symbol discrimination. In children with CVI, reaction times in the ADT were affected as much as those in the VDT, suggesting more general sensorimotor problems in CVI.

CONCLUSIONS. The speed-acuity test offers additional insight in visual impairment. Children with VIo and CVI are abnormally slow in discerning foveal details. Magnification of materials is often insufficient to compensate for this deficit, partly because stimulus detection is already hampered.

Keywords: visual impairment, children, visual acuity, reaction times, visual development

According to the World Health Organization (WHO), visual impairment is characterized by low visual acuity and visual field deficits.1 Based on these criteria, worldwide, approximately 19 million children are considered visually impaired.2 Visual impairment in children is most often caused by ocular diseases and/or genetic factors affecting the eye, such as retinal dystrophies, albinism, optic atrophies, retinopathy of prematurity, and congenital cataract.3–5 The most prevalent cause of visual impairment in children in developed countries is cerebral visual impairment.3,4,6,7 Cerebral visual impairment (CVI) results from diverse developmental disorders and brain injuries, such as genetic disorders, malformations of cortical development, preterm birth, closed head trauma, encephalitis, hypoxia, and epilepsy.8–10 Because of its diverse etiology, a wide variety of visual problems may occur in CVI, ranging from deficits in lower visual functions, such as visual acuity, visual field, and contrast sensitivity, to higher visual functions, such as visual attention, movement processing, and visual search.8,10,11 Thus, the WHO definition of visual impairment may be too narrow for children with CVI, as well as for children with other visual impairments.12–14

Presently, clinical tests of visual function do not assess visual processing speed. However, nontimed visual acuity tests may not reflect the demands of daily life activities.15,16 Therefore, it has been argued that measurements, which take into account speed and accuracy are key to a better quantitative assessment of visual impairment.17 This argument is strengthened by our finding that the basic ability to quickly discern visual details improves considerably in children with normal vision (NV) between 5 and 12 years of age due to faster, rather than more accurate, visual discrimination performance.18 This suggests that in addition to high-acuity vision, there is a need for fast visual processing to cope with daily life demands. Reduced visual processing speed may explain some of the problems in higher visual functions in children with visual impairments. For example, studies have shown that children with CVI display orienting responses with longer latencies19 as well as longer search times.20 Also, children with other visual impairments (VIo) due to congenital ocular disorders and/or retinal abnormalities have longer search times15,14 and lower reading speeds21,22 compared with children with NV. Furthermore, in adults, visual acuity correlates with performance on visual
processing speed tests\textsuperscript{23,24} and visual acuity is a significant predictor of reaction times in adults with macular degeneration.\textsuperscript{25} Although these studies correlated spatial and temporal aspects of vision, none of the studies above tested visual processing speed and visual acuity simultaneously.

In the present study, we therefore employed an easy-to-administer vision test that allows quick, simultaneous assessment of visual acuity and visual discrimination speed, which we also used to investigate the developmental improvement of symbol recognition in school children.\textsuperscript{18} The aim was to test if children with visual impairments due to congenital ocular disorders and/or retinal abnormalities (VLo) and children with cerebral visual impairments (CVI) are indeed slower in discerning visual details than children with NV, and to assess if such differences may be explained by their reduced acuity alone. In addition, we tested whether these children were slow in detecting and responding to large visual stimuli in the first place, as may be expected if they have, for example, reduced contrast and/or luminance sensitivity. To further assess whether the outcomes were influenced by developmental delays and/or more general problems in sensorimotor processing, as may be expected (e.g., in the case of abnormal brain development), we also measured their reaction times on an auditory detection task. Finally, we explored whether abnormal reaction times on the two detection tasks could account for abnormal reaction times in the speed-acuity test, or whether the fine spatial discrimination required for the speed-acuity test takes extra time in children with visual impairment.

**METHODS**

**Participants**

Forty-seven children participated in this study, 30 children (8.6 ± 2.3 years) with VLo, and 17 children (9.0 ± 1.5 years) with CVI. Control data were derived from 94 children (9.4 ± 2.0 years) with NV and normal development who were included in a separate study.\textsuperscript{18}

Children with VLo and CVI were recruited from Bartiméus, a Dutch institute for the rehabilitation of visually impaired people. The institution sent letters to the parents of children that met the inclusion criteria, and all children whose parents responded positively to this call were included (unless later testing showed that the child did not meet the inclusion criteria). Children with NV were recruited from primary schools in the neighborhood of this institute. The schools sent letters to the parents of all children, and those responding positively after reviewing the information brochure were included.

Inclusion criteria for the children with NV and VLo were as follows: age 5 to 12 years, normal birth weight (>2500 g), birth at term (>36 weeks), no perinatal complications, and normal development. For children with VLo, additional criteria were an ophthalmologic diagnosis and a crowded distant visual acuity (DVA) between 0.2 and 1.3 logMAR. Children with NV had to have a crowded DVA of 0.1 logMAR or better. Inclusion criteria for the children with CVI were age 5 to 12 years, being diagnosed of having CVI (by the Bartiméus institute), and having a crowded visual acuity of 1.3 logMAR or better. The diagnosis of CVI was based on a thorough ophthalmologic examination by a qualified pediatric ophthalmologist and orthoptist, including visual acuity and visual field tests, fundoscopy, and a detailed patient history, including a review of information available in medical records. Children who did not have the mental and motor skills to understand and execute the tasks were excluded, based on the judgment of their parents before the tests and on careful monitoring during testing by the examiner. The Freiburg visual acuity test (FrACT)\textsuperscript{26} was used to verify that the visual acuity of the children fell within the inclusion criteria (see section: Test Procedures and Equipment). Children with prescription glasses wore them during all tests.

Supplementary Table S1 presents the ophthalmologic diagnosis, clinical characteristics (i.e., presence of nystagmus and strabismus), and binocular visual acuities of all participants with VLo and CVI. The most prevalent diagnosis for the children with VLo was albinism (n = 8), followed by congenital stationary night blindness (n = 6), infantile nystagmus (n = 5), and hypermetropia (n = 3). Most children with CVI were born prematurely or suffered from perinatal complications.

The study was approved by the local ethics committee (CMO Arnhem-Nijmegen, the Netherlands) and conducted according to the principles of the Declaration of Helsinki and the Dutch code of conduct regarding the participation of minors.\textsuperscript{27} Informed consent was obtained in writing from all parents before the start of the measurements.

**Test Procedures and Equipment**

Test procedures and equipment were mostly the same as in the companion paper.\textsuperscript{18} Key properties of the stimuli and psychophysical methods are reproduced here for the reader’s convenience and supplemented where necessary. In short, crowded and uncrowded visual acuity was measured binocularly at 5 m (direct view) with the FrACT software, which employs a 24-trial staircase procedure (best PEST\textsuperscript{28}) to determine the subject’s threshold.\textsuperscript{29} Stimuli were black Landolt-Cs (2.1 cd/m\textsuperscript{2}) with four possible orientations against a white background (235.6 cd/m\textsuperscript{2}) on a 23-inch liquid-crystal display screen (Dell U2412M, 1920 × 1200 pixels, pixel pitch 0.27 mm; Dell Inc., Round Rock, TX, USA). The children indicated the perceived orientation of the Landolt-C by pointing or giving a verbal response, and could take as long as they felt necessary to respond.

Subsequently, children performed the speed-acuity test binocularly at 5 m using the same screen, luminance levels, and contrast. In this two alternative forced choice (2AFC) reaction time task children had to indicate, as quickly and accurately as possible, where the opening of a high contrast (98.2% Michelson) black Landolt-C was located by pressing one of two mouse buttons (Fig. 1A). Optotype sizes (n = 9), presented in pseudorandom order, ranged from −0.3 logMAR below to 1.2 logMAR above a child’s uncrowded binocular visual acuity (as determined with the FrACT) with steps of approximately 0.1 logMAR around visual acuity and approximately 0.2 logMAR for the larger optotype sizes (method of constant stimuli, 10 trials per optotype size). In children with NV, the range was fixed (−0.45 to 1.09 logMAR). We employed a 2AFC paradigm, instead of the FrACT’s 4AFC, to simplify the stimulus-response associations and movement components of the task in order to encourage and facilitate quick responses.

Two additional experiments were performed to examine whether the children’s slower responses represented a general deficit in sensorimotor processes, or whether they were specific to visual tasks requiring fine spatial discrimination. First, we measured their reaction times on a visual detection task (VDT) in which they had to press a button as soon as they saw a large (1.3 logMAR), high contrast (98.2% Michelson), a black “O” appears on the screen (Fig. 1B, left). And, to further probe for other, perhaps more general (developmental) problems in sensory processing and/or movement execution, we also tested them with an auditory detection task (ADT) in which they had to press a button as soon as they heard a loud (75 dBA) sound stimulus (Fig. 1B, right).

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Two children with VI (aged 6 and 8) the data from the speed-acuity test for the 5 largest optotypes was lower than 87.5% correct. For children with CVI (aged 7 and 8 years) data from the speed-acuity test were excluded because the large number of trials was too low. The variance term (VARj) was estimated from age-matched normative data, obtained using Equations 1 and 2 at each optotype size (j). These reaction times were log transformed to account for the fact that their distributions are skewed toward longer reaction times (see, e.g., the 95% prediction intervals of the chronometric curves in Fig. 2, bottom panels). The variance term (VARj) was estimated from Equation 1 with parameter values of \( x_0 = -0.43 \), \( A' = 0.37 \), \( k' = 57.27 \), and \( t_R = 0.0157 \). In this way, the delay index provides an age- and optotype-size invariant measure of a child’s response delay. 18

\[
\begin{align*}
A' &= \exp(0.189 - 0.027 \cdot \text{Age}) \\
k' &= \exp(1.558 + 0.076 \cdot \text{Age}) \\
t_R &= 1.031 - 0.048 \cdot \text{Age}
\end{align*}
\]

Thus, by combining Equations 1 and 2, we could obtain age-matched, normative reaction times as a function of optotype size for each child with VI, and CVI given his/her age (in years). The measured reaction times of each child were then compared with the age-matched control data from children with NV between 5 and 12 years of age are well described by the following set of equations for the three model parameters 18:

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The DI was computed as the ratio of the difference between the child’s reaction time (\( RT_{\text{obs}} \)) and the age-matched norm value (\( RT_{\text{norm,j}} \)).

\[
DI = \frac{1}{n_{\text{opt}}} \sum_{j=1}^{n_{\text{opt}}} \frac{\log(\text{RT}_{\text{obs, j}}) - \log(\text{RT}_{\text{norm, j}})}{\sqrt{\text{VAR}_{j}}}
\]

In which \( x = \text{size of the optotype (in logMAR)} \) to which the child responds, and \( x_0 = -0.43 \log\text{MAR} \) is the size of the largest optotype at which children with NV perform at, or close to, chance level (referred to as the critical optotype size). The parameter \( t_R \) is the residual time that indicates the minimum amount of time that a child needs to respond. The reaction time difference between the responses at critical optotype size and those at the largest optotype size is reflected in the choice delay limit (\( A'^2 \)). Parameter \( k' \) is a measure for the sensitivity of the visual system and is a scaling factor for the decrease in reaction times as optotype sizes increase. Furthermore, the age dependency of the average reaction time curves for children with NV between 5 and 12 years of age are well described by the following set of equations for the three model parameters 18:

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The custom Matlab software (version 2013b; MathWorks, Inc., Natick, MA, USA) for the speed-acuity test, the ADT, and the VDT recorded and stored stimulus timing and button presses at 1-ms precision using the Psychophysics Toolbox. 29

Data Analysis

Data analysis was performed in Matlab using the statistical toolbox (version 2013b). First, mean reaction times were calculated. After discarding reaction times less than 0.1 second, further trials were excluded if the reaction time deviated by more than 3 times the median absolute deviation (MAD) from the median50 for each test and each optotype size. On average, 7% of the trials were excluded for the speed-acuity test, 6% for the VDT, and 8% for the ADT. Most of the excluded trials were actually the first trial in a test because the children often did not realize that the test had started. Two children with VIo (aged 7 and 8 years) could not perform the ADT due to technical problems and for one 5-year-old child with VIo, the results on the ADT were excluded because the large number of premature responses (reaction time <100 ms in ~40% of the trials) indicated noncompliance with the task. For two children with CVI (aged 7 and 8 years) data from the speed-acuity test had to be excluded from further analysis because they appeared to have been guessing even for large optotypes well above their visual acuity (the median of their accuracy scores for the 5 largest optotypes was lower than 87.5% correct). For two children with VIo (aged 6 and 8) the data from the speed-acuity test were excluded because they did not finish the test.

For the speed-acuity test, the reaction time data and accuracy data (percent correct) as a function of optotype size were analyzed separately. The visual acuity was determined from the cumulative Gaussian function fitted to the accuracy data (75% correct threshold, see Fig. 2 for illustration).34 The guess rate was fixed to the 50% chance level performance for a 2AFC task and the lapse rate was allowed to vary between 0% and 10%. The reaction times were analyzed in relation to the chronometric response functions obtained in children with NV. 18

The chronometric response functions of children with NV are well described by a reaction time model,32 which uses the following hyperbolic tangent function (Equation 1)18:

\[
RT(x) = \begin{cases} 
A' \frac{x - x_0}{C0} \tanh(A'k'(x - x_0)) + t_R & x > x_0 \\
A'^2 + t_R & x \leq x_0
\end{cases}
\]

in which \( x \) is the size of the optotype (in logMAR) to which the child responds, and \( x_0 = -0.43 \log\text{MAR} \) is the size of the largest optotype at which children with NV perform at, or close to, chance level (referred to as the critical optotype size). The parameter \( t_R \) is the residual time that indicates the minimum amount of time that a child needs to respond. The reaction time difference between the responses at critical optotype size and those at the largest optotype size is reflected in the choice delay limit (\( A'^2 \)). Parameter \( k' \) is a measure for the sensitivity of the visual system and is a scaling factor for the decrease in reaction times as optotype sizes increase. Furthermore, the age dependency of the average reaction time curves for children with NV between 5 and 12 years of age are well described by the following set of equations for the three model parameters 18:

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Thus, by combining Equations 1 and 2, we could obtain age-matched, normative reaction times as a function of optotype size for each child with VIo, and CVI given his/her age (in years). The measured reaction times of each child were then compared with the age-matched control data from children with NV using a summery score, the delay index (DI), which aggregates the reaction time differences across all optotypes18:

\[
DI = \frac{1}{n_{\text{opt}}} \sum_{j=1}^{n_{\text{opt}}} \frac{\log(\text{RT}_{\text{obs, j}}) - \log(\text{RT}_{\text{norm, j}})}{\sqrt{\text{VAR}_{j}}}
\]


Optotype sizes less than 1.1 logMAR were used to calculate the DI, because this was the largest optotype size used in the children with NV. Of the children with NV, 95% have a DI/C20 1.39 SD units. A child with VIo or CVI was therefore considered slow if its DI exceeded this 95th percentile score.

Note that the standard DI from Equation 3 does not account for the reduced visual acuity of children with VIo and CVI. Therefore, an acuity-adjusted DI was calculated as well. To compute this acuity-adjusted DI, the age-matched, normative reaction time curves in Equation 3 were shifted toward the right (i.e., toward larger optotype sizes) by modifying the value of the critical optotype size, $x_0$, in Equation 1 according to a child’s response accuracy. That is, the critical optotype size of a child was estimated from the slope of his/her psychometric response function at the 75% correct performance level by calculating the optotype size at which the tangent line at this inflection point intersects the 50% correct chance level (Fig. 2, upper panels). As a result, the acuity-adjusted DI accounted for the child’s reduced visual acuity. Because the reaction time model of Equation 1 could adequately describe the reaction times of the children with visual impairments if it included $x_0$ as an additional free-fit parameter (the average $R^2$ of individual fits was 0.82 ± 0.18; not shown), an acuity-adjusted DI of zero is expected if reduced visual acuity alone accounts for their response delays.

**Statistical Analysis**

Our goal was to determine whether children with visual impairments are slower than children of the same age with NV. Therefore, we performed linear regression analyses with both age and group (NV, VIo, and CVI) as independent variables. For all regression analyses age was centered on the age of 9, the middle of the inclusion range. In this way, the differences between the regression-line intercepts quantify the mean reaction-time differences at the age of 9. Unless stated otherwise, these vertical offsets adequately quantified the age-adjusted differences between the groups because there were no significant interactions between age and group (i.e., the slopes of the regression lines were not significantly different).

Type I error was set at 0.05 for all statistical group comparisons. Values are reported as means ± 1 SD. An individual child was classified as slow on a given task if his or her score (reaction time or DI) exceeded the upper 95th percentile of the normative data.
**RESULTS**

**Speed-Acuity Test: Visual Acuity**

Figure 2 shows the psychometric and chronometric response curves for two visually impaired children, as well as the normative psychometric curves for normally sighted children of the same age (blue). The mean visual acuity estimated from the psychometric response functions was $0.30 \pm 0.25 \log_{10} \text{MAR}$ for the children with VIo, and $0.16 \pm 0.29 \log_{10} \text{MAR}$ for the children with CVI. Despite the time pressure in the speed-acuity task, these averages were significantly lower than the mean uncrowded acuity found with a standard C-test, the FranCT ($\text{VI}_0$: difference $-0.07 \pm 0.11 \log_{10} \text{MAR}$, Wilcoxon signed rank test, $Z = -2.94, P = 0.003$; CVI: difference $-0.08 \pm 0.12 \log_{10} \text{MAR}$, Wilcoxon signed rank test, $Z = -2.22, P = 0.03$). However, the absolute intraclass correlation between the two acuity measures of all children was 0.88 (95% CI: 0.70–0.95), which demonstrates high agreement. For 56% (24/43) of the children the difference between the two acuity measures was within 0.1 logMAR, for 86% (36/43) of the children the difference was within 0.2 logMAR and for 95% (41/43) of the children the difference was within 0.25 logMAR. There was no significant effect of age on the uncrowded visual acuity in children the difference was within 0.25 logMAR and for 95% (41/43) of the children the difference between the two acuity measures was within 0.1 logMAR, for 84% (36/43) of the children the difference was within 0.2 logMAR and for 95% (41/43) of the children the difference was within 0.25 logMAR. There was no significant effect of age on the uncrowded visual acuity in children the difference was within 0.25 logMAR and for 95% (41/43) of the children the difference between the two acuity measures was within 0.1 logMAR, for 84% (36/43) of the children the difference was within 0.2 logMAR and for 95% (41/43) of the children the difference was within 0.25 logMAR. There was no significant effect of age on the uncrowded visual acuity in children the difference was within 0.25 logMAR and for 95% (41/43) of the children the difference between the two acuity measures was within 0.1 logMAR, for 84% (36/43) of the children the difference was within 0.2 logMAR and for 95% (41/43) of the children the difference was within 0.25 logMAR.

**Speed-Acuity Test: Reaction Times**

The chronometric response curves for the two children with visual impairments in the lower panels of Figure 2 (red curves) show that both children were typically slower compared with 95% of the children with NV of the same age (blue). For the child in Figure 2A, only the reaction times for the smaller optotype sizes were longer, whereas for the largest optotype sizes this child performed within the normal range (shaded area). If the chronometric curve of this child is shifted along the horizontal axis to align its critical optotype size (dashed red line) with the critical optotype size of children with NV, the chronometric curve would fall within the normal range. Thus, this child had longer reaction times on the speed-acuity test compared with the children with NV, but if its reduced visual acuity is taken into account, these longer reaction times are to be expected. For the child in Figure 2B, on the other hand, the longer reaction times cannot be explained by his/her reduced visual acuity alone. The reaction times for the largest optotypes are an indication of the minimum time children needed to discriminate the orientation of the Landolt-C. Therefore, we first analyzed the children’s mean reaction time for the easiest optotypes to determine whether the children with VIo and CVI were slower in just detecting the appearance of a salient visual stimuli.

To test whether the longer reaction times may be explained by the children’s reduced visual acuity, acuity-adjusted DIs were calculated (Fig. 4B). In this case the optotype sizes were redefined relative to the critical optotype size (i.e., the optotype size at which the children performed at chance level). As expected, the average acuity-adjusted DIs were lower than the standard DIs for the children with VIo ($1.1 \pm 1.1$, Wilcoxon signed rank test, $Z = -4.6, P < 0.001$) as well as for the children with CVI ($1.6 \pm 1.6$, Wilcoxon signed rank test, $Z = -5.4, P < 0.001$). For 60% of children the acuity-adjusted DIs fell within normal range (VIo: 18/28 children, CVI: 8/15 children). However, a large proportion of the children had acuity-adjusted DIs that were still outside the normal limits, 36% (10/28) of those with VIo and 47% (7/15) of those with CVI had scores above the 95th percentile of children with NV. This indicates that these children were significantly slower on the speed-acuity test than one might expect from their impaired visual acuity alone. In fact, the average acuity-adjusted DIs were significantly higher than the standard DI of children with NV (Mann-Whitney $U$ test, $Z = 5.19, P < 0.001$ and CVI: $Z = 3.6, P < 0.001$), a feature that was not significantly different between the two clinical groups (Mann-Whitney $U$ test, $Z = -0.57, P = 0.57$).

**Delay Index**

The analysis shown in Figure 3 does not take into account the entire chronometric curve. The DI, on the other hand, provides a summary measure for the response delay by comparing the reaction times for all optotype sizes to the reaction times of children with NV in SD units. A DI value of 0 signifies that a child responds as fast as an average child with NV of the same age, while a DI value of, for example, 2 indicates that his/her reaction time curve is on average 2 SD above the average performance of children with NV. As shown in Figure 4A, the average DI was $3.3 \pm 1.9$ for children with VIo and $3.0 \pm 2.2$ for children with CVI, which was significantly above the DI $\equiv 0$ score of children with NV ($\text{Mann-Whitney } U$ test, $Z = 7.7, P < 0.001$ and $z = 5.6, P < 0.001$). The DIs for the two individual subjects shown in Figures 2A and 2B were 2.94 and 6.94, respectively. Only one child with VIo (4%, 1/28) and only two children with CVI (13%, 2/15) scored under the 95th percentile of children with NV. This indicates that the vast majority of the children with VIo and CVI were overall slower on the speed-acuity test if we directly compare their reaction time curves with the reaction time curves of the children with NV of the same age. The DIs were not significantly different between the two clinical groups (Mann-Whitney $U$ test, $Z = 1.26, P = 0.21$).

Detection Tasks

The children also performed a VDT to examine whether they had difficulties in just detecting the appearance of a salient visual stimulus. The regression analysis of these data revealed that both clinical groups were significantly slower than the controls (Fig. 5A, Supplementary Table S3). In children with VIo reaction times were on average 79 ± 15 ms longer than the children with NV ($1_{32} = 5.19, P < 0.001$), whereas children with CVI reacted on average 144 ± 19 ms later than children with NV ($1_{32} = 7.72, P < 0.001$). In fact, half (15/30) of the children with VIo and 76% (13/17) of the children with CVI scored above the 95th percentile norm, indicating that these children were already late in detecting large, high-contrast visual stimuli.

To test if the significant delays in detecting the visual stimulus might have been due to other, more general (developmental) problems rather than visual impairments alone, we also tested the children in an auditory detection.
The regression analysis of these data (Fig. 5B, Supplementary Table S3) revealed that the children with CVI responded on average 106 ± 14 ms later than normal on the ADT ($t_{127} = 7.51, P < 0.001$). In total, 59% (10/17) of the children with CVI showed abnormally late reactions on the ADT (i.e., above the 95th percentile norm). To our surprise, 26% (7/27) of the children with VIo also needed significantly more time to detect the sound stimulus than children with NV.

Despite their normal hearing, the group of children with VIo was significantly slower on the ADT than the children with NV ($t_{127} = 2.52, P = 0.01$). The mean reaction time difference was only 29 ± 12 ms, but this was still approximately 10% slower than normal.

In contrast to the speed-acuity test and the VDT, in which the two clinical groups showed age-related improvements in reaction times comparable to those of the children with NV.

**Figure 3.** (A) Mean reaction times for discriminating the easiest optotypes in the speed-acuity test for the children with VIo (red numbers) and the children with CVI (black numbers). Numbers correspond to individual participants (Supplementary Table S1). The lines are the results of the linear regression analysis (red: VIo, black: CVI and blue: NV). The dashed blue line indicates the 95th percentile of children with NV. Slopes were not significantly different between groups (Supplementary Table S2). Age-adjusted reaction times of children with VIo and CVI were on average longer than those of children with NV.

**Figure 4.** The delay indices on the speed-acuity test for the children with VIo (red numbers) and CVI (black numbers). Numbers correspond with individual participants (Supplementary Table S1). (A) The delay indices. (B) The acuity-adjusted delay indices which take into account the subjects’ reduced visual acuity. The dashed blue lines indicate the 95th percentile of the children with NV. The average DIs were significantly elevated in both clinical groups, even after adjustment for their reduced visual acuity.
(Figs. 3 and 5A), the decrease in reaction time with age on the ADT seems to differ in the CVI group. More specifically, the slope of the regression line for children with CVI was significantly steeper than the slope of the regression line for children with NV (slope CVI: $-55 \pm 10$ ms/year, slope NV: $-18 \pm 3$ ms/year, $t_{127} = -3.65, P < 0.001$). This effect is mainly attributable to the results of the younger children (<9 years) with CVI. For the children with VIo, the slope of the regression line was not significantly different from the control line (slope VIo: $-15 \pm 5$ ms/year, $t_{127} = 0.64, P = 0.52$).

The results from the detection tasks indicate that children with CVI tend to respond quite late on both the VDT and the ADT, while children with VIo only exhibit pronounced delays on the VDT. This suggests that in children with CVI the response delays might be caused by more general deficits, whereas in children with VI the lagging reactions may be primarily due to visual problems. If this is the case, than one would expect that the within-subject difference between the VDT and ADT in children with CVI does not exceed the reaction-time differences found in controls, whereas larger reaction-time differences are expected in children with VIo. Although the data are noisy, linear regression analysis confirmed these expectations (Fig. 5C). The difference in reaction time between the VDT and the ADT was $28 \pm 13$ ms larger for the children with VIo compared with the controls ($t_{127} = 2.18, P = 0.03$), while the regression line in the children with CVI was not statistically significant from the control line (difference at age 9: $18 \pm 15$ ms, $t_{127} = 1.14, P = 0.26$).

**Discrimination Versus Detection**

Children with visual impairments had abnormally long reaction times on the speed-acuity test (Fig. 3) and the two detection tests (Fig. 5). The question is whether the longer reaction times on the speed-acuity test can be explained by a lag in stimulus detection alone, or whether the stimulus discrimination process takes longer too. Therefore, we compared the reaction times for the easy optotypes with the reaction times on the detection tasks (Fig. 6, Supplementary Table S4). The vertical offset of the regression lines revealed that, on average, the difference between the reaction time for the easy optotypes and the VDT was $92 \pm 24$ ms larger for the children with VIo than for the children with NV ($t_{127} = 3.79, P < 0.001$). For the children with CVI, the difference was on average $99 \pm 31$ ms larger ($t_{127} = 3.14, P = 0.002$). This indicates that children with VIo and CVI discriminated the symbols significantly later than one might expect from their increased reaction times in the VDT alone. In total, 25% (7/28) of the children with VIo and 40% (6/15) of the children with CVI needed more time than expected from their increased reaction times in the VDT alone. Thus, even after correcting for the time children needed to detect and respond to a visual stimulus, children with VIo and children with CVI needed significantly more time to discriminate and respond to the easy optotypes, which suggests that the sensory discrimination process is slower in these children compared with children with NV. Similar results were found for the difference between the reaction time on the easy optotypes and the reaction time on the ADT. The vertical offset of the regression lines revealed that the children with VIo,
reacted on average 116 ± 27 ms later than one might expect from their increased reaction times in the ADT alone (t_{124} = 4.30, P < 0.001) and in the children with CVI this extra delay in responding was on average 95 ± 34 ms (t_{124} = 2.78, P = 0.006). After correcting for (increases in) reaction times on the ADT, 38% (10/26) of the children with VIo and 33% (5/15) of the children with CVI were still abnormally late in discriminating symbols.

DISCUSSION

Poor vision may affect not just the accuracy, but also the speed of visual judgments. In the present study we assessed both aspects simultaneously in 5- to 12-year-old children with VIo and CVI. As we expected, almost all children with VIo and CVI were slower on the speed-acuity test than children with NV for the same optotype sizes. This deficit was reflected in significant elevations of the delay index, a summary score that takes the entire reaction time curve into account (Fig. 4A). For 60% of the children, this impairment in visual discrimination speed could be explained by their reduced acuity as indicated by their acuity-adjusted delay index (Fig. 4B). However, the remaining 40% of the children still had longer reaction times than one would expect from their reduced visual acuity alone. This indicates that even if materials are magnified according to their visual acuity, a large number of children with VIo and CVI still need more time to discriminate visual stimuli. Thus, magnification may be insufficient to compensate for delays in visual discrimination. This conclusion is further supported by the fact that many of the children with VIo and CVI were abnormally slow in discriminating the largest symbols (Fig. 3), even if one accounts for the possibility that this may have been due to slow stimulus detection and/or movement execution (Fig. 6). Some of the children whose delay index fell out of range had normal reaction times on the easiest optotypes. This is an indication that these children are slow at discerning small optotypes but that they may be able to perform at normal speed if materials are large enough. However, for children with an elevated delay index and longer reaction times on the largest optotypes, magnification of materials alone cannot fully compensate for their deficit.

Relation to Previous Research

The observed delays in symbol discrimination are in line with a recent study showing that children with visual impairments have lower maximal reading speed on the MNREAD test compared with age-matched controls (DeCarlo DK, et al. IOVS 2015;56:ARVO E-Abstract 4787). Our findings suggest that at least part of these reading deficits may be explained by a reduction in the basic ability to discern symbols in a timely manner. This deficit could also be one of the underlying causes of longer search times in children with visual impairments. Other studies have shown that children with visual impairments need more time to perform fine motor tasks. Although the tasks in our study did not require a complicated motor response, problems with fine motor skills could have resulted in longer reaction times for some of the children. Perhaps this might account for the unexpected finding that some of the children with VIo needed more time on the ADT. Conversely, it is quite likely that the reduced speed of visual processing, as demonstrated by our findings, contributes significantly to the extra time that children with visual impairments need to perform fine motor tasks.

Study Population

We included children with a wide variety of ophthalmologic diagnoses and underlying causes of CVI. This reflects the heterogeneity of visual impairments that is present in children.
in western Europe.\textsuperscript{3,4} It is therefore no surprise that the delay indices obtained with the speed-acuity test could not distinguish between the two clinical groups. Nevertheless, children with CVI were typically slower than children with VIo in both detection tasks and to some extent in discriminating large optotypes. Our finding that the group of children with CVI showed comparatively large delays in the VDT and similarly large delays in the ADT (Fig. 5), suggests that general sensorimotor deficits and/or developmental delays played a more prominent role in this group, whereas the impairments in children with VIo seemed mostly due to slower visual processing alone. For individual children, however, the pattern could differ. Some children who responded late in the speed-acuity test had normal reaction times on the detection tasks, indicating that their response delays were not caused by delays in detection of the stimuli, or the ensuing motor response. For others, the increased reaction times on the easiest optotypes in the speed-acuity test were paralleled by increased reaction times on the visual or auditory detection tasks. For these children, the increase in reaction time can be explained by delays in the detection of stimuli and/or the increase in time that they need to generate the motor output. Thus, children with CVI and VIo showed individual differences, as might be expected with the diversity of causal factors and developmental differences.

Limitations

Both clinical groups showed significant response delays on the speed-acuity test, even after correction for their impaired visual acuity, but the limited number of children that we could include with a particular diagnosis makes it difficult to draw conclusions about whether children with certain diagnoses or characteristics (e.g., retinal abnormalities, nystagmus, or strabismus) have a higher risk of being slower. Furthermore, a large group of children with CVI, the ones with significant motor problems and/or significant cognitive developmental delays, could not be included in this study because they lack the skills needed to perform the tasks. Therefore, our results may not generalize to children with more severe CVI. Most likely, their speed of visual processing is even more severely affected. When children with significant cognitive delays are included in a study, it might be especially beneficial to use developmental age as an additional covariate in the analysis (although this is perhaps easier said than done, because, to our knowledge, there is no unequivocal measure of developmental age). In the current analyses, we only used the chronological age of the children as a covariate because data on their developmental age was not available. We believe, however, that the detection tasks already control for possible developmental delays, at least to some extent (see also Ref. 34 for a similar argument). We therefore argue that developmental delays alone cannot account for the reduced symbol discrimination speeds in the speed-acuity test that we have found in the children with CVI.

Developmental Differences

Children with normal vision show large developmental improvements in their reaction times, both on the detection tasks and on the speed-acuity test.\textsuperscript{18} Despite being slower than normal, children with VIo, seem to show similar age-related improvements on all tasks as suggested by the fact that the slopes of the regression lines were not statistically different from the slopes of the regression lines for children with NV (Figs. 3, 5, and 6, Supplementary Tables S2–S4). The reaction times of the children with CVI on the ADT, but not on the other tasks, changed with age in a manner different to that of the NV children. This might indicate that the children with CVI develop differently compared with the children with NV. However, this effect could also be the result of the relatively low sample size and the heterogeneity of the group. Longitudinal studies and larger groups are necessary to conclude whether or not children with VIo and CVI develop differently on the tasks we have used.

CONCLUSIONS

The speed-acuity test can be used in clinical pediatric populations and may provide important diagnostic insight for clinical and rehabilitation purposes by assessing visual recognition acuity and speed simultaneously. A significant number of children with VIo and CVI were slower on this test compared with children with NV, even if their reduced visual acuities are taken into account. We therefore argue that visual acuity measures alone do not adequately capture the ability to discern foveal details quickly. Thus, measures that also assess the speed of visual processes should be employed, given that this aspect of visual processing may be crucial for a child’s normal participation in school and society. The observed deficits seem to be caused by (at least) two of the following bottlenecks: one related to simply detecting and responding to visual stimuli, and the other one related to slower accumulation of sensory evidence to discriminate between visual stimuli.

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References

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