Development of Symbol Discrimination Speed in Children With Normal Vision

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Purpose. Many visually guided tasks require rapid perception of visual details, but how fast children can discern foveal stimuli and how this ability improves with age are still unknown. To fill this gap, we tested normally sighted children between 5 and 12 years of age with a combined symbol-discrimination reaction-time test.

Methods. Children (n = 94) had to indicate, as fast and accurately as possible, the orientation of a Landolt C symbol (90 trials). Task difficulty was manipulated by varying symbol size (~0.43 to 1.09 logMAR at 5 m). The resulting reaction times were analyzed with a drift-diffusion model. Reaction times on a visual and auditory detection task were measured to assess the contribution of other factors, such as delays in stimulus detection and executing the motor response.

Results. Detection and discrimination were significantly faster in older children. Five-year-olds needed ~440 ms for visual detection and ~980 ms for discrimination of the largest symbols while 12-year-olds needed only ~250 ms and ~500 ms for this. The extra time needed for discrimination compared with detection decreased with age. The decrease in reaction time with increasing optotype size was also age-dependent and indicated an increase in sensitivity with age. Despite the time pressure, acuity thresholds were normal (within the EN ISO-8597 standard).

Conclusions. Our data revealed substantial developmental improvements in visual discrimination speed, which suggests that an important optimization takes place in the developing visual system of 5- to 12-year-old children. Since the speed-acuity test allows for quick and reliable assessment of visual recognition acuity and speed, it may be useful in clinical testing too.

Keywords: visual acuity, reaction times, visual detection, auditory detection, visual discrimination, mental chronometry, normally sighted children, visual development
these aspects of vision are tested most often. However, purely spatial approaches to vision or purely temporal approaches to vision are insufficient, as they cannot be easily separated. Furthermore, it has been argued that nontimed VA tests may not reflect the demands in activities of daily living. Studies on visual processing speed in older adults have revealed that slower visual processing is related to an elevated risk of at-fault traffic accidents and decreased performance on other aspects of daily living (for an overview, see, e.g., Refs. 33 and 34). Therefore, it has been argued that measurements taking speed and accuracy into account are key to a better quantitative assessment of VI.

The studies mentioned above stress the importance of assessing VA and processing speed simultaneously. The advantage of the MNREAD is that it allows the assessment of reading speed and reading acuity simultaneously. However, younger children are unable to read, which limits the age range for which the test can be used. Moreover, factors such as visual span and crowding that develop in childhood are predictors of reading speed and therefore likely to influence the results on the MNREAD in school-aged children. Therefore, a test that allows assessment of visual recognition acuity and visual recognition speed is more suitable for children, as it could be used in a wider age range and would eliminate confounding factors such as crowding, visual span, or reading fluency. Additionally, such a test provides insight into whether one of the underlying mechanisms for the developmental effects on reading speed could be the development of fast visual discrimination abilities.

Our goal was to investigate developmental effects on the ability to discern visual details fast by measuring VA and visual discrimination speed simultaneously. To that end, we quantified how fast and how accurately 5- to 12-year-old children discriminate optotypes of different sizes using a speed–acuity test in which the children had to indicate, as fast and accurately as possible, the orientation of a Landolt C symbol. To quantify the effects of age on the reaction times, we used a drift–diffusion model to account for the nonlinear relationship between reaction time and optotype size. We also measured reaction times on a visual and auditory detection task to investigate to what extent the reaction times in the speed–acuity test could be explained by delays in detecting stimuli and executing the motor response. Our results reveal strong developmental improvements in visual discrimination speed that have not been reported previously. They also provide normative reaction-time data for children between 5 and 12 years old against which clinical results can be compared.

**METHODS**

**Participants**

Ninety-four children (9.4 ± 2.0 years) with normal vision participated. Inclusion criteria were age 5 to 12 years, normal birth weight (>2500 g), birth at term (>36 weeks), no perinatal complications, no complaints of slow visual processing, crowded VA of 0.1 logMAR or better, and normal development. The children were recruited from schools around the Bartiméus Institute, a Dutch institute for the visually impaired, and the children were tested at their own primary schools. Children with glasses had to wear them during all tests. The children were considered to have no eye problems by their parents and teachers. To verify that the children had a crowded VA of 0.1 logMAR or better, we measured crowded distance visual acuity (DVA) at the start of the experiments (see “Standard Acuity Measurements” below).

Informed consent was obtained from the parents of all participants. 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.

**Standard Acuity Measurements**

The Freiburg visual acuity test (FrACT) software was used to measure DVA (crowded and uncrowded) at 5 m with the Landolt C test on a 23-inch LCD screen. A four-alternative forced-choice procedure was used. The children were seated and instructed to indicate the orientation of a black Landolt C on a white background, either verbally or by pointing in that direction. The children could take as long as they wanted to respond. Uncrowded DVA was measured mono- and binocularly. Crowded DVA was measured binocularly using flanking rings with fixed interletter spacing of 2.6 arcmin. Each test consisted of 24 trials with a staircase procedure (Best PEST) to determine the thresholds. The difference between crowded and uncrowded acuities in logMAR was calculated to obtain the crowding intensity.

**Speed–Acuity Test**

The speed–acuity test (Fig. 1A) was administered binocularly with the children still seated at 5 m from the screen. Each trial consisted of a single high-contrast (98.2% Michelson) black Landolt C (2.1 cd/m²) presented at the center of the screen against a white background (235.6 cd/m²). Children had to indicate, as fast and accurately as possible, on which side, right or left, the opening of the Landolt C was located by pressing one of two mouse buttons in a two-alternative forced-choice task (2AFC). We chose Landolt Cs with their opening to the left/right because of the intuitive link with left and right mouse buttons. The stimulus was presented until the child responded. The opening of the Landolt C was unrendered to have clear edges. The round parts of the Landolt C were rendered to prevent pixelated edges. Task difficulty was manipulated by presenting nine different optotype sizes: −0.43, −0.25, −0.13, −0.03, 0.05, 0.27, 0.50, 0.68, and 1.09 logMAR (method of constant stimuli). The different sizes were presented pseudo-randomly in such a way that there was always at least a 0.2 logMAR difference between subsequent trials. Between trials, a white screen was presented for a random period of 0.5 to 1.5 seconds. The test consisted of 90 trials, 10 trials per optotype size. Children needed on average approximately 5 minutes to finish the test (range, ~2.5–4.5 minutes). Children took the test twice with a short break in between. Including this break and the instruction, testing took between 10 and 15 minutes in total.

**Detection Tasks**

The children also performed a visual detection task (VDT) and an auditory detection task (ADT) in which we measured the time children needed to respond to the presentation of a suprathreshold stimulus (Fig. 1B). We collected these measures to investigate how other task factors, such as stimulus detection and execution of the motor response, influence the reaction time. Both tests consisted of 20 trials with random intertrial durations of 1 to 4 seconds. In the VDT the children had to press the mouse button as soon as they saw the visual stimulus. The children were seated at 65 cm from the screen. The stimulus was a high-contrast (98.2% Michelson) black letter “O” (2.1 cd/m²) against a white background (235.6 cd/m²) of 1.3 logMAR. In the ADT the children had to press the mouse button as soon as they heard the stimulus. The sound...
stimulus consisted of a white noise burst of approximately 75 dBA that lasted 500 ms. The sound stimulus was played through the speakers of a laptop that was placed approximately 65 cm in front of the children.

**Equipment**

The software for the speed–acuity test, the VDT, and the ADT was written in Matlab (version 2013b; MathWorks, Inc., Natick, MA, USA) using the Psychophysics Toolbox.49 Stimulus timing and button presses were recorded and stored at 1-ms precision for offline analysis. The stimulus software was executed on a laptop (Dell M3800; Dell, Inc., Round Rock, TX, USA) equipped with an OpenGL graphics card (Nvidia Quadro K1100M; Santa Clara, CA, USA). The visual stimuli were presented on a 23-inch LCD screen (Dell, Inc. U2412M, 1920 × 1200 pixels, pixel pitch 0.27 mm). Visual stimulus properties were measured with a luminance meter (Minolta LS-100; Minolta Co. Ltd., Osaka, Japan). Ambient light conditions were controlled by shutting blinds or covering windows, and ranged from 100 to 350 lux as measured with a lux meter (Volcraft MS-1500; Hirschau, Germany). Sound intensity was measured with a sound level meter (ISO-TECH SLM 1352P; ISO-Tech, Taipei, Taiwan) at the location of the subjects’ ears.

**Data Analyses**

The offline analysis of the results was performed in Matlab. We first computed mean reaction times for the VDT, the ADT, and the speed–acuity tests after removing atypically long or short reaction times. For each test and each optotype size, trials were excluded from the mean if the reaction time deviated more than three times the median absolute deviation (MAD) from the median40 after discarding reaction times

\[ \text{median} \times 40 \]

and the speed–acuity tests after removing atypically long or short reaction times. For each test and each optotype size, trials were excluded from the mean if the reaction time deviated more than three times the median absolute deviation (MAD) from the median\(^40\) after discarding reaction times \(< 0.1 \) second. On average, 7% of the trials were excluded for the VDT, 6% for the ADT, and 3% for the speed–acuity test. For two 6-year-old children, we had to exclude the results of the VDT and ADT. Their behavior in the speed–acuity test was normal, but their reaction times in both detection tests were atypically long (more than three times the SD), presumably because they had not understood the instructions well enough. We then performed linear regression analyses to investigate developmental effects on VA and reaction-time measures. Regression parameters were obtained with a linear least-squares algorithm (fitlm, Matlab statistical toolbox). To estimate the range of reaction times that can be considered normal, we also calculated the 95% prediction intervals, that is, the interval in which one can expect 95% of the future observations to fall, given the current data from normally sighted children.41

For the speed–acuity test, the results consisted of the accuracy of the responses (percent correct) and the mean reaction time per optotype size. The speed–acuity test was run twice, resulting in two psychometric response functions for the accuracy data and two chronometric response curves for the reaction-time data for all but six participants. In one 11-year-old the measurements failed due to technical problems; one 5-year-old refused to perform the speed–acuity test; one 7-year-old did not complete the second test; and for the other three children (6, 7, and 10 years old) data from the second test had to be excluded from further analysis because they were no longer performing the task (as inferred from the fact that the median of their accuracy scores for the optotypes > 0.2 logMAR was lower than 87.5% correct).

The accuracy data and reaction-time data obtained in the speed–acuity test were analyzed separately (see Supplementary Material S1 for a detailed description). To determine the VA, we used the psychometric response curves with the psignifit toolbox for Matlab version 4.0.42 The threshold was taken at 75% correct, which is halfway between chance-level performance for a 2AFC task and the 100% correct rate.

To quantify the average reaction times as a function of optotype size \( x \) (pooled across correct and incorrect choices), we used a well-documented model from the literature, which uses a hyperbolic tangent function to describe chronometric response functions obtained in 2AFC sensory discrimination tasks (Equation 1)\(^{43}\):

\[
RT(x) = \begin{cases} 
\frac{A}{x(x-x_0)} - \frac{1}{x+x_0} & x > x_0 \\
\frac{A^2}{x} + \frac{1}{x+x_0} & x \leq x_0
\end{cases}
\]

This reaction-time model is based on a body of literature (see, e.g., Refs. 24 and 43 through 46) suggesting that the brain accumulates noisy sensory evidence over time and that a decision is made when the accumulated evidence scores reach a fixed decision bound (see Supplementary Material S1). The
model has parameters $x_0$ (critical optotype size), $t_0$ (residual time), $A'$ ($/C_0$ is the choice delay limit), and $k'$ (sensitivity). The critical optotype size, $x_0$, is the largest optotype size at which a child performs at chance level. The residual time, $t_0$, is the minimum time a child needs to respond and provides the lower bound of the chronometric curve. The residual time is thought to reflect the sum of sensory afferent delays, efferent motor delays, and other fixed delays. The upper bound of the chronometric curve is reached at the critical optotype size. It is the sum of the residual time and $A'$, which we refer to as the choice delay limit. The choice delay limit reflects how much more time a child needs for optotype sizes at which he or she performs at chance level compared to the largest optotype size. The sensitivity parameter, $k'$, is a scaling factor for the decrease in reaction times with increasing optotype sizes. Fit parameters for individualized fits were determined with a Levenberg-Marquardt nonlinear least-squares algorithm (fitnlm, Matlab statistical toolbox). In these fits, we fixed the critical optotype size, $x_0$, to the value of $-0.43$ logMAR based on the observation that subjects approached chance-level performance at this smallest optotype size present in our stimulus set.

To assess the effect of age on the reaction times in the speed–acuity test, and to obtain 95% prediction intervals for newly measured reaction times, we analyzed the chronometric functions with a mixed nonlinear regression model in which the parameters $A'$, $k'$, and $t_0$ of the reaction-time model were a function of age (see Supplementary Material S1). This allowed us to investigate whether these three parameters of the reaction-time model ($t_0$, $A'$, and $k'$) were age dependent. The values of the parameters that were obtained with this mixed model analysis were then used to predict the reaction-time curves one may expect for an average child of a certain age. Bootstrap procedures using the data of all children were used to obtain 95% prediction intervals for the individual fits and for the predicted reaction-time curves (see Supplementary Material S1).

As an indication of the repeatability of the speed–acuity test we calculated the absolute intraclass correlation coefficient (ICC) between response curves from the two test runs. Subsequently, the absolute ICC was calculated for the visual acuities for the two runs and a paired-samples $t$-test was performed to test for differences between the two runs.

Unless stated otherwise, values in the text are reported as means ± 1 standard deviation (SD). The type 1 error ($\alpha$) was set to 0.05 for all analyses.

**Results**

**Standard Acuity Measurements**

We first assessed the children’s uncrowded acuity using a Landolt C test in which there was no time pressure on the discrimination process. The average uncrowded DVA measured with the FrACT was $-0.23 \pm 0.08$ logMAR binocularly, $-0.14 \pm 0.14$ logMAR for the right eye, $-0.16 \pm 0.12$ logMAR for the left eye. We also tested their crowded acuity because this measure is more sensitive in detecting visual problems than uncrowded VA. The average crowded DVA was $-0.17 \pm 0.10$ logMAR binocularly. The average crowding intensity was 0.06 $\pm 0.08$ logMAR. Furthermore, linear regression analysis (Supplementary Table S1) showed the expected developmental effect of age on the crowded DVA and the crowding intensity ($R^2 = 0.15$, $P < 0.001$ and $R^2 = 0.17$, $P < 0.001$, respectively). The older children showed better crowded visual acuities and lower crowding intensities than the younger children. Thus, all children had normal vision as inferred from their monocular and binocular acuities.

**Speed–Acuity Test: Acuity**

The average accuracy of the responses in the speed–acuity test are presented in Figure 2A for four different age groups. As expected, the accuracy improves as the optotype size increases in all age groups. The mean VA estimated from the psychometric response functions was $-0.28 \pm 0.05$ logMAR. This was significantly lower (paired $t$-test, $t(91) = -6.62$, $P < 0.001$) than the mean acuity found with the FrACT. However, the average within-subject difference between the FrACT and the speed-acuity test was only $-0.04 \pm 0.06$ logMAR. Linear regression analysis of these data indicated that there were no significant effects of age on the uncrowded VA (Supplementary Table S1), as one would expect for children between 5 and 12.

**Speed–Acuity Test: Reaction Times**

The reaction times of the children decreased as the optotype size increased (Fig. 2B). The reaction time for the smallest optotype, which was below the children’s VA threshold, was on average 0.94 second longer than the reaction time for the largest optotype. For the second optotype size of $-0.25$ logMAR, which was around the children’s VA threshold, the difference was on average 0.45 second. For large optotypes the chronometric functions approach an asymptote. Note, however, that for the third, fourth, and fifth optotype sizes ($-0.12$, $-0.03$, and 0.05 logMAR), which were all above threshold, the asymptote is not yet reached; the mean reaction times were still 0.23, 0.15, and 0.11 second above it. Furthermore, older children were faster than younger children. For instance, the average reaction time for the 5- and 6-year-old children for the largest optotype was on average 0.33 second slower than for the 11- and 12-year-olds. This difference was $-0.53$ second around the VA threshold.

This coarse inspection of the data thus shows a clear developmental dissociation between speed and accuracy; where the psychometric curves fall practically on top of one another (Fig. 2A), the chronometric curves clearly differ between the age groups (Fig. 2B). This is evidently different from the speed–accuracy trade-off one can expect from an individual participant under different task conditions. For this reason, we analyzed the reaction-time data independent of the acuity data. As a first step in this analysis we quantified the reaction times as a function of optotype size by fitting the reaction-time model (Equation 1) to the individual chronometric curves. Figure 3A shows the results of such an individual fit along with the measured reaction times. The average $R^2$ for the individual fits was 0.96 $\pm 0.07$ (range, 0.65–1.00). The individual fit parameters along with the 95% prediction intervals for these parameters are presented in Figures 3B through 3D. Linear regressions applied to these fit parameters showed significant age effects on all parameters of the reaction-time curves (Supplementary Table S2). The residual time decreased with age ($\beta = -0.046$, $t(176) = -10.65$, $P < 0.001$), the log-transformed choice delay limit decreased with age ($\beta = -0.037$, $t(176) = -5.03$, $P = 0.003$), and the log-transformed sensitivity parameter increased with age ($\beta = -0.056$, $t(176) = 2.00$, $P = 0.047$), which all points toward a significant increase in optotype discrimination speed.

Normative developmental data from cross-sectional studies such as ours are often stratified according to restricted age groups. However, this approach is not very efficient in terms of statistical power since more and smaller age groups are needed to characterize steeper age effects with sufficient resolution. In the present study, we therefore used a mixed nonlinear regression model to quantify the steep changes in reaction times as a continuous function of age (and optotype size), together with a numerical approach (bootstrapping) to
estimate the range of reaction times that can be considered normal (Supplementary Material S1). Collectively, the fixed and random effects in this model accounted for 86% of the total variance in the reaction times across all optotype sizes and all subjects (conditional $R^2 = 0.86$), indicating that this model provided a very good description of our data. Furthermore, the three fixed effects that captured the developmental improvements in visual discrimination speed were all statistically significant (Supplementary Table S3). This bolsters the conclusion from Figure 3 that the developmental enhancement of optotype recognition consists of an overall, size-invariant decrease in reaction time, as indexed by the decrease in residual time, as well as size-specific reductions in discrimination time as indexed by the decrease in the choice delay limit and increase in sensitivity.

The parameter values that this mixed regression model predicts for the reaction-time curves for a child of a certain age can be calculated from the model’s fixed effects in the following way (Equation 2):

$$A' = \exp(0.189 - 0.027 \cdot \text{Age})$$

$$k' = \exp(1.558 + 0.076 \cdot \text{Age})$$

(2)

$$t_R = 1.031 - 0.048 \cdot \text{Age}$$

By substituting these parameter values in Equation 1, one can compute the expected reaction time for this child for each optotype size, $x$, to obtain the norm (i.e., the marginal response).

The resulting norm curves and corresponding prediction intervals for the average reaction times of an individual subject with 10 trials per optotype size are presented for eight different ages in Figures 4A through 4H. The age effects are clearly visible: (1) the predicted reaction times for the 12-year-olds are systematically shorter than for the 5-year-olds; (2) the shape of the predicted curve depends on age (Fig. 4I); and (3) the difference between the maximal and minimal reaction times is smaller for the older children and their reaction time decreases faster with optotype size. Additionally, the width of the prediction intervals decreases with increasing optotype size and age. There is also overlap between the ranges of responses that can be considered normal for adjacent ages. This is most prominent for the smallest optotypes, which can be understood from the logarithmic scaling of the choice delay limit and sensitivity with age (Figs. 3C, 3D). Because of the overlap of the prediction intervals, it is of interest to aggregate the reaction-time data across the optotype sizes in a summary score. We derived such a measure in Supplementary Material S2.

**Detection Tasks**

The children performed two detection tasks for investigation of how much of the age-dependent reduction in reaction times that was found in the speed–acuity test might be due to faster visual discrimination compared with other factors that also influence the reaction time, such as stimulus detection and execution of the motor response. The results of the simple visual and auditory detection tasks are shown in Figure 5. Linear regression analysis of these data (Supplementary Table S4) indicated that age explained
Thus, it appears that the speed of visual detection catches up with the average difference between the VDT and ADT decreased by was indeed significantly steeper for the VDT (slope ADT: [math formula]) of this ANCOVA confirmed that the slope of the regression line repeated-measures analysis of covariance (ANCOVA). The results slopes of the regression lines for the ADT and the VDT with a small and the explained variance low, we also compared the times on the detection tasks should correspond to the residual time. To test whether this assumption holds true, the children's reaction time for discriminating the easiest optotypes in the speed–acuity task were compared to their reaction time for detecting the salient stimuli in the VDT and the ADT. We first evaluated the effect of age on the children’s mean reaction time for the largest three optotypes (Fig. 6A) as a model-invariant estimate of the residual time. In line with the results shown in Figure 3B, linear regression analysis of these data (Supplementary Table S5) showed a significant decrease in the reaction times with age ([math formula], [math formula]), explaining 61% of the variance in reaction time for discriminating the easiest optotypes. Note that the decrease in reaction time with age is 61 ± 5 ms/year, resulting in a total decrease of nearly half a second over the 8 years inclusion range.

Figure 6B presents the difference between the reaction time for the easiest optotypes in the speed–acuity test and the VDT as a function of age. The children needed on average 0.36 ± 0.11 second (range, 0.14–0.69) more to discriminate on which side the opening of the large Landolt Cs was located during the speed–acuity test compared to detecting a large “O” in the VDT. Regression analysis (Supplementary Table S5) revealed that this reaction-time difference decreases 36 ± 5 ms/year, reducing the time needed for the discrimination response by ~290 ms across the 8 years inclusion range. Figure 6C presents the reaction-time difference with the ADT as a function of age. On average the children needed 0.42 ± 0.12 second (range, 0.20–0.77 second) more to discriminate the orientation of large optotypes compared to detecting the sound in the ADT. Furthermore, linear regression analysis (Supplementary Table S5) showed that the reaction-time difference decreases more than 40 ± 5 ms/year. Taken together, these reaction-time differences with the VDT and ADT show that the assumption that the residual time is unrelated to the discrimination process is not correct; a substantial fraction of the age-dependent decrease in reaction time in the speed–acuity test can be explained by improved discrimination of the visual stimuli.

**Test–Retest Reliability**

No significant differences were found between the VA measured in the first (-0.28 ± 0.05 logMAR) and second (-0.28 ± 0.04 logMAR) test runs (paired t-test, [math formula] = 0.51,
The difference between the VA thresholds of the two test runs ranged from −0.25 to 0.14 logMAR, and was less than 0.1 logMAR for 94% of the participants. The absolute intraclass correlation between the first and second test was 0.78 (95% confidence interval [CI]: 0.75–0.80) for the percentage correct answers and 0.74 (95% CI: 0.63–0.82) for the acuity estimates.

Furthermore, the average within-subject difference between the mean reaction times per optotype size of the first and second test run was 0.05 ± 0.13 second (paired t-test, \( t(87) = 3.376, P = 0.001 \)), indicating that the children were slightly faster on the second test. Even so, the absolute intraclass correlation between reaction times in the first and second test was 0.78 (95% CI: 0.75–0.81).

**DISCUSSION**

The goal of this study was to investigate developmental effects on the speed of visual symbol discrimination in children between 5 and 12 years old, because a child's ability to distinguish visual details fast is important for participation in school and society. Toward that end, we used an optotype-discrimination reaction-time task that measures VA and visual discrimination speed simultaneously. We found that it is feasible to use such a test for children in this age group, and the results show that there are considerable developmental improvements in visual discrimination speed. This suggests that an important optimization of the visual discrimination process takes place in the developing visual system of 5- to 12-year-old children. The developmental dissociation between speed and accuracy that is revealed by our data implies that VA alone cannot predict how long it takes for a child to see. The combination measurement of recognition acuity and recognition speed is therefore relevant for the assessment of a child's visual development, and may be of aid in clinical diagnostics of VI and rehabilitation indications.

**Development of Visual Discrimination Speed**

The reaction times in the speed–acuity test depend strongly on the size of the Landolt C. This is in line with a series of previous studies on the effect of stimulus strength on reaction time.\(^{24–27}\) Additionally, the decrease in reaction times as optotype size increases is comparable to the effect of print size on reading.
Critical print size, that is, the smallest print size at which participants approach the asymptote of reading speed, is on average approximately 0.2 logMAR above VA threshold. The current findings indicate that the smallest optotype size at which participants approach the asymptote on the speed–acuity test is even larger—roughly 0.3 to 0.5 logMAR above the acuity threshold (Fig. 2B).

The reaction-time model with a hyperbolic tangent function adequately described the effect of stimulus size on the reaction times. We are aware that a variety of alternative sensory decision-making models exist. Given the relative simplicity of this particular model, and the goodness of fit for most participants, we think, however, that the applied model is a useful tool in the analysis of visual discrimination speed. Indeed, by incorporating this quantitative description of reaction time as a function of optotype size in a mixed nonlinear regression analysis, we were able to identify distinct effects of age on the speed of visual processing in children with normal vision and normal development.

First and foremost, we found that the residual time was much shorter in the oldest children compared with the youngest. This effect is clearly seen as a shift of the chronometric functions along the vertical axis (Fig. 2B). Although the results from the ADT indicate that a significant fraction (~140 ms of the ~400 ms total decline over 8 years) of this general decrease in reaction times with age cannot be attributed to developmental effects within the visual system (Fig. 6B), comparison of the auditory and VDTs (Fig. 5C) shows that a part of the reaction-time decrease is due to a general increase in the speed of the visual discrimination process (~50 ms over the course of 8 years). Interestingly, however, this general speed-up of visual processing accounted for only a limited fraction of the general decrease in reaction times on the speed–acuity task. As is revealed by subtracting the reaction times obtained in the VDT from the ones obtained for discriminating large optotypes (Fig. 6C), there is an additional increase in discrimination performance of near 250 ms on average over the course of 8 years of development. Where does this improvement come from? Does it reflect a developmental improvement in visual processing, or is it related to nonvisual factors? One possible explanation is that the additional processing required in the speed–acuity task over the detection task becomes more efficient with age. The difference in processing includes more complex cognitive judgment (discriminating between two alternative orientations of a symbol versus registration of a suprathreshold sensory stimulus) and a more complex motor response (pressing one of two buttons versus pressing a single button). Alternatively, there could be a general decrease in noise levels within the visual system that allows the older children to respond faster (by adopting lower decision bounds) while maintaining a similar accuracy.

On top of the large effect of age on the residual time, we also found that the shape of the chronometric curves changed with age. Since these shape changes relate to the size of the visual stimulus and not to any other component of the speed–acuity task, they expose an optimization of the decision-making process that can only be attributed to developmental changes in visual processing. Indeed, the extra time that subjects needed to reach a decision regarding the orientation of the smallest Landolt C compared with the largest C was larger in the younger children. Since their acuities were not significantly different from those of the older children, this increase in the choice delay limit (Figs. 5C, 4) suggests that the younger children needed more evidence to reach a decision (i.e., they applied a higher decision bound), thereby sacrificing speed for
accuracy to compensate for increased noise levels in their visual system. In addition, the decrease in reaction time as a function of optotype size was steeper in the older children, as is reflected in a compression of the chronometric curves along the horizontal axis (Figs. 3D, 4). Although this effect was also not as strong as the effect on the residual time, it shows that the sensitivity of extracting the relevant information from the stimulus was higher for the older children.

In children with VI, one might expect significant effects on their reaction-time curves because of their reduced sensitivity. Whether this prediction holds across clinical populations remains to be tested (see Ref. 55). Others have already demonstrated that differences in VA resulted in differences on computerized neurobehavioral tests,17 the useful field of view test,15 cognitive tests,56 and neural markers of visual processing.57 Similarly, simulated VI influenced the outcome of cognitive and neuropsychological tests,16,58 and VA was a significant predictor of reaction time on a computer task in patients with macular degeneration.59 However, none of these studies tested visual processing speed and VA simultaneously.

Test Features
The speed–acuity test is an objective, easy-to-administer vision test that allows quick (≈5 minutes), simultaneous assessment of VA and visual discrimination speed. Visual discrimination speed, as measured with our speed–acuity test, can be conveniently summarized by a single delay index that provides an age-invariant comparative measure for the speed with which a subject is able to discriminate optotypes (Supplementary Material S2). The difference between the VA determined with the speed–acuity test and the FrACT was on average only 0.04 logMAR. This difference is within acceptable limits according to the international standard EN ISO 8597.60 A possible explanation for this difference in acuities could be that during the FrACT, children responded verbally and during the speed–acuity test they responded with button presses. Some children refused to guess when the optotypes in the FrACT were small, which could have resulted in an underestimation of the acuity with the FrACT. In addition, the repeatability of the test was good,61 with ICCs of 0.78 for the accuracy curves, 0.74 for the VA thresholds, and 0.78 for the reaction-time curves. Moreover, no significant differences were found between the VA thresholds of both test runs. Therefore, the speed–acuity test proves to be a valid test to measure visual discrimination speed and VA simultaneously in children. The test–retest repeatability with longer intervals between tests needs to be addressed in further research.

Prediction intervals that were obtained by pooling the reaction times from the two test runs into one average per optotype size (not shown) were very similar to the ones shown in Figures 3 and 4 for a single test consisting of 10 trials per optotype size. Only the upper bound of prediction interval for the sensitivity parameter ($k'$) was somewhat lower. Thus, as expected from the high ICCs, the benefit of adding more trials to the standard test seems to be of little practical importance. The reliability of the estimation of the VA threshold and the shape parameters ($A'$ and $k'$) of the reaction-time curve might perhaps be improved further by adding optotype sizes around the VA threshold. Note, however, that there are certain limitations to this that are imposed by the available space (distance from participant to screen) and display resolution.
CONCLUSIONS

The data we obtained from 5- to 12-year-old schoolchildren with normal vision revealed large improvements in visual processing speed over the course of 8 years of development that have not been documented before. This suggests that quantitative assessment of visual processing speed may be crucial for a better understanding of the developing visual system in general and better assessment of the impact of VI in clinical populations. The current data provide the required normative data.

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