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Development of Visual Acuity in Children: Assessing the Contributions of Cognition and Age in Lea Chart Acuity Readings

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The development of human vision has been thoroughly investigated in infants, and it is well known that there is a very rapid improvement in many visual functions from birth until the child is a few months old.[1, 2] After this, development typically progresses at a slower rate until adult levels are reached. The once common belief that vision was fully developed before the age of ten has, however, been successfully challenged. For example, De Vries-Khoe and Spekreijse used pattern visual evoked potentials (VEPs) to demonstrate that visual acuity continues to mature until puberty. [3] Similarly, depending on the method used, contrast sensitivity has been found to continue to mature beyond puberty. [4, 5] Developmental changes in refractive error have also been confirmed by a number of researchers with reports of decreasing hyperopia or increasing myopia in schoolchildren. [6-9] Thus, there is a body of research that has demonstrated continuing visual development in acuity and refraction in school age children.

Later occurring developmental changes have been documented for several aspects of visual function. [10-14] However, there are, to date, no studies which have compared these developmental changes with other predictors of change. It is therefore possible that the developmental changes reported are the result of improvements in other related abilities. For instance, it has been demonstrated that age related changes in cognitive processing can disappear when controlling for visual acuity. [15] This suggests that there is a need to consider the mutual relationships between age, cognition and visual acuity. Consequently, the power of age and cognition to predict visual acuity in school age children has been investigated in this study. From a clinical point of view, a strong relationship between vision and cognition should encourage practitioners to take both into account – preferably by better multidisciplinary collaboration to fulfill the patient’s needs. We predicted that even basic visual tasks like visual acuity might be at least as dependent on cognitive ability as age.

Methods

Participants

The data reported here were collected to serve as control data for a larger study investigating visual function in premature children. For the purpose of the study, 90 typical children; 15 typical children each from kindergarten aged between 5.0 and 6.0 years, and school grades one to five, aged 6.5 to 11.0 years, were recruited, and the results from this group are analyzed here. The rationale for choosing this age-range and the numbers from each grade was to provide suitable developmental trajectories for comparisons with a more limited index-group of premature children in our larger study. The typical children were born at term (+/- 2 weeks), were equally distributed by gender (53% Female) and came from similar socioeconomic areas in the western part of Oslo. Nine children from this group were excluded from analyses; two children due to premature birth, one child due to a diagnosis of autism, two children with previously undetected low visual acuities in both eyes (best eye > 0.4 logMAR at three meters), and four additional children because of under-correction of more than -0.25DS (spherical equivalent by retinoscopy). This cut-off point was chosen because distance acuity was tested at three meters, and higher levels of myopia will result in a reduction in acuity at this distance. Thus, data from 81 children (42 Female) were included in the analyses. Prior analyses showed that there was no significant change in refraction as a function of age in this specific group, and the mean spherical equivalent refraction was +0.82 (standard error: 0.10) for 162 eyes. Informed consent was obtained from all participating families after they had received an explanation of the nature and possible consequences of the study in writing. Both parental consent and individual child participant assent were obtained. The study was approved by the regional ethics committee for medical research at the University of Oslo and followed the tenets of the Declaration of Helsinki.

Clinical tests

For the purpose of this study, tests were limited to habitual/presenting visual acuities at 3 m (Lea chart) and a test of cognitive ability (Raven's Colored Progressive Matrices; RCPM).

The recommended standard test procedure was used for the Lea chart. This chart has five symbols in each row, and the children were first asked to read the symbol on the same side as the eye that was being assessed, i.e. left side for left eye, for each row from the top until they made a mistake. They were then instructed to read the row above the mistaken symbol. Support was given by covering symbols below with a blank sheet, but single symbols were not indicated by pointing. If the children were able to read more than three symbols in a row, they were asked to move to the next line. If less than three symbols were named correctly, they were asked to try the row above. In order to calculate visual acuity, we counted the number of symbols identified correctly and used this to calculate mean logMAR acuities for each child's left and right eye as indicated in the procedure for this test. An overall mean acuity was then calculated by taking the mean of left and right eye acuities. This overall mean has been used in the analysis below as an alternative to binocular visual acuity to avoid the potential source of error from any binocular vision problem.

The rationale for choosing the Lea chart in this research is that it is easily accessible, it can be used to compare visual acuity in readers and non-readers while still providing a reliable measure of visual acuity, similar to the letter chart. Moreover, the need to persuade reluctant children to make guesses was reduced because all the symbols typically look like circles when they are too small for the child to discriminate. This makes it suitable for use with the complete age range of children used in this research

The Raven's Colored Progressive Matrices (RCPM) test is a common standardized test for measuring cognitive ability in children between the ages of five and eleven years, the age span used in this study. [16-18] We used a computerized version of the test. The English computerized version has been found to be as reliable as the paper based version. [19] We have translated the English instructions and comments into Norwegian using a professional sound studio to ensure optimal quality of the sound files. Thus, each participant was ensured an identical set of instructions.

While there are age norms available for the RCPM test, we have chosen to use simple raw scores in our analyses. On average, older children will achieve higher raw scores on this test (more matrices correctly completed), however we argue that the raw score is a purer measure of intelligence since these scores are not corrected for age. Whatever the age of the child, a score of, e.g. 10 completed matrices, is treated the same whether achieved by a child of 8 or 12 years of age.

Procedure and scoring:

The child was first shown an instructional video on the computer. It showed that a piece was missing in a figure, and explained why some of the six pattern samples did not fit. The child was then asked to point at (or report the number adjacent to) the correct pattern. If the wrong pattern was chosen, more explanations were given. Otherwise, the test commenced. The RCPM test compromises three sets of twelve tasks with increasing difficulty. A raw score of 36 is therefore the highest achievable score.

Analysis

Analysis by gender revealed no significant differences in any of the variables measured, thus all analyses were collapsed across gender.

In order to explore visual development in typical children, continuous variables have been analyzed. Variables were tested for normality using the Kolmogorov-Smirnoff (KS) test and by evaluating histograms, probability-probability (P-P) plots and levels of skew and kurtosis.

Since partial correlations require data to be normally distributed, the SPSS bootstrap facility has been used to ensure that the Pearson correlation factor is valid for all variables. In this case, the impact of outliers and anomalies has been reduced by resampling each sampling distribution from the data set 1,000 times, allowing for a robust outcome.

Trajectories for change in visual acuity by age and cognitive ability have been plotted. Lines indicating 95% confidence intervals for linear fits to the data were calculated. In addition, for the relation between logMAR visual acuity and age, an asymptotic fit was also calculated since this reflects developmental changes that occur in the first years but flatten out later during development. Fitting an asymptotic curve provides estimates for two parameter: the age at which acuity reaches an asymptote ($ß_0$) and the age at which the level of acuity doubles ($ß_1$). Visual acuity measures were converted to MAR before estimating the asymptotic function. Parameter estimation was based on minimization of the least squares of the residuals. Parameters were then converted back to logMAR acuity in order to be comparable to linear fits.

Pearson correlations were calculated to investigate associations between measures of visual acuity, cognitive ability and age. These are then followed by a regression analysis in which the impacts of cognition and age on visual acuity have been examined.

SPSS v. 21 and Microsoft Excel for Mac v 16 were used for analyses.

Results

Developmental trajectories

We conducted correlation analysis to determine the linear relationships between acuity and age and acuity and cognition. Data for the primary correlation analyses are shown in Table 1.

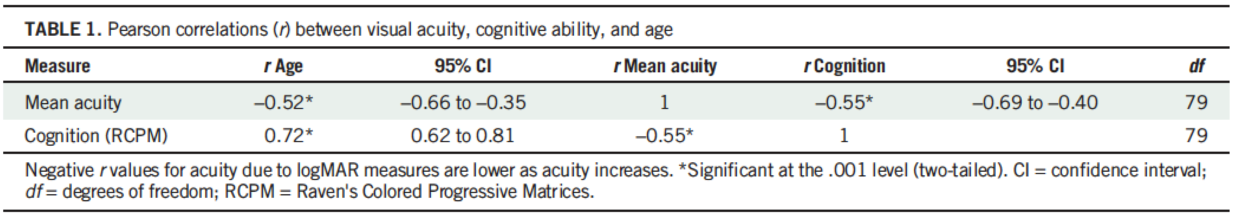

TABLE 1. Pearson correlations (*r*) between visual acuity, cognitive ability, and age

Measure	*r* Age	95% CI	*r* Mean acuity	*r* Cognition	95% CI	*df*
Mean acuity	–0.52*	–0.66 to –0.35	1	–0.55*	–0.69 to –0.40	79
Cognition (RCPM)	0.72*	0.62 to 0.81	–0.55*	1		79

Negative *r* values for acuity due to logMAR measures are lower as acuity increases. *Significant at the .001 level (two-tailed). CI = confidence interval; *df* = degrees of freedom; RCPM = Raven's Colored Progressive Matrices.

Significant linear correlations were found between acuity and both age and cognition.

The development of visual acuity as a function of age and cognition, respectively, in this sample of typical children aged 5 to 11 years old is shown in Figures 1 and 2. An asymptotic function produced a good fitting trajectory for the relationship between age and acuity (logMAR VA = ß$_0$*2^(ß$_1$/age) ß$_0$ = -0.16; 95% CI = -0.12 to -0.21; ß$_1$ = 3.18; 95% CI = 2.45 to 3.92**:** Figure 1: Upper Panel). Acuity increased with age until about 8 years of age after which the trajectory became shallow demonstrating less change after this point. However, a linear fit also produced a significant fit (logMAR VA = -0.031*age + 0.18: $R^2 = .26$, $p < .001$: Lower Panel). Least squares normalized error for the asymptotic (0.69) and linear fit (0.77) were not significantly different (Paired T-Test: t = -1.76, *p* (two-tailed) = 0.081).

A linear fit was calculated for the relationship between RCPM score and acuity (Figure 2). The linear fit provided a good fit for the relationship between acuity and cognitive ability (logMAR VA = -0.0084*RCPM Raw Score + 0.15: $R^2 = .32$ $p < .001$).

Figure 3 shows the significant positive linear correlation between age and cognition in this sample of typical children (RCPM = 3.05* Age + 1.95: $R^2 = .55$, $p < .0001$).

***** Figures 1, 2 and 3 about here *****

Since cognitive ability and age are each strongly correlated with acuity in this sample, it is possible that the association between acuity and age is moderated or mediated by cognitive ability.

To investigate this further, and since we found strong linear relationships between visual acuity and both age and cognitive ability, partial correlations with acuity against age or cognition were calculated while controlling for cognition or age respectively (Table 2). These analyses show that while age no longer predicted developmental changes in visual acuity after controlling for cognition, cognition continued to predict changes in visual acuity after controlling for age.

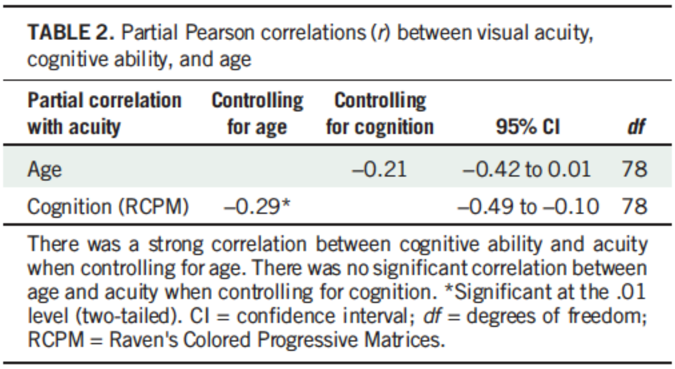

TABLE 2. Partial Pearson correlations (*r*) between visual acuity, cognitive ability, and age

Partial correlation with acuity	Controlling for age	Controlling for cognition	95% CI	*df*
Age		−0.21	−0.42 to 0.01	78
Cognition (RCPM)	−0.29*		−0.49 to −0.10	78

There was a strong correlation between cognitive ability and acuity when controlling for age. There was no significant correlation between age and acuity when controlling for cognition. *Significant at the .01 level (two-tailed). CI = confidence interval; *df* = degrees of freedom; RCPM = Raven's Colored Progressive Matrices.

The relative predictive value of age *vs.* cognition was also examined using regression/ANOVA analysis, with visual acuity as the dependent variable. The results show a significant effect of cognition on acuity, $F(1, 78) = 7.37$, $p = .008$ ($B = -.005$, 95% confidence limits: -.009 to -.001) with the effect of age on acuity only approaching significance, $F(1, 78) = 3.57$, $p = .063$ ($B = -.015$, 95% confidence limits: -.032 to .001).

Discussion

Developmental trajectories and baseline data for typical Norwegian children aged five to eleven years for age, cognitive ability and distance visual acuity are reported. Both age and cognitive ability were found to be predictors of developmental changes in visual acuity.

As seen from the age-dependent trajectory, there is a clear improvement in visual acuity in our sample (Figure 1). This is in contrast to earlier research, suggesting that acuities are fully developed by the age of six [20] but is in line with more recent publications which suggest that acuity develops beyond this age. [21] Explanations for these differences include type of test used, ceiling effects and age span of the children examined. Lewis and Maurer (2005) suggested for example that while grating acuity was adult-like by four to six years of age, letter acuity reached adult levels at six years of age. [20] Langaas measured binocular and monocular visual acuity with Glasgow Acuity Cards (logMAR crowded) in a group of 75 emmetropic children aged five to eleven years. [21] Monocular measures were compared with single-letter acuity (logMAR non-crowded) for a similar group of 52 children. The results demonstrated that crowded letter acuity but not single-letter acuity significantly improved with age in children aged five to eleven years. This supports our finding of improvement in crowded letter acuity over the same age range. Another reason for differences in findings is that some acuity tests stop at 20/20 (1.0 or logMAR 0.0) Snellen acuity, which is regarded as adult-like. [22] It is therefore not unusual to end testing in a study when this level is reached and conclude that this age level represents the age of fully developed acuity. Our study is not the first to show that mean acuity can be considerably better than 20/20 in school-aged children. [23] Both linear and asymptotic functions provided good fits to the data with no significant difference in the least squares normalized errors. Thus, while an asymptotic curve for the development of acuity suggesting a limit for acuity improvement, the data is equally well fit by a linear function suggesting that there is continuing improvement in visual acuity across the age range tested here (5-11 years of age). For the association between acuity and cognition, the relationship was best fitted by a linear trajectory suggesting that cognitive ability was predictive of visual acuity across the whole range of abilities measured in this sample.

In this study, we found significant associations between age and acuity and cognition and acuity. Several previous studies have also described such associations. For example, Haugen, et al. found a correlation between performance IQ measured with the WPSSI-R test and visual acuity in their group of extremely premature children. [24] Heron and Chown described an association between reduced Raven's progressive matrices score and decline in visual acuity amongst elderly people [25] and it has also been suggested that there must be a common factor for decline in visual acuity and cognitive function. [26] Thus, visual acuity and cognition appear to be associated. Our data confirms the existence of a such an association in typical school age children.

Visual acuity is a measure of the ability to detect small, i.e. high spatial frequency, objects at high contrast, and the different methods available require varying degrees of visual perceptual and cognitive abilities from the individual being tested. Electro-physiological Visual Evoked Potentials (VEPs) measured in a lab can provide an objective measure of acuity with very low demands from the patient. It is therefore possible that this measure of acuity will be relatively independent of cognition as few cognitive demands are made of the participant. Similarly, preferential looking tasks, such as Teller Acuity Cards (grating acuity) or the Cardiff Acuity test, only require a “pattern-seeking brain” to direct eye-movements towards an object and are therefore low in task demand. By contrast, crowded letter charts demand several skills, including language, directionality, spatial abilities and memory. As a result, the cognitive demands of this type of test are greater and therefore more likely to be influenced by the cognitive ability of the child.

The relationship between Lea chart acuity and RCPM cognitive abilities might be the result of shared visual demands for these tasks. While the demands on fine visual acuity to solve the RCPM tasks are very low, visual abilities such as directionality, understanding patterns and the ability to concentrate on several symbols simultaneously are required when children are tested using both the RCPM and acuity charts.

Despite the low demands on visual acuity on RCPM tasks, refractive errors could perhaps interfere with the RCPM scores due to fatigue or distortions. It has also been shown that higher levels of hyperopia in children (> +5.00 DS in one meridian) correlate with reduced levels of cognition – even when the refractive errors have been corrected. [27] The population of typical children tested in this study did not have large refractive errors and so this is unlikely to have contributed to the results reported here.

It is in the nature of RCPM that there is an effect of chronological age on cognition since older children are able to solve more of the matrices and therefore receive a higher raw score (Figure 3). The relationship between the two is not perfect however (r^2 = 0.52). In developmental research it is common to distinguish chronological age from cognitive or mental age.[28] Mental age is derived from cognitive test performance predicted for a particular chronological age and so is a measure of how a particular child compares to their peer group. Since measuring visual acuity, while a relatively simple task, has some cognitive demands, the cognitive age of a child might be expected to be predictive of this measure in addition to chronological age. The results of this study indeed suggest that cognitive abilities are a predictor of visual acuity.

One important limitation of this study is the use of The Raven's Colored Progressive Matrices (RCPM) as the only test for cognition. This test does not cover cognitive factors such as working memory, problem solving, or learning ability well. Nonetheless, the RCPM is recognized as a test of non-verbal reasoning abilities and non-verbal or general intelligence, and visual perception is an essential part of it. [18]

Another limitation is that correlation analyses are not suited to infer causation. There is still a possibility that reduced acuity might create limitations in development of cognition or that both are dependent on a common factor, as suggested by Salthouse et al. [26]

We acknowledge that Lea charts are more cognitively demanding than other forms of acuity tests, and that we cannot state that development of visual acuity per se is more related to RCPM cognition than age. An idea for further research would be to repeat this study with a more objective test for acuity, such as preferential looking tasks or Visual Evoked Potentials (VEPs). Unfortunately, this is complicated by the smaller time-window for development of acuity assessed by these methods and the age limitations for the RCPM test from five to eleven years.

Conclusions

It is clear that visual acuity continues to develop during the school years, although this measure has previously been suggested to be fully developed in the preschool child. Of particular interest is that acuity seems to be mediated by both cognitive ability and age as predictors of developmental change. Thus, future studies should control for aspects of cognition when investigating visual function development.

From a clinical perspective, these results suggest that it might be important to develop norms for acuity that take into account both age and cognitive ability. These would provide more accurate norms from which to assess whether an individual child's acuity is within the expected range. This study is unable to conclude whether measured acuity is worse for children with lower cognitive ability because of the demands of the acuity test or because of some direct relationship between development of acuity and cognition. It will therefore be important to determine whether changing the cognitive demands of acuity testing improves measured acuity (suggesting a link between task demand and acuity) or not (suggesting a more direct link between development of acuity and cognition). Until these relationships are fully explored, clinicians might be best advised to use tests of acuity that have low cognitive demands, for instance, single letter acuity tests, to measure best possible acuity. Additional tests will then be necessary to determine the effect of crowding on acuity.

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Preliminary results in the form of age-related trajectories for this group of children have been presented as a poster at the Child Vision Research Society Conference, Royal Visio, The Netherlands, in 2011. The authors have no declared conflict of interest or financial disclosure.

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Figures

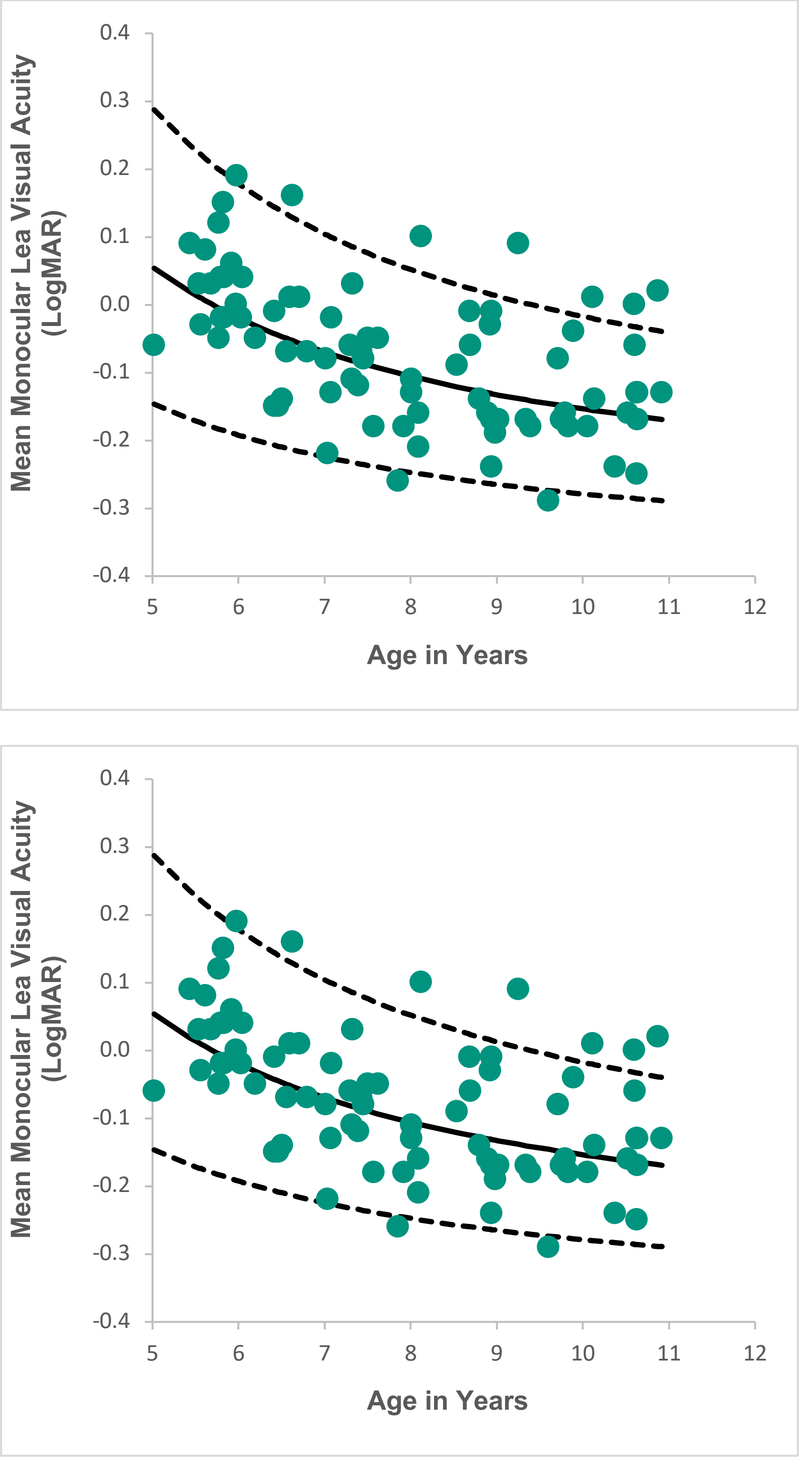

Figure 1 logMAR visual acuity tested with Lea symbols as a function of age. The upper panel shows the data fitted by an asymptotic curve (solid line). Mean logMAR acuity @ 3 meters, (logMAR VA = β_0*2^(β_1/age) β_0 = -0.16; 95% CI = -0.12 to -0.21; β_1 = 3.18; 95% CI = 2.45 to 3.92. The lower panel shows the data fitted by a linear regression (solid line). Mean logMAR acuity @ 3 meters, (logMAR VA = -0.031*age+1.18): R^2 = .26, p < .001. Dotted lines represent 95% confidence intervals.

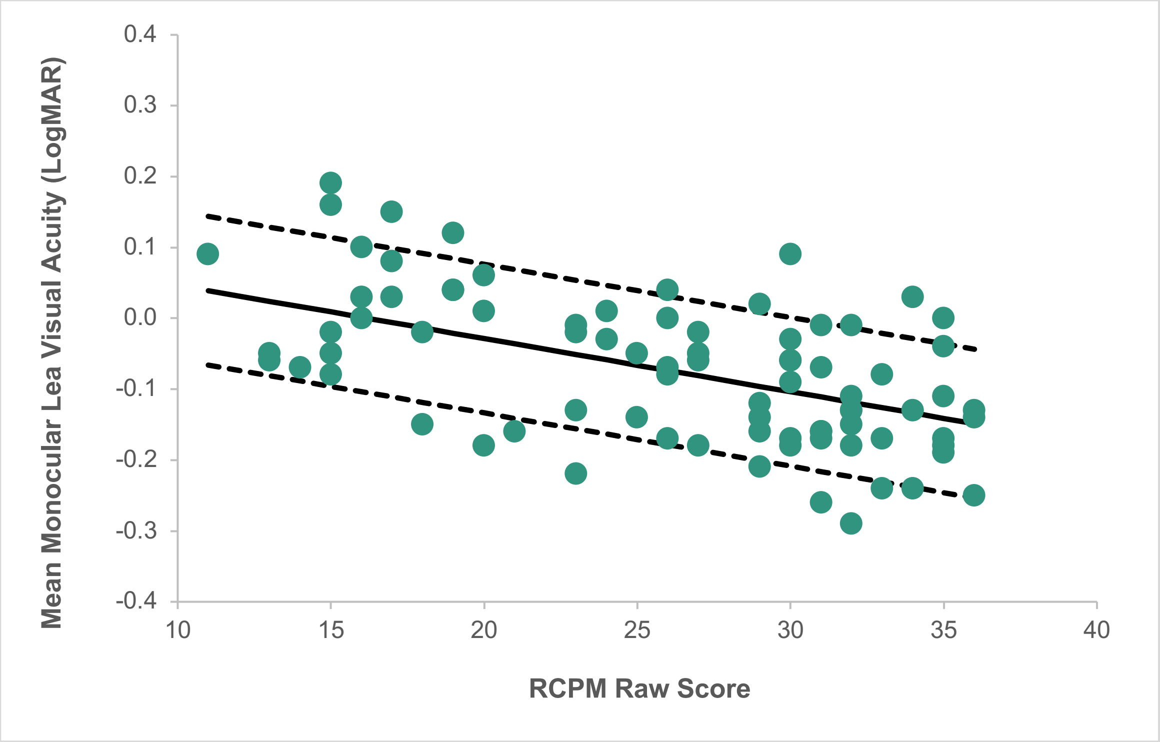

Figure 2 logMAR visual acuity tested with Lea symbols as a function of cognition (RCPM**;** Raven's Colored Progressive Matrices raw score). The solid line represents the fit to the data and dotted lines represent 95% confidence intervals. The data are best fitted by a linear regression. Mean logMAR acuity @ 3meters, (logMAR VA = -0.0084*RCPM + 0.15: R^2 = .32, p < .001).

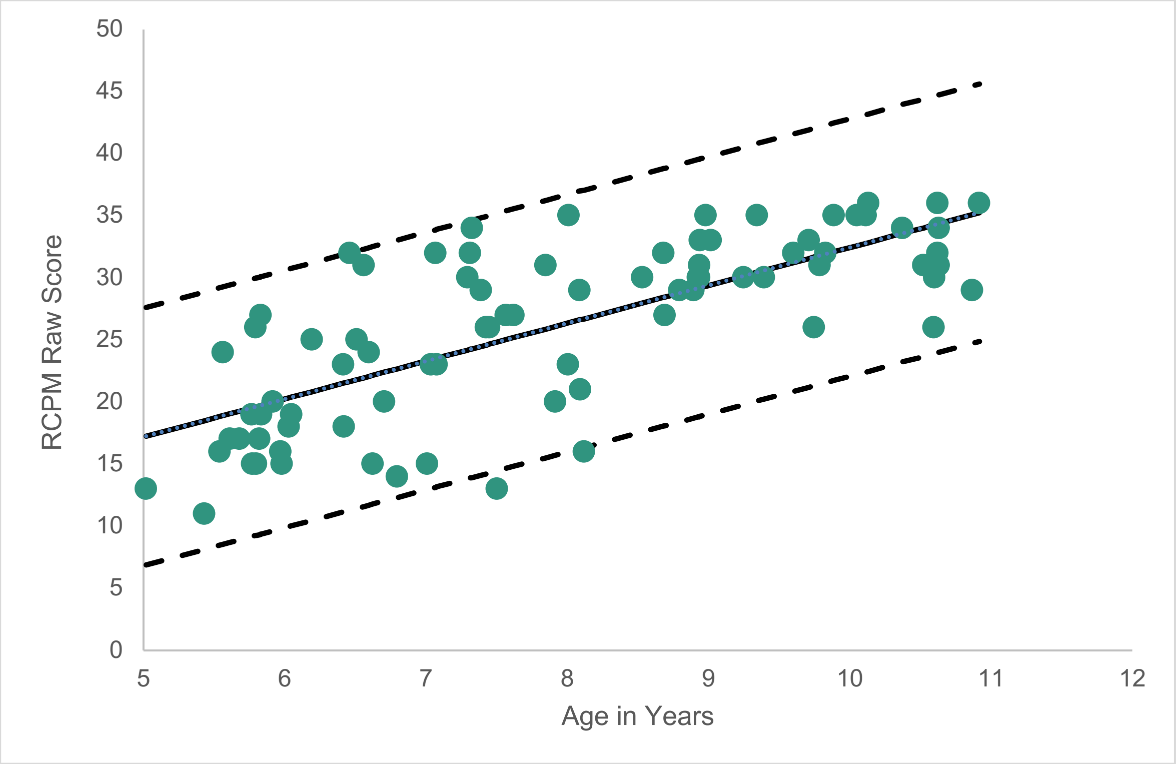

Figure 3 RCPM (Raven's Colored Progressive Matrices raw score) as a function of age. The solid line represents the fit to the data and dotted lines represent 95% confidence intervals. The data are best fit by a straight line (RCPM = 3.05* Age + 1.95: $R^2 = .55$, $p < .0001$).