

The Influence of Age on Eye Movements during Reading in Early Elementary School Children

Untersuchung der Augenbewegungen bei Kindern im frühen Grundschulalter während des Lesens

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ABSTRACT

Purpose Eye movement disorders have been observed in many eye diseases, such as amblyopia and developmental dyslexia. The detection of pathological eye movement behaviour is difficult and requires more data for comparison. Therefore, the main purpose of this study was to evaluate the influence of age, school level, gender, and mother tongue on eye movements while reading.

Methods One hundred and twenty-seven normally sighted children aged 7–12 were recruited from grades 2–5. The chil-

dren were asked to read aloud two texts of The New International Reading Speed Text (IREST) of similar difficulty. Eye movements while reading were recorded by eyetracking technology (SMI RED 250, SensoMotoric Instruments, Teltow, Germany). The eye movement parameters were obtained from 118 children, and reading speed (words/minute), number of saccades, number of fixations, reading errors, and influence of school grade were analyzed.

Results We showed a significant influence of age in all eye movement parameters. The main finding of this study is that younger children performed more saccades, a higher number of fixations per word, and more reading errors while taking more time to read the text than older children in higher grades. In early grades, non-native German speakers read more slowly and performed more saccades and fixations, but no more differences were seen by grade 5. Overall, there was no significant influence of gender or school system on reading parameters.

Conclusion This study highlights the need for an age-appropriate normative database for eye movements during reading.

ZUSAMMENFASSUNG

Hintergrund Augenbewegungsstörungen wurden bei vielen Augenkrankheiten beobachtet, z. B. bei Amblyopie und Legasthenie. Der Nachweis eines pathologischen Augenbewegungsmusters ist schwierig und erfordert mehr Normwerte zum Vergleich. Daher war das Hauptziel dieser Studie, den Einfluss von Alter, Schulstufe, Geschlecht und Muttersprache auf die Augenbewegungen beim Lesen zu untersuchen.

Methode Insgesamt wurden 127 Primarschulkinder (2.–5. Klasse) im Alter von 7–12 Jahren untersucht. Die Kinder wurden gebeten, zwei Texte des New International Reading Speed Texts (IREST) mit ähnlichem Schwierigkeitsgrad laut vorzulesen. Die Augenbewegungen während des Lesens wurden mit der Eye-Tracking-Technologie (SMI RED 250, SensoMotoric Instruments, Teltow, Deutschland) aufgezeichnet. Die Augenbewegungsparameter von 118 Kindern wurden analysiert in Bezug auf die Lesegeschwindigkeit (Wörter/Minute), Anzahl der Sakkaden und Fixationen, Lesefehler und Einfluss der Schulstufe.

Ergebnis Wir konnten einen signifikanten Einfluss des Alters auf alle Augenbewegungsparameter nachweisen. Das Hauptergebnis dieser Studie ist, dass jüngere Kinder mehr Sakkaden, eine höhere Anzahl von Fixationen pro Wort und mehr Lesefehler zeigten, sowie mehr Zeit zum Lesen des Textes benötigten als ältere Kinder in höheren Klassenstufen. In den ersten Klassenstufen lasen Nichtmuttersprachler langsamer

und führten mehr Sakkaden und Fixationen aus, aber in der fünften Klasse wurden keine Unterschiede mehr festgestellt. Insgesamt zeigte sich kein signifikanter Einfluss des Geschlechts oder des Schulsystems auf die Leseparameter.

Diskussion Diese Studie veranschaulicht den Bedarf an altersgerechten normativen Daten zur Beurteilung von Augenbewegungen beim Lesen.

Background

Accurate reading as well as reading comprehension are fundamental in today's society. Reading is an acquired and complex task that requires a wide range of capabilities, strategies, knowledge bases, and cognitive processes [1].

While reading a text, the eyes make a series of fast movements (saccades) separated by pauses (fixations). The saccades are typically forward movements of 7–9 characters where the eyes fixate from one point to the next [2], but they occasionally move backwards (backward saccade) to refixate a previous point [3–7]. The assessment and process of reading has been evaluated extensively in competent adult readers, as well in readers with visual disabilities [5,8]. Numerous investigators who evaluated reading skills have focused on reading speed as a measure of performance. The results of early studies have shown that competent fast readers produce fewer and larger saccades, fewer fixations, fixations of shorter duration, and fewer regressions [9].

Only a few studies have evaluated the developmental aspects of eye movements during reading [5,8]. Compared with adult readers, children need more and smaller saccades, more and prolonged fixations and thus read slower [10–13]. There is also a big difference in the recognition and perceptual span, which is the area where readers can acquire useful information around each fixation. Competent adult English readers typically have a perceptual span ranging from 3 to 4 letter spaces to the left and 14 to 15 letter spaces to the right of the fixation [14,15]. Several authors have shown that the perceptual span is smaller in people learning to read and in dyslexic readers compared to proficient readers [11,16–18].

Eye movements are affected in many diseases, which may influence reading ability. One of the most common learning disabilities is dyslexia, which is a phonetic disorder where, as a result, individuals have difficulties with accurate or fluent reading. The prevalence of dyslexia is estimated to be 5–17% of school-aged children [19] and there is a significantly higher male-to-female prevalence ratio (2–4:1) [20]. The eye movement behaviour in dyslexic children differs from competent readers in that they need more and longer fixations as well as more saccades with shorter amplitudes and more backward saccades and thus need 2.7–2.9 times as long to read a given text [21,22].

The International Reading Speed Texts (IReST) [23] test was used to assess the reading speed of normally sighted young children in this study. Ten texts were designed for 17 languages and are matched in content, length, and difficulty. The IReST allows a standardised assessment of mean reading speed and variance that allows for the comparison of an individual's reading performance,

especially for comparing results while reading before and after interventions with different texts.

Abnormal eye movements while reading may be influenced by other factors such as age, gender, grade of school, or mother tongue [24]. In an earlier study, we showed the feasibility of recording eye movements in 10- and 11-year-old children (N = 27) while reading [25]. In this current study, we recruited a large cohort of young primary school children and analysed their eye movements across different primary schools and four different school grades. Furthermore, we investigated the influence of age, gender, school level, and mother tongue on reading performance. Finally, we took all these factors into account and included data obtained from the initial feasibility study [25].

Methods and Material

Children were recruited from grades 2–5 from 4 primary schools of the German-speaking part of Switzerland. The study was approved by the Swiss Ethics Committees on research involving humans and conducted in accordance with the Declaration of Helsinki. The class teachers were informed about the aim of the study and its purpose, and permission was obtained. The parents of the participants or the legal guardian signed the written consent, and the children gave their informed consent orally. The children had the possibility of terminating the measurement at any time.

Recruitment criteria for this study were: binocular visual acuity, if applicable with their current correction, > 80 Snellen, no known reading difficulties, no history of difficulty with near vision, no history of vision impairment, and attending primary school. To screen visual impairments, all participants underwent an ophthalmological examination including binocular visual acuity with the eye chart or with the Freiburg Vision Acuity Test (FrACT) [26], cover-uncover test at near to rule out manifest strabismus, and assessment of stereopsis with the Lang II test.

Children were asked to read two texts that were presented in a randomised order in black letters on a white background (New Times Roman, font size of 26) on a laptop screen. These standardised texts were developed by the IReST Study Group and are matched in content, length, difficulty, and linguistic complexity for 19 languages to assess reading speed in normally sighted people [23]. We chose two texts of similar difficulty:

- Text 1: “Biber” with 137 words, 224 syllables, and 681 characters
- Text 2: “Beute” with 138 words, 232 syllables, and 671 characters

The examination was performed in a separate dark room of the primary school as described previously [25]. Briefly, the children

► **Table 1** The table presents age and gender distribution of our children and shows the number of children excluded due to refractive errors per age (worn glasses).

Age		7	8	9	10	11	12
	N = 118	N = 6	N = 11	N = 26	N = 33	N = 36	N = 6
M	58 (49.2%)	5 (83.3%)	6 (54.5%)	14 (53.8%)	18 (54.5%)	12 (33.3%)	3 (50.0%)
F	60 (50.8%)	1 (16.7%)	5 (45.5%)	12 (46.2%)	15 (45.5%)	24 (66.7%)	3 (50.0%)
Excluded	9	1	1		4	3	

sat comfortably at a desk on which a laptop was placed (15-inch HP notebook, resolution: 1920 × 1080 pixels) at a distance of 50 to 80 cm. The children were instructed to read a text aloud as soon as it appeared on the laptop screen and to not correct any mistakes nor go back in the text.

Eye movements were recorded with the SMI eye tracker RED 250 m (SensoMotoric Instruments, Teltow, Germany; <http://www.smivision.com>). The tracker bar was attached below the screen of the laptop. All recordings were obtained binocularly with a sampling rate of 250 Hz and with a gaze position accuracy of 0.4° (tracking resolution: < 0.01 degrees of visual angle). Following a five-point calibration routine [27], two IReST texts were presented in randomised order with a short break of 0.1–1 minute in between.

Analysis of the raw data were processed using the SMI software BeGaze, provided with the SMI RED 250 eye tracker (SensoMotoric Instruments, Teltow, Germany). We evaluated reading speed (words/minute), total number of saccades, number of saccades per word, total number of fixations, number of fixations per word, total reading time, and reading errors. Gender, age, school grade, and native language were also examined as possible factors that could influence outcome parameters. The number of mistakes made (words misread) were noted by the examiner and also evaluated.

Descriptive statistics are shown as counts and frequencies for categorical data, and mean (standard deviation) and median (interquartile range) for metric variables. We employed the Kruskal-Wallis test for means, and chi-squared or exact Fisher test when the expected frequencies were less than 5 in some cell. Overall p values correlate to the t-test for means and a p value < 0.05 was considered significant. All statistical analysis described above were performed by using the statistical software program R version 3.1.1 (R Core Team, R Foundation for Statistical Computing, Vienna, Austria, URL <https://www.R-project.org/>).

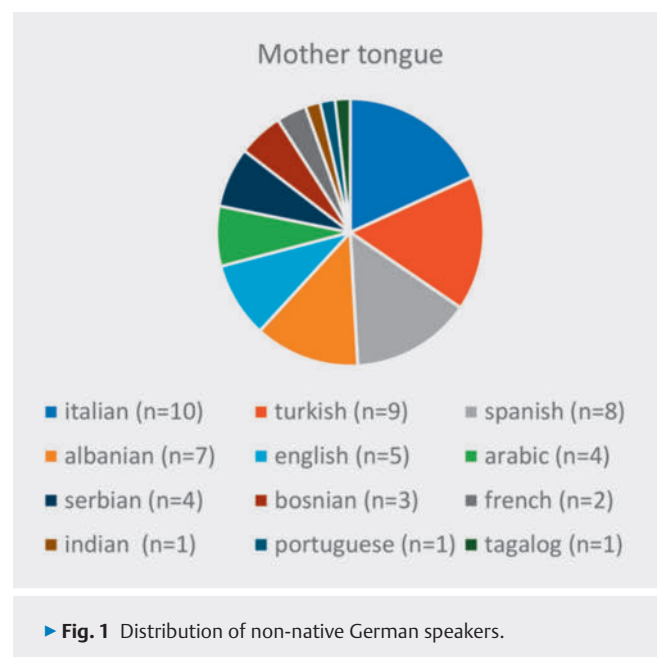
Results

One hundred and twenty-seven children volunteered to take part in this study. The age of the children ranged from 7 to 12 years, and all were recruited from the 2nd–5th grade of 4 different primary schools in Switzerland (Zufikon AG, Pratteln BL, Birsfelden BL, and Rudolf Steiner Schule Basel). Nine children had to be excluded as the eye tracker could not measure the eye movements due to reflections of the corrective glasses they wore. Thus, 118 children (mean age 9.8 SD 1.24, m = 58, f = 60) were included in the data

analysis whose demographics are given in ► **Table 1**. Overall, there was an equal distribution of gender with 60 female and 58 male children. Sixteen children were in 2nd grade, 29 in 3rd grade, 27 in 4th grade, and 46 in 5th grade. Most children were aged 9–11, but only 6 children volunteered to participate at ages 7 and 12. Sixty-three children were German native speakers and 55 had another mother tongue (► **Fig. 1**, p 0.15). Ophthalmic screening showed no visual impairments in any of the participants. The best-corrected Snellen distance visual acuity measured using the Snellen visual acuity was over 1.0 in all but one child, who had an acuity of 0.80. In all individuals, the Lang II was positive and there was no manifest strabismus. No significant difference was found between the parameters of the “Biber” and the “Beute” text. Therefore, we pooled the data from both texts and present our results in the form of one boxplot for each parameter analysed.

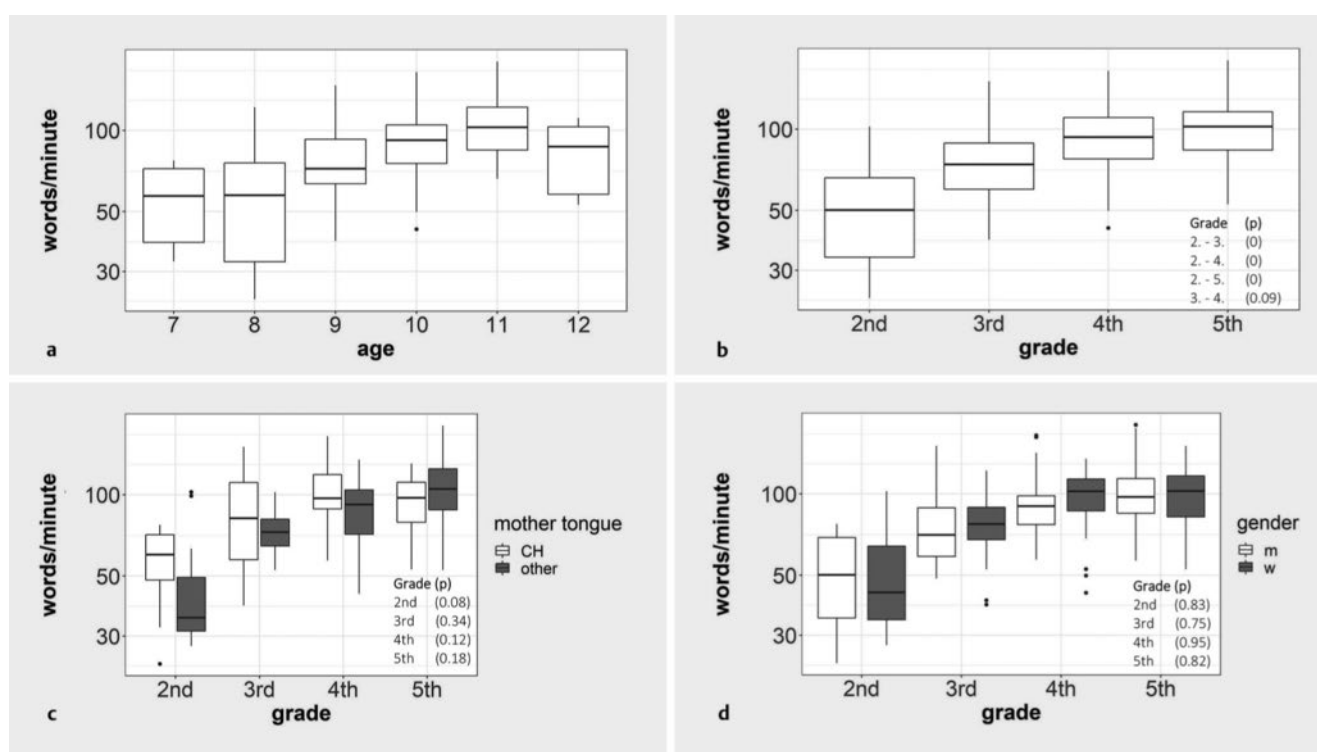
► **Table 2** depicts an overview of the results obtained for children attending the 2nd–5th school grade. ► **Fig. 2** depicts the increase in reading speed according to age (► **Fig. 2a**) and school grade (► **Fig. 2b**), and the influence of mother tongue (► **Fig. 2c**) and gender (► **Fig. 2d**) on the number of words read per minute.

The higher the school grade, the faster the reading speed (► **Fig. 2b**). While 7- and 8-year-old children averaged 57.1 (SD



► **Table 2** The table shows median normative data and 10th and 90th percentiles for each school grade tested.

School level	Percentiles	Reading speed (words/minute)	Number of saccades (saccades/word)	Number of fixations (fixations/word)	Reading errors (reading errors/word)
2nd class	10th	29.92	0.88	0.82	0.02
	median	50.13	2.52	2.21	0.05
	90th	74.27	10.35	4.74	0.10
3rd class	10th	52.69	0.72	0.89	0.01
	median	74.06	1.05	1.29	0.04
	90th	111.2	1.43	1.70	0.07
4th class	10th	67.15	0.88	1.12	0.01
	median	93.41	1.16	1.44	0.03
	90th	133.4	2.79	2.21	0.06
5th class	10th	68.55	0.85	0.97	0.01
	median	102.2	1.19	1.36	0.03
	90th	129.2	2.05	2.03	0.05

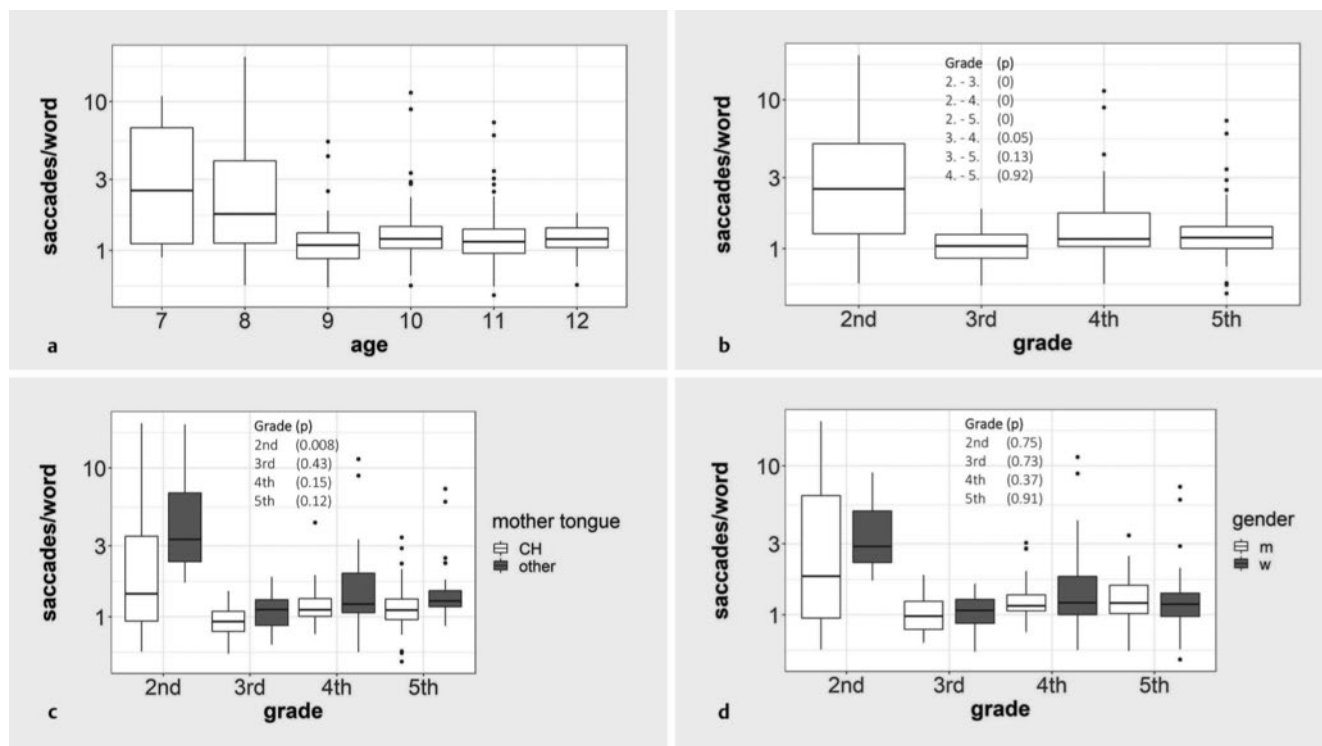


► **Fig. 2** Boxplots of reading speed in words/minute according to (a) age, (b) school level, (c) mother tongue, and (d) gender. For each boxplot, the bottom of the rectangle indicates the first quartile, the top indicates the third quartile, and the horizontal line in the middle of the rectangle marks the median.

17.27) vs. 57.49 (SD 29.27) words per minute, mean reading speed increased to 72.11 (SD 24.62) at 9 years of age, 92 (SD 26.24) at 10 years, and to 102 (SD 25.41) words/minute at 11 years of age. At 12 years of age, this was slightly slower with 87.01 (SD 22.99) words/minute; however, this age group consisted of only 6 children (► **Fig. 2a**). The influence of mother tongue was not statistically significant. However, ► **Fig. 2c** shows that German native speakers read much faster in 2nd and 3rd grade but the reading

speed of children with a non-German mother tongue increased faster with school grade and they had caught up to native speakers by 5th grade. Overall, reading speed did not differ significantly between genders except for a slower reading speed in girls aged 7 and 12; however, there were only 6 children in these age groups, and this was not statistically significant (► **Fig. 2d**).

► **Fig. 3** shows boxplots of the number of saccades/word and ► **Fig. 4** of fixations/word according to (► **Fig. 4a**) age, (► **Fig. 4b**)



► **Fig. 3** Saccades/word according to (a) age, (b) school level, (c) mother tongue, and (d) gender. For each boxplot, the bottom of the rectangle indicates the first quartile, the top indicates the third quartile, and the horizontal line in the middle of the rectangle marks the median.

school level, (► **Fig. 4c**) mother tongue, and (► **Fig. 4d**) gender. Younger children aged 7 and 8 (► **Fig. 3a**) that is, the children in grade 2 (► **Fig. 3b**), needed significantly more saccades/word and also fixations/word (► **Fig. 4a** and **b**) than the older children. From the age of 9 years and grade 3 onwards, the eye movement parameters did not change significantly. Native German speakers who attend the 2nd grade needed significantly less saccades/word ($p = 0.008$) and fixations/word ($p = 0.03$; ► **Fig. 3c** + ► **Fig. 4c**). There was no gender difference in the number of saccades/word (► **Fig. 3d**) and fixations/word (► **Fig. 4d**).

► **Fig. 5** indicates the total number of errors, that is, mistakes made while reading out aloud. Children aged 7 and 8 made the most errors/word of 0.06 (SD 0.03; ► **Fig. 5a**). The total number of errors decreased with increasing age, apart from the 12-year-old children, who showed slightly more reading errors (► **Fig. 5a**). Consistently, children made significantly more mistakes in grade 2 compared to higher grades. Thereafter, the number of mistakes decreased slowly but not significantly through to grade 5 (► **Fig. 5b**).

The relationship between reading errors/word and mother tongue is shown in ► **Fig. 5c**. Second grade children with a foreign native language made significantly more reading errors compared to German native speakers. Thereafter, a significant difference was no longer observed, as reading errors improved rapidly until 5th grade, where they made less mistakes. Overall, there was no significant influence of gender (► **Fig. 5d**).

► **Fig. 6** demonstrates the correlation between saccades and fixations per word, and between reading speed and reading errors per word. Children who made more saccades also made more fix-

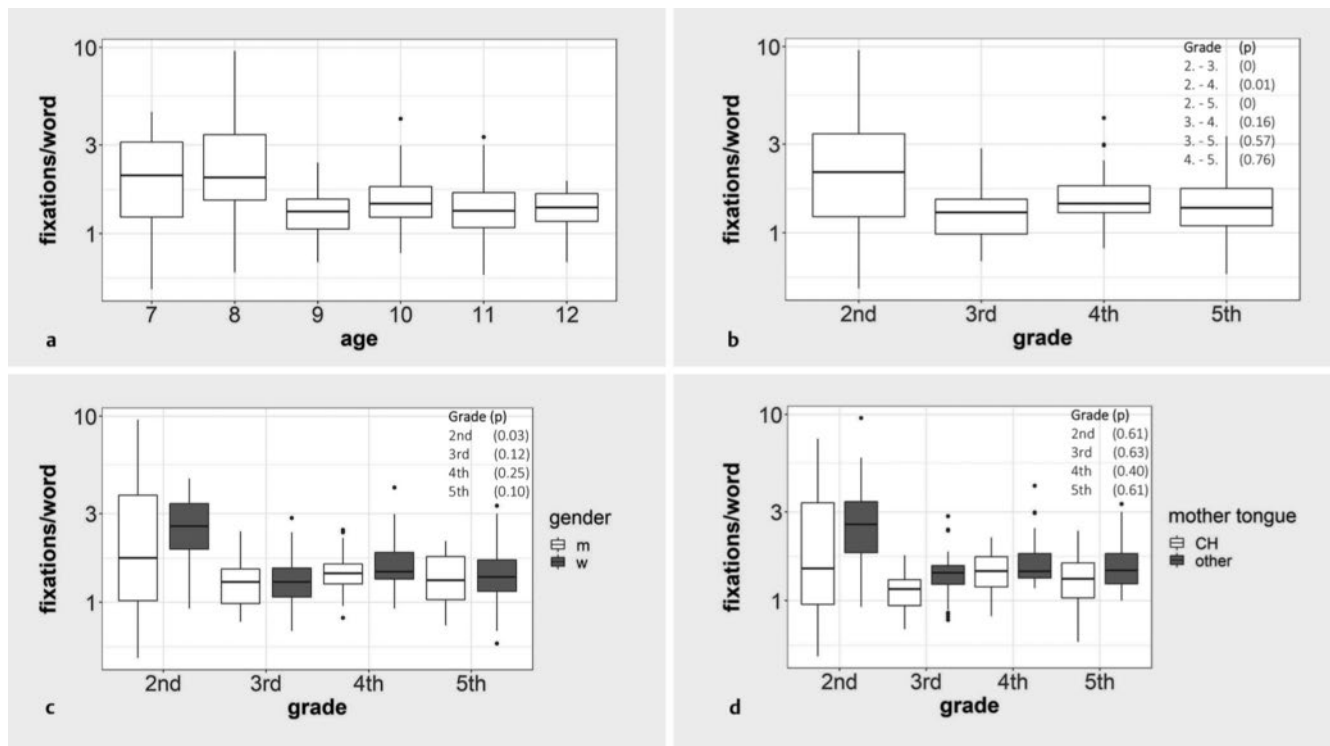
ations. Finally, the faster the children read, the fewer mistakes they made.

Interestingly, we did not find any significant difference in reading parameters between the different schools, three of which were public schools and one a private school with an anthroposophical teaching concept.

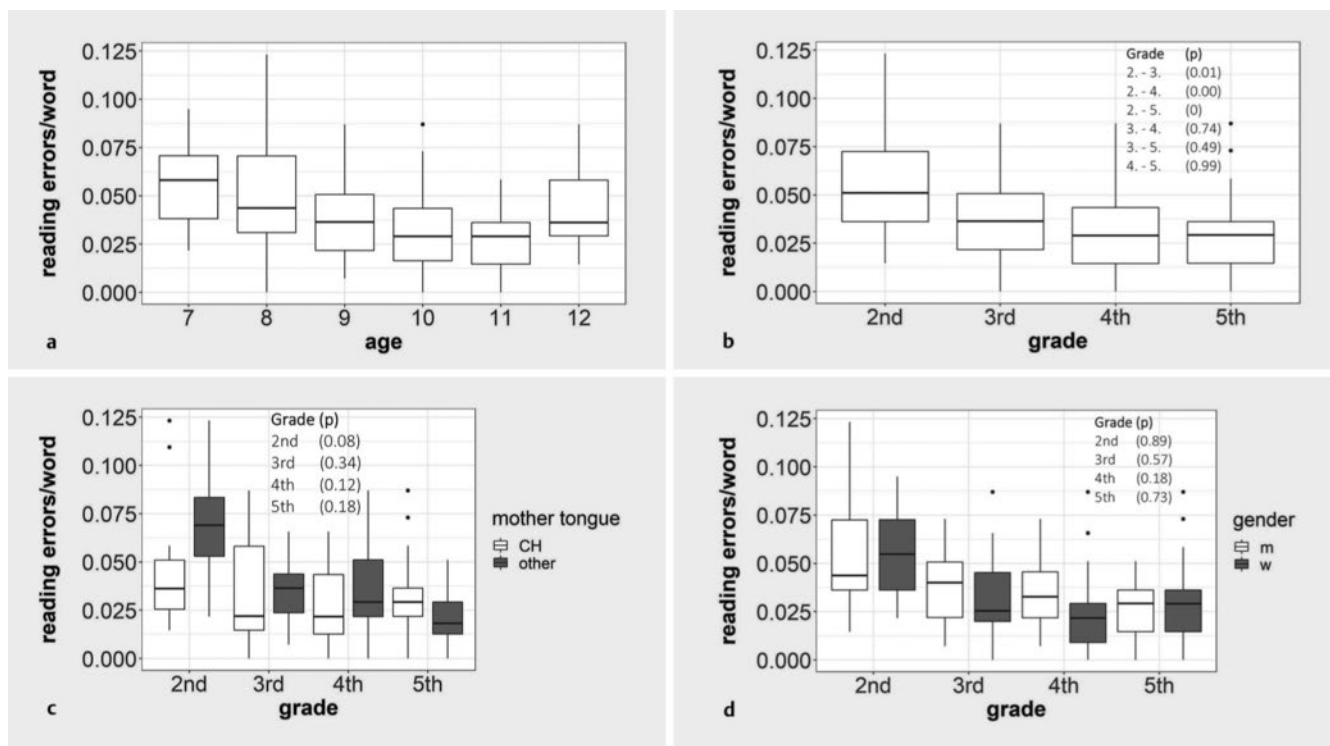
Discussion

Our main objective was to analyse the eye movement patterns during reading in a large cohort of 118 young children of primary school age (grades 2–5) in order to establish normative data and assess the influence of age, school level, sex, and mother tongue. Although the IReST contains reading texts of a difficulty level for 6th grade, we intentionally chose to apply the same reading text for all age groups to assess the reading performance of the same texts.

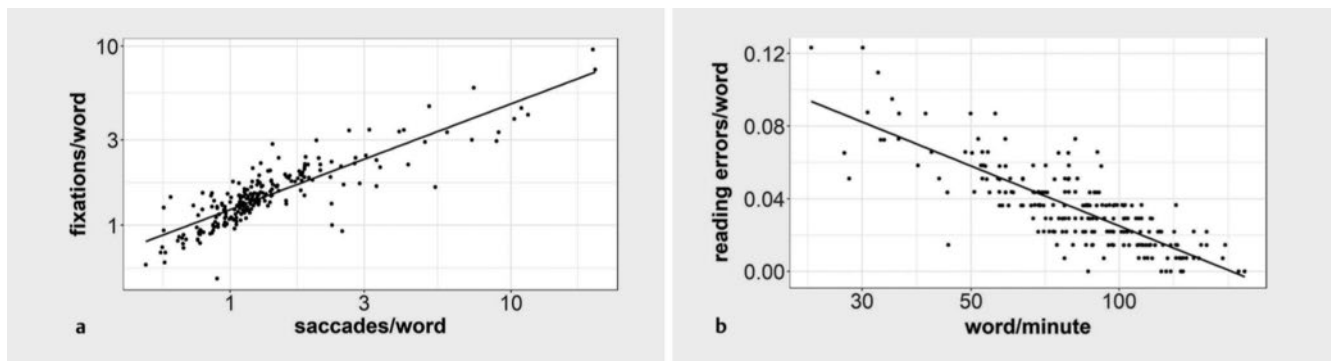
The main finding of this study is an increasing reading speed with age, which confirms the need for normative values in childhood dependent on age and school grade. Reading speed is influenced by several factors, such as age, cognitive ability, reading skill, difficulty of the reading task, and reading aloud or silently. In our study, children of grade 2, who were beginners in reading, showed the slowest reading with most saccades, fixations/word, and reading errors. With increased schooling, reading speed increased, the saccades and fixations needed per word decreased, and errors diminished. The fastest mean reading speed was seen in children in 5th grade, with a median of 102.2 words/minute. This is still 1.75 times slower than in young German adults (18–



► **Fig. 4** Fixations/word according to (a) age, (b) school level, (c) mother tongue, and (d) gender. For each boxplot, the bottom of the rectangle indicates the first quartile, the top indicates the third quartile, and the horizontal line in the middle of the rectangle marks the median.



► **Fig. 5** Reading errors according to (a) age, (b) school level, (c) mother tongue, and (d) gender. For each boxplot, the bottom of the rectangle indicates the first quartile, the top indicates the third quartile, and the horizontal line in the middle of the rectangle marks the median.



► **Fig. 6** Correlation between saccades and fixations per word (a), as well the reading speed and reading errors per word (b).

35) whose mean reading speed was 179 words/minute while reading an IReST text of the same difficulty (6th grade) [23]. Healthy German-speaking children aged 9.6 ± 0.4 years (grades 4 and 5) performed at a mean reading speed of 119.56 (SD 17.60) words/minute [22] for an easier reading task from the Salzburger Lese- und Rechtschreibtest (SLRT) [28], which contains material of third and fourth grade. The slight difference is likely due to the more difficult reading task of IReST (6th grade) but may also be influenced by the different ages at which schooling begins in different countries (6 years in Germany compared to, at the time, 7 years for average first graders in Switzerland).

The same study showed 9.6-year-old children to need between 1.37 (SD 0.20) saccades/word and 1.58 (SD 0.23) fixations/word in the 1st text and 1.21 (SD 0.90) saccades/word and 1.38 (SD 0.26) fixations/word in the 2nd text [22]. The first more difficult text was age appropriate and designed for children in 3rd and 4th grade, while the 2nd text was easier as it was designed for children in 1st and 2nd school grade. This compares to a mean number of 1.79 (SD 2.33) saccades/word and 1.62 (SD 0.97) fixations/word in our children (mean age 9.8 years, SD 1.24). Thus, even though the IReST we applied was designed for 6th grade, our children aged 9.6 (3rd grade) only needed 0.04 fixations/word more compared to an age appropriate SLRT text used in the same age group. In this context, it is important to note that our saccades include both forward and backward saccades.

In the US, English-speaking students in the 4th grade showed a mean reading speed of 119 words/minute [29] for the reading task from the National Assessment of Educational Progress (NAEP, 4th grade difficulty), which was faster than the reading speed in our 4th grade children (median 93.41 words/minute). Another study by Vagge et al. [30] showed competent Italian readers aged 8–13 to use 1.51 (SD 0.50) saccades/word when reading a text silently. In this context, one has to mention that our children read the IReST text aloud, which may have contributed to them needing more time. These results correspond with systematic reviews, which investigated eye movements in silent and oral reading. In three studies, authors have reported significant differences between these two reading modes in adults. They have shown that fixation duration is about 50 ms longer, saccadic amplitude is shorter, and the number of regressions is higher when reading out aloud [5, 8, 31]. As part of the initial diagnostics to determine dyslexia, a reading

test is performed. Various reading tests have been designed to make a statement of the quality of reading, reading comprehension, reading speed, and reading errors. For example, the SLRT (Salzburger Lese- und Rechtschreibtest [28]) and the ZLT-II (Zürcher Lesetest [32]) are reading tasks that the participants read aloud. Other reading tests such as Würzburger Leise Leseprobe [33] are performed silently. Although reading silently is more in line with the natural reading situation, the advantage of reading aloud is that the investigator can evaluate the reading errors.

Overall, German native speakers read faster (94 s vs. 99.25 s) and needed fewer saccades/word (1.09 vs. 1.29) and fewer fixations/word (1.3 vs. 1.48) but made similar reading errors/word of 0.03. Non-native German-speaking children differed significantly from native speakers only in 2nd grade. They quickly improved their skills and there was no more difference by grade 5. An explanation might be that these children attend additional German courses and therefore have more practice in reading.

A gender gap in reading abilities has been recognised and researched over the past couple of decades. A large study by Hedges and Nowell [34] found that girls perform significantly better in reading than boys in each year of assessment (1971–1992). This gender gap has been confirmed in 31 countries and thus seems to be a cross-culture phenomenon [35]. However, in our study, we found no significant influence of gender on reading performance.

Conclusion

This study was performed to establish normative data of eye movements in young children (grades 2–5, aged 7–12) while reading an IReST text. The number of saccades/word, fixations/word, and reading errors decrease with age and school grade in children attending primary school. Thus, the reading speed is higher in older children compared to young beginners in reading. There was no significant influence of gender. While native German speakers had an initial better performance, no significant difference was observed by grade 3. The results of our study indicate the need for an age-appropriate normative database for eye movements in reading.

CONCLUSION BOX

Already known:

- Eye movement disorders have been observed in many eye diseases, but to detect pathology, normative values are important for comparison.

Newly described:

- We established normative data of eye movements in young children.
- Native German speakers had an initial better performance, but no significant difference was observed by grade 3.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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