Vision Research 113 (2015) 33–43

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Word length and frequency effects on children's eye movements during silent reading

Simon P. Tiffin-Richards *, Sascha Schroeder

Max Planck Institute for Human Development, Berlin, Germany

ARTICLE INFO

Article history:
Received 23 December 2014
Received in revised form 8 May 2015
Available online 3 June 2015

Keywords:
Eye movements
Silent reading
Children
Length effects
Frequency effects

ABSTRACT

In the present study we measured the eye movements of a large sample of 2nd grade German speaking children and a control group of adults during a silent reading task. To be able to directly investigate the interaction of word length and frequency effects we employed controlled sentence frames with embedded target words in an experimental design in which length and frequency were manipulated independently of one another. Unlike previous studies which have investigated the interaction of word length and frequency effects in children, we used age-appropriate word frequencies for children. We found significant effects of word length and frequency for both children and adults while effects were generally greater for children. The interaction of word length and frequency was significant for children in gaze duration and total viewing time eye movement measures but not for adults. Our results suggest that children rely on sublexical decoding of infrequent words, leading to greater length effects for infrequent than frequent words while adults do not show this effect when reading children's reading materials.

1. Introduction

Early developmental studies of eye movements clearly show that young beginning readers fixated words for longer than older children and adults (McConkie et al., 1991). The number of fixations on words and hence the probability with which words are refixated also decreases with children's reading proficiency and chronological age (Feng et al., 2009). These developmental trends are generally considered to be due to the increasing efficiency of reading processes, rather than the maturation of ocular-motor control (Blythe, 2014; Reichle et al., 2013; Huestegge, Radach, Corbic, & Huestegge, 2009; Feng et al., 2009). In the present study, we investigate the developmental differences in the effect of word properties on children's and adults' eye movements during reading.

Word length and frequency are two text characteristics which have a direct influence on eye movements of adults during reading of connected text (Rayner, 1998; Rayner, 2009). Long words generally receive longer and more fixations than short words (Hyönä & Olson, 1995; Just & Carpenter, 1980; Kliegl, Grabner, Rolfs, & Engbert, 2004) and infrequent words are fixated longer than frequent words (Inhoff & Rayner, 1986; Rayner & Duffy, 1986). Similar effects have been found in beginning readers (for reviews see Reichle et al., 2013; Blythe & Joseph, 2011). Indeed, younger children show stronger length effects than older children (Huestegge, Radach, Corbic, & Huestegge, 2009), beginning readers generally show stronger effects than skilled adult readers (Blythe et al., 2011; Joseph et al., 2009), and dyslexic reading deficits in children also lead to stronger word length effects (Hutzler & Wimmer, 2004). Similarly, word frequency effects appear larger for children than for adults (Blythe et al., 2009; Joseph, Nation, & Liversedge, 2013). There is also some evidence for stronger word length effects for infrequent than frequent words in children's eye movements (Hyönä & Olson, 1995; Rau, Moeller, & Landerl, 2014; Rau, Moll, Snowling, & Landerl, 2015) while the evidence for adults is less consistent. However, only a few studies have used eye tracking methods with children in experimental designs to investigate the joint effects of word length and frequency on eye movements during reading (Huestegge, Radach, Corbic, & Huestegge, 2009; Hyönä & Olson, 1995; Rau, Moeller, & Landerl, 2014; Rau, Moll, Snowling, & Landerl, 2015). Findings are mixed and may reflect differences in participant ages and reading ability as well as the nature of reading materials used in these studies. In addition, as in all four studies participants read aloud, it is unclear whether findings generalize to children's silent reading (see Ashby, Yang, Evans, & Rayner, 2012; Vorstius, Radach, & Lonigan, 2014). To investigate this issue we present empirical evidence from a silent reading experiment and focus specifically on the interaction of word length and frequency effects

* Corresponding author at: Reading Education and Development (REaD), Max Planck Institute for Human Development, Berlin, Germany.
E-mail address: tiffin-richards@mpib-berlin.mpg.de (S.P. Tiffin-Richards).

http://dx.doi.org/10.1016/j.visres.2015.05.008
0042-6989/

in children compared to adults using strictly controlled target words with age-appropriate word frequencies.

1.1. Routes of visual word recognition

Effects of word length and frequency on word identification play important roles in both theoretical models such as dual route models of visual word recognition (DRC, Coltheart et al., 2001; CDP+, Perry, Ziegler, & Zorzi, 2007; Zorzi, 2010) as well as for computational models of eye movement control during reading such as SWIFT (Engbert, Longtin, & Kliegl, 2002) or EZ-Reader (Reichle et al., 2013). A few studies use theoretical models such as the DRC to interpret the interaction of word length and frequency effects on eye movements and map effects onto different routes of visual word processing (Hawelka, Gagl, & Wimmer, 2010; Rau, Moeller, & Landerl, 2014; Rau, Moll, Snowling, & Landerl, 2015). The DRC, which was originally developed to account for oral reading of single words, assumes that printed words are processed via two competing routes. In the slow, sublexical route words are decoded serially using grapheme-to-phoneme correspondence (GPC) rules to assemble the phonological representations of words (Coltheart, Curtis, Atkins, & Haller, 1993). These phonological representations are then used to activate entries in the phonological lexicon. Word length effects are presumed to indicate sublexical route processes, where words are decoded letter by letter, in which case processing time increases with the number of letters to be processed. In contrast, the faster lexical route searches for a direct match of a words' spelling with representations in the orthographic lexicon. Successful matching leads to fast activation of the corresponding phonological and semantic representations. This process requires the reader to have highly specified mental representations of words which, according to the phonological self-teaching hypothesis, are the result of repeated exposure and successful decoding of a word (Share, 1995; Share, 1999). This item-based learning mechanism implies that the frequency with which a word occurs in written form will affect how often it is encountered and successfully decoded, resulting in higher quality mental representations of high frequency words (lexical quality, Perfetti, 2007). Words which fail to be matched with a corresponding entry in the orthographic lexicon must be decoded using the more laborious sublexical GPC rules. Words with lower natural frequencies are thus more likely to fail to find a direct orthographic match and be processed via the sublexical route which is sensitive to word length, while high frequency words are more likely to be processed via the more direct lexical route in which processing time is not as strongly affected by word length. This account leads to the expectation of an interaction between word length and frequency effects on eye movements during reading, in which word length results in longer fixation durations for infrequent words but not necessarily for frequent words. As children are expected to have a smaller mental lexicon and encounter more unknown or less well known words than adults, the interaction of word length and frequency might be expected to be greater for children than adults.

1.2. Word length and frequency effects in children and adults

There is a large amount of empirical evidence documenting the effects of word length and frequency in adult reading, while the studies of children's eye-movements are quite limited (see reviews in Blythe, 2014; Blythe & Joseph, 2011; Reichle et al., 2013). Longer words are generally fixated for longer durations (Just & Carpenter, 1980), even when fixated only once (Rayner & Fischer, 1996; Rayner & McConkie, 1976), are more likely to receive multiple fixations (Brysbaert & Vitu, 1998; McConkie & Rayner, 1976; Rayner & McConkie, 1976), and are less likely to be skipped by adult readers (McConkie & Rayner, 1976). Studies of word length effects in children suggest a similar pattern for young readers. Studies by Hyönä and Olson (1995) and Vitu et al. (2001) found longer gaze durations and total viewing times for long words than short words in children. These studies did not, however, experimentally manipulate word length, relying rather on post hoc analyses, and did not make direct comparisons with adults. More recently, Joseph et al. (2009) investigated landing positions and fixation durations of children and adults reading words of different lengths, while controlling for word frequency and predictability using carefully designed sentence frames for the target words. They found that children showed stronger effects of word length in gaze duration and in the number of within-word refixations compared to adults. The stronger effects of word length in gaze duration and the number of fixations is hence a consequence of children refixating words on their first pass. This refixation strategy of younger readers was also shown by Blythe et al. (2011) using a disappearing word paradigm in which target words disappeared within 60 ms of being fixated (Rayner, Liversedge, White, & Vergilino-Perez, 2003; Liversedge et al., 2004). This effectively inhibited multiple first pass fixations and reduced fixation durations for both adults and children. However, children tended to regress back to longer words for a second visual sample, suggesting that beginning readers depend on multiple fixations on longer words for complete lexical processing (Aghababian & Nazir, 2000). The evidence thus suggests that children show effects of word length in gaze duration and the number of fixations, not unlike skilled adult readers, and a refixation strategy for long words.

The frequency with which a word occurs in written language has also been shown to have a reliable effect on adult reader's eye movements (Rayner & Liversedge, 2011). Words which are infrequently encountered in written language take more time to process and consequently produce longer fixation durations, are less likely to be skipped, and more likely to receive multiple fixations by skilled adult readers (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kliegl, Nuthmann, & Engbert, 2006; Rayner & Duffy, 1986). Words of high printed frequency are read more often and thus have higher quality representations in the mental lexicon, facilitating word recognition processes. As children have less exposure to written material and hence poorer orthographic lexicon entries, it is highly plausible that frequency effects should be more pronounced in beginning readers (Joseph, Nation, & Liversedge, 2013). Blythe et al. (2009) demonstrated that both children and adults exhibit longer single fixations, first fixations, and gaze durations on low frequency than high frequency words, using the disappearing word paradigm. While not significantly different, the frequency effects were numerically larger for children than adults. In an experiment where children and adults read sentences with embedded words of experimentally varied frequency and controlled length, Joseph, Nation, and Liversedge (2013) also found frequency effects for children in gaze duration and total viewing time, while adults only showed frequency effects in total viewing time. The important aspect of their study was that Joseph, Nation, and Liversedge (2013) used word frequency counts appropriate for children from two corpora ([CPWD] Children's Printed Word Database, Stuart et al., 2003; [WFG] Educator's Word Frequency Guide, Zeno, Ivens, Millard, & Duvvuri, 1995), while the corresponding CELEX word frequencies for adults (Baayan, Piepenbrock, & Gulikers, 1995) did not differ between the high and low frequency target words. Finally, Rau, Moeller, and Landerl (2014) also found a word familiarity effect for children and adults in gaze duration, while Rau, Moll, Snowling, and Landerl (2015) found the effect in both first fixation and gaze durations for children and adults. In summary, the few studies which have measured word frequency or familiarity effects in children suggest that children show word frequency effects which are possibly greater than those found for adults.

Only four studies have so far included both word length and frequency as factors in their designs, allowing an evaluation of their interaction (Huestegge, Radach, Corbic, & Huestegge, 2009; Hyönä & Olson, 1995; Rau, Moeller, & Landerl, 2014; Rau, Moll, Snowling, & Landerl, 2015). The synthesis of their results, however, presents a number of inconsistencies. Hyönä and Olson (1995) found longer gaze durations for long words than short words in their sample of children (mean age 10.5 years) and shorter first fixations and gaze durations for frequent than infrequent words. They also report an interaction between word length and frequency, indicating that the word length effect was greater for infrequent than frequent words in both first fixation and gaze duration. In a longitudinal study, Huestegge, Radach, Corbic, and Huestegge (2009) found a decrease in word length effects in gaze duration and total viewing time from 2nd garde (mean age 8 years) to 4th grade (mean age 10 years) as well as a decrease in the number of refixations on longer words. Similarly, frequency effects were significant in gaze duration and total viewing time and greater for 2nd than 4th graders in total viewing time. However, Huestegge, Radach, Corbic, and Huestegge (2009) did not find an interaction of the two effects (L. Huestegge, personal communication, February, 26, 2015) and neither of these studies compared the effects of word length and frequency on eye movements between children and adults. Two more recent studies have included comparisons between children of different ages and adults. Rau, Moeller, and Landerl (2014) found word length effects in children in grades two (mean age 7.8 years), three (mean age 8.7 years), and four (mean age 10.2 years) as well as adults in gaze duration. The length effects were equal for the youngest children between words of differing familiarity, while length effects were greater for low than high familiarity words for children in grades three and four as well as for adults. In a cross-lingual study Rau, Moll, Snowling, and Landerl (2015) similarly found word length effects for children in gaze duration and word frequency effects in first fixation and gaze durations. They also found stronger length effects for infrequent than frequent words for children in first fixation and gaze duration as well as for adults in gaze duration. An important difference between the materials used in these last two studies and the other studies reported here is that they employed nonwords as low frequency targets (Rau, Moeller, & Landerl, 2014; Rau, Moll, Snowling, & Landerl, 2015) which may have introduced specific nonword reading strategies (see Brown & Deavers, 1999). A possibly more important issue, however, is that all of the four studies of word length and frequency effects reviewed here employed an oral reading paradigm which was necessary to score reading errors. The evidence for an influence of reading modality (e.g., aloud vs. silent) is mixed. While Huestegge (2010) did not find large qualitative differences in eye movements between different experiments in which adult participants read aloud or silently, eye movements have been shown to be influenced by online articulation and word processing (Inhoff, Solomon, Radach, & Seymour, 2011). Ashby, Yang, Evans, and Rayner (2012) for instance found that speech production in adults leads to lower rates of parafoveal processing in oral than in silent reading. The first large scale study of differences in oral and silent reading in children also suggests that reading aloud results in longer fixation durations, possibly due to speech and eye-voice coordination demands on working memory during reading (Vorstius, Radach, & Lonigan, 2014). The study also suggested that frequency effects may be attenuated in reading aloud compared to silent reading. The effect of vocalizations on eye movements has also been demonstrated in lower level tasks. A recent study, for instance, showed that saccades onto a displayed target were prolonged when an accompanying vocalized response was required, suggesting that dual responses are associated with a performance cost (Huestegge, Pieczykolan, & Koch, 2014). The evidence for differences in eye movements depending on whether sentences are read aloud or silently is hence mixed for adult readers and there are currently no comparisons of reading modality for children.

In summary, there is evidence that children show word length and frequency effects and there is some indication that word length effects are stronger for infrequent than frequent words for children and possibly also for adults. However, the studies which have so far investigated both word length and frequency in children use different designs and materials and it is further unclear whether their results generalize to silent reading tasks. The aim of our study was to contribute an experiment which was specifically designed to test the hypothesized joint effects of word length and frequency in children's silent reading.

1.3. The present study

In the present study we measured the eye movements of a large sample of 2nd grade German speaking children and a control group of adults during a silent reading task. To be able to investigate word length and frequency effects we used controlled sentence frames with embedded target words in an experimental design in which length and frequency were manipulated independently of one another. Reading materials were selected using age-appropriate word frequencies for children. Consistent with previous findings, we predicted children to exhibit larger word length and frequency effects than adults. Our design also allowed us to directly test the strength of the interaction of word length and frequency in beginning and skilled adult readers. With the assumption that beginning readers have a smaller mental lexicon, resulting in greater reliance on sublexical processing, we expected a stronger interaction of word length and frequency for children than adults when reading materials constructed for children.

2. Method

2.1. Participants

We recruited 103 children (age: $M = 7.80$, $SD = 0.53$, years; 54 girls) from six 2nd grade classes at two primary schools in Berlin and 24 adults (age: $M = 25.75$, $SD = 3.23$, years; 14 female), using the participant database of the Max Planck Institute for Human Development, Berlin. All participants were German speakers, had normal or corrected vision, and had no record of reading disability. Twenty-five children were excluded from the analyses due to either incomplete eye tracking data because of very slow reading ($n = 14$), severe calibration problems ($n = 5$), illness or other absence ($n = 6$). Three further children were excluded from the analysis due to accuracy scores below 70% on comprehension questions. This left an effective sample size of 75 children. Of these 71 had lived in Germany since birth and the remaining four had moved to Germany before the age of five. Fifty-eight children had learned only German as their first language at home, while eleven children had learned both German and a second language at home, one child had learned a second language at home, and no data was available for the remaining five children. Adult participants were compensated with €10 while children participated with the written consent of their parents and school authorities and received a small gift after the test session.

2.2. Materials

2.2.1. Word targets

Forty capitalized nouns were selected as short (3–4 letters), long (8–9 letters), frequent (>1.2 log10 lemma frequency in the

German childLex corpus, Schroeder et al., 2014), and infrequent (<0.1 log10 lemma frequency) target words. Of these ten were long (M = 8.40, SD = 0.24 letters) and frequent (M = 1.77, SD = 0.70), ten were long (M = 8.50, SD = 0.32 letters) and infrequent (M = 0.55, SD = 0.71 log10 lemma frequency), a further ten words were short (M = 3.90, SD = 0.11 letters) and frequent (M = 1.90, SD = 0.32 log10 lemma frequency) and a final ten were short (M = 3.80, SD = 0.30, letters), and infrequent (M = 0.63, SD = 0.42 log10 lemma frequency). An ANOVA with the dependent variable word length and factors of length (long vs. short) and frequency (frequent vs. infrequent) found that long and short target words were also of identical average frequency and there was no significant interaction between word length and frequency (p = 0.58). An ANOVA with the log10 transformed dependent variable lemma frequency and the factors of word length and frequency further demonstrated that frequent and infrequent target words did not differ significantly in their average length (p = 0.18) and that there was no significant interaction between word length and frequency (p = 0.79).

As we selected our reading materials on the basis of age-appropriate word frequencies for children, we also checked our target words with age-appropriate DWDS corpus (Heister et al., 2011) word frequencies for adults. Generally, the DWDS word frequencies were higher than the frequencies appropriate for children. An ANOVA with the log10 transformed dependent variable DWDS lemma frequency and the factors of word length and frequency further found that frequent and infrequent target words did not differ in their average length (p = 0.15) but that there was a significant interaction between word length and frequency (p = 0.013). Pair-wise comparisons found that long frequent words had significantly lower DWDS word frequencies than short frequent words (p = 0.032), while long infrequent and short infrequent words had equal DWDS frequencies (p = 0.858). The disparity between DWDS and childLex frequencies for the target words is due to the long frequent words selected for children (e.g., "Zauberer", engl. wizard; "Gespenst", engl. ghost) being typical children's words and much less typical for adult reading material while long infrequent words (e.g., "Präsident", engl. president; "Explosion", engl. explosion) were more frequent for adults than children. As our experimental manipulation was designed to differentiate between high and low frequency words appropriate for children, weaker frequency effects for adults could be attributed to the use of reading materials appropriate for children.

2.2.2. Stimulus sentences

Target words were embedded in sentences written for primary school children with age appropriate themes. To maximize our manipulation of word length and frequency we opted to use different sentence frames for each target word to avoid additional semantic constraints in target word selection (see Blythe et al., 2006 for an alternative approach). To ensure that the sentence frames were as similar as possible between target word categories, sentence characteristics as well as pre-target and post-target words were controlled. Sentences were 7–11 words long (M = 8.88, SD = 0.91) and target words were positioned at 5th, 6th or 7th position. The average word length in the stimulus sentences was 5 letters (SD = 2.44) with an average log lemma frequency of 2.79 (SD = 1.32). Each target was preceded by an adjective with an average length of 7.58 letters (SD = 1.92). The length of the adjective was identical for long and short targets, as well as frequent and infrequent target words (ps > 0.1). The type frequency of the inflected adjectives also did not differ between long and short target words (F = 1.470, p = 0.234) and infrequent and frequent words (F = 0.220, p = 0.642). The length of the word directly following the target also did not differ between target words of different length (F = 0.007, p = 0.935) or frequency (F = 0.171, p = 0.682). The frequency of the post-target word similarly did not differ between target words of different length (F = 1.866, p = 0.180) or frequency (F = 0.216, p = 0.645).

The sentences were presented to 49 children aged 8–9 to assess the predictability and plausibility of the target words in their respective sentence frames as well as the overall difficulty of the sentences in three separate tasks. To ensure ecological validity between eye tracking and rating data, the ratings were conducted ten months after the eye tracking study at the same schools with a partially overlapping sample. Predictability was measured by presenting the stimulus sentences in which target words and all following words were deleted. The participating children were instructed to complete the sentence with one or more words. Plausibility was measured by presenting the children with sentences in which the target word was printed in bold and asking them to rate the fit of the word to the sentence on a four point scale. The difficulty of the stimulus sentences was measured on a four-point scale ranging from "very difficult" to "very easy". Sentences were presented in one of the three tasks and rotated across three test booklets. There were small but significant differences (t = 2.845, p = 0.009) in the mean predictability of frequent (M = 0.16) and infrequent (M = 0.02) target words. We consider this a likely methodological artifact as children may have avoided infrequent continuations of the sentence fragments. This interpretation is corroborated by the finding that the sentence frames did not differ in their average rated plausibility or difficulty between target word categories, suggesting that they provided low constraining contexts and were easily understood by the children. We nevertheless controlled for target word predictability in all following analyses to be sure that frequency effects were not influenced due to frequent words having higher predictabilities than low frequency targets. Indeed, the pattern of results was unaffected by the inclusion of target word predictability in our analyses.

2.3. Apparatus

An EyeLink 1000 eyetracker (SR Research, Ontario, Canada) was used to record eye-movements during reading at a rate of 1000 Hz. Stimuli sentences were presented on a 21″ ASUS LCD monitor, with a refresh rate of 120 Hz. Participants sat at a viewing distance of 65 cm with an assisting head and chin rest to reduce head movements. Sentences were presented in Courier New font in white, size 14, on a black background using the UMass Eye Track 7.10 m software (Stracuzzi & Kinsey, 2006).

2.4. Procedure

The experiment was conducted as part of a larger longitudinal study. In the section of the study relevant here, participating children took part in two test sessions within their schools in rooms suitable for eye tracking. Tests sessions were conducted within 2–10 days of one another. Adults were tested in a single session in laboratory rooms at the Max Planck Institute for Human Development, Berlin. A three dot calibration of the eyetracker was conducted and validated with each participant until a calibration accuracy of at least 0.3° was achieved. Four practice sentences were each followed by a yes–no comprehension question, to which participants responded to on a gamepad. Incorrect answers to the comprehension questions during the practice trials were corrected. Two lists of 20 sentences with embedded target words of which five were short and infrequent, five were long and infrequent, five were short and frequent and five were long and frequent, were generated. Each list was intermixed with sentence trials from an experiment not reported on here and presented in random order. The two lists were read in separate test sessions and the order of presentation was counterbalanced between participants. The

eyetracker was recalibrated after the practice trials as well as after each break and as necessary when *x*- or *y*-axis drift was detected. As the study was designed to investigate silent reading processes, children were instructed to read each sentence quietly to themselves and were reminded whenever vocalizations were audible to the test instructor. Reading was binocular and the right eye was tracked. Each sentence was preceded by a fixation cross which triggered the stimulus sentence on fixation and participants ended the trial by pressing a button on a gamepad. After 25% of the sentence trials participants responded with yes or no to a comprehension question on the gamepad. Different buttons were assigned to the yes/no responses and to end trials.

2.5. Analysis

The eye movement data was cleaned in two stages. First, all trials were deleted if a blink occurred on the target word or directly preceding the first fixation of the target. In this step 8% of trials were excluded for adults and 12% of trials for children. Fixations of less than 80 ms were combined with an adjacent fixation if this was within 1 character. Shorter fixations of 40 ms or less were deleted if within 3 characters of the nearest fixation. In the second step, fixations were deleted for each participant if their duration was 2.5 standard deviations above the mean for each eye movement measure. Four standard eye movement measures were calculated (Rayner, 2009), including *single fixation duration* (cases where only a single fixation is made on a target), *first fixation duration* (all single and first of multiple fixations on a target), *gaze duration* (all fixations on a target before the first saccade leaves a target), and *total viewing time* (all fixations on a target). In this step less than 2% of fixations were deleted for children and adults in each dependent measure.

Linear-mixed models (lme) were used to analyze the eye movement data for each dependent measure in the R environment (R Development Core Team, 2012) with the lme4 package version 1.17 (Bates, Maechler, & Bolker, 2012). Participants and items were treated as crossed random effects and all fixation duration measures were log transformed. Age group (child vs. adult) was included as a between-subjects fixed effect and target word length and frequency as within-subjects fixed effects. Target word predictability was included as a continuous control variable. Cell-mean coding was used and planned contrasts were estimated for each effect using the multicomp package function glth (Hothorn, Bretz, & Hothorn, 2013). All cell-means and contrasts between conditions were back-transformed from their logarithmic model estimates and are reported in milliseconds.

3. Results

3.1. Global measures

Adults and children had mean z-transformed word and nonword reading scores on the Salzburger Leserechtschreibtest (SLRT-II, Moll & Landerl, 2010) which did not fall below 1 *SD* of the population mean, suggesting they were close to the population-based average reading level for their respective age groups. Children read an average of 46 words (*SD* = 30) and 42 nonwords (*SD* = 29) in 60 s, while adults read 123 words (*SD* = 78) and 78 nonwords (*SD* = 15) in the same time. Children answered 86% of the comprehension questions correctly while adults were significantly more accurate ($|t| > 2$) with 96% accuracy. The global eye movement measures displayed in Table 1 shows a typical developmental pattern for children and adults (Rayner, 1998). Children made more and longer fixations than adults ($|ts| > 2$) and tended to fixate the initial letters of words and refixate the word multiple times, while adults were more likely to fixate each word just once and more to the center of the word ($|ts| > 2$). Adults consequently made more single fixations than children and were more likely to skip words completely ($|ts| > 2$).

3.2. Target measures

The dependent eye tracking measures are summarized in Table 2, including average fixation durations and standard errors in each target word category for children and adults. In the following sections we present the effects of word length, frequency and their interactions for children and adults. *F*-tests for all main effects and interactions are given in Table 3. Due to the fact that children rarely fixated target words only once, single fixation durations are only reported for adult participants.

The expected developmental differences between young beginning and skilled adult readers were consistently significant, $ts > |2|$, where children had significantly longer fixation durations in all dependent measures than adults. These developmental differences are therefore only mentioned further in relation to their interactions with word length and frequency. Target word predictability was included in all models to control for predictability of target words of different categories. Predictability did not have a significant effect on single fixation or first fixation durations, but had a significant main effect in gaze duration ($b = -0.402$, $SE = 0.147$) and total viewing time ($b = -0.499$, $SE = 0.160$), where targets with lower predictabilities received longer fixations. However, the significant effect of predictability did not qualitatively affect the pattern of length and frequency effects. We nevertheless report all effects of age group, word length, word frequency, and their interactions corrected for the influence of predictability.

3.2.1. Length effects

For adults, single fixation duration increased with word length resulting in a significant 46 ms length effect ($b = 0.207$, $SE = 0.025$, $t = 8.218$, $p < 0.001$). In first fixation duration we also found a significant word length effect which differed qualitatively between age groups. First fixations were 35 ms longer for long compared to short words for adults ($b = 0.152$, $SE = -0.029$, $t = 5.174$, $p < 0.001$) while first fixations were 31 ms shorter for long words than short words for children ($b = -0.067$, $SE = 0.018$, $t = -3.683$, $p < 0.001$). This may be explained by adults generally fixating words just once and exhibiting longer fixations on long words while children typically refixated words with increasing length, resulting in shorter first fixations. In gaze duration we again found a significant word length effect and a significant interaction of word length and age group which indicated that the length effect of 688 ms for children ($b = 0.685$, $SE = 0.046$, $t = 14.828$, $p = <0.001$) was larger than the 82 ms effect for adults ($b = 0.309$,

Table 1
Global mean fixation probability, number of fixations, landing position and fixation duration for all words in the stimulus sentences.

	Children *M* (*SE*)	Adults *M* (*SE*)
Probability of first pass		
Single fixation (%)	30.66 (0.28)	51.52 (0.55)
Within-word refixation (%)	56.35 (0.30)	16.08 (0.40)
Skipping (%)	12.98 (0.21)	32.38 (0.51)
First pass fixations		
Number per sentence (n)	16.91	7.14
Landing position (char)	1.66 (0.01)	2.52 (0.02)
Duration (ms)	333 (1.09)	210 (0.86)

Note: char = character.

Table 2
Mean fixation duration on short vs. long and infrequent vs. frequent target words.

Measure	High Frequency		Low Frequency	
	Short	Long	Short	Long
Children				
Single fixation	348 (10)	344 (15)	425 (14)	416 (34)
First fixation	313 (6)	294 (5)	357 (8)	315 (6)
Gaze duration	629 (20)	1016 (31)	742 (22)	1730 (45)
Total time	803 (23)	1273 (37)	1000 (29)	1979 (47)
Adults				
Single fixation	198 (4)	238 (5)	214 (4)	266 (5)
First fixation	197 (4)	226 (4)	210 (4)	250 (5)
Gaze duration	210 (5)	271 (6)	216 (5)	319 (8)
Total time	243 (8)	309 (10)	251 (8)	371 (11)

Note: Standard errors are reported in parentheses.

$SE = 0.054$, $t = 5.713$, $p < 0.001$). In total viewing time we similarly found a significant effect of word length and a significant interaction between word length and age group where the 725 ms length effect for children ($b = 0.614$, $SE = 0.050$, $t = 12.228$, $p < 0.001$) was significantly larger than the 93 ms effect for adults ($b = 0.306$, $SE = 0.057$, $t = 5.395$, $p < 0.001$).

In summary, children showed predicted positive word length effects in gaze duration and total viewing time and an unexpected negative word length effect in first fixation duration. While adults showed positive word length effects in all eye movement measures, word length effects were stronger for children in gaze duration and total viewing time.

3.2.2. Frequency effects

Adults' single fixation durations were shorter for frequent than infrequent words, resulting in a significant 22 ms frequency effect ($b = -0.092$, $SE = 0.027$, $t = -3.344$, $p < 0.001$). In first fixation duration the significant interaction between word frequency and age group indicated that the 33 ms frequency effect for children ($b = -0.067$, $SE = 0.020$, $t = -3.380$, $p = 0.001$) was larger than the 19 ms effect for adults ($b = -0.068$, $SE = 0.030$, $t = -2.236$, $p = 0.025$). The effect of word frequency also differed between children and adults in gaze duration and total viewing time. There were significant main effects of word frequency and significant interactions between frequency and age group in both gaze duration and total viewing time. However, contrasts revealed that while children showed a significant 414 ms frequency effect in gaze duration ($b = -0.310$, $SE = 0.051$, $t = -6.107$, $p < 0.001$) and a 452 ms frequency effect in total viewing time ($b = -0.290$, $SE = 0.055$, $t = -5.267$, $p < 0.001$), adults showed no significant frequency effect in either gaze duration ($b = -0.034$, $SE = 0.058$, $t = -0.579$, $p = .563$) or total viewing time ($b = -0.043$, $SE = 0.061$, $t = -0.700$, $p = .484$). In summary, children showed significant effects of word frequency in first fixation, gaze duration, and total viewing time measures. While adults showed frequency effects only in single and first fixation durations, frequency effects were stronger for children in the first fixation measure.

3.2.3. Length by frequency effects

The main aim of the current study was to investigate the strength of the interaction of word length and frequency on children's eye movements during silent reading, compared to skilled adult readers. The pattern of interactions was very clear. While there was no interaction of word length and frequency in single or first fixation durations, the interaction was significant in both gaze duration and total viewing time which was qualified by a significant three-way interaction with age group. We therefore present the interaction effects first for children and then for adults in the following sections.

In first fixation duration there was no significant interaction of word length and frequency in the children's eye movements. However, the length effect was greater for infrequent ($b = -0.044$, $SE = 0.012$, $t = -3.442$, $p < 0.001$) than frequent words ($b = -0.022$, $SE = 0.012$, $t = -1.767$, $p = 0.077$), suggesting a tendency towards an interaction effect. The interaction was significant in gaze duration which indicated a stronger word length effect for infrequent than frequent words for children ($b = 0.379$, $SE = 0.092$, $t = 4.097$, $p < 0.001$). The pattern was almost identical for total viewing time where the word length by frequency interaction was again significant ($b = 0.294$, $SE = 0.100$, $t = 2.933$, $p = 0.003$). These results show a clear interaction of word length and frequency in gaze duration and total viewing time and a tendency towards a similar interaction in first fixation duration for children.

The evidence for an interaction of word length and frequency was less pronounced for adults. While there were no significant interaction effects, there was a consistent tendency for the word length effects to be greater for infrequent than frequent target words. In single fixation duration, adults did not show a significant interaction of word length and frequency, although the word length effect was numerically greater for infrequent ($b = 0.233$, $SE = 0.035$, $t = 6.554$, $p < 0.001$) than frequent words ($b = 0.181$, $SE = 0.035$, $t = 5.101$, $p < 0.001$). The same was true for first fixation duration were there was no significant interaction but greater length effects for infrequent ($b = 0.086$, $SE = 0.020$, $t = 4.184$, $p < 0.001$) than frequent words ($b = 0.065$, $SE = 0.020$, $t = 3.151$, $p = 0.002$). The pattern was also evident for gaze duration in which the word length effect was again greater for infrequent words ($b = 0.186$, $SE = 0.038$, $t = 4.877$, $p < 0.001$) than frequent words ($b = 0.123$, $SE = 0.038$, $t = 3.214$, $p < 0.001$) and in total viewing time where the word length effect was also greater for infrequent ($b = 0.114$, $SE = 0.040$, $t = 4.789$, $p < 0.001$) than frequent words ($b = 0.114$, $SE = 0.040$, $t = 2.849$, $p = 0.004$).

The results show that children had significantly stronger word length effects for infrequent than frequent words in the eye

Table 3
F-tests and *p*-values for main effects and interactions of word length and frequency for children and adults in four eye movement measures.

Effect	Single fixation[a]		First fixation		Gaze duration		Total time	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Length	67.42	<0.001	1.30	0.263	175.39	<0.001	120.54	<0.001
Frequency	11.18	<0.001	13.35	0.001	23.28	<0.001	17.86	<0.001
Predictability	<0.01	0.978	1.37	0.251	7.47	0.010	9.66	0.004
Age group	–	–	66.32	<0.001	148.29	<0.001	173.27	<0.001
Length × frequency	1.107	0.299	0.51	0.479	12.59	0.001	7.03	0.012
Length × age	–	–	51.12	<0.001	98.76	<0.001	73.87	<0.001
Frequency × age	–	–	0.05	0.828	62.07	<0.001	51.75	<0.001
Length × frequency × age	–	–	1.98	0.159	11.21	0.001	3.83	0.050

[a] Single fixations are reported only for adult participants.

movement measures of gaze duration and total viewing time. The length by frequency interaction was significantly less pronounced in adults, who only displayed a corresponding non-significant trend towards an interaction.

3.2.4. Fixation location and refixation probability

To provide additional information on children's and adults' saccades and fixations, we investigated the dependencies of incoming saccade launch site on first fixation landing position and the ensuing refixation probability on target words. The distribution of saccade launch sites and corresponding landing positions is displayed for four-letter ($n = 17$) and eight-letter ($n = 13$) words in the top half of Fig. 1. The position of the first fixations on short ($F = 138.68$, $p < 0.001$) and long words ($F = 64.81$, $p < 0.001$) was significantly affected by the length of the incoming saccades. Children's first fixations tended to fall closer to the beginning of words while adults' first fixations tended to fall closer to the center of target words, resulting in a main effect age group on landing position for short ($F = 73.81$, $p < 0.001$) and long words ($F = 69.82$, $p < 0.001$). There was also an interaction of saccade launch site and landing position with age group for long words, indicating that the incoming saccade length effect was greater for children than adults ($F = 10.01$, $p < 0.001$). The probability of within-word refixations is illustrated in the bottom half of Fig. 1. For short words, the closer the landing position to the beginning of a word, the higher the probability of a refixation ($\chi^2 = 65.62$, $p < 0.001$), while children made significantly more refixations than adults ($\chi^2 = 45.91$, $p = 91$). The significant interaction between landing position and age group ($\chi^2 = 9.32$, $p = 0.002$) indicates that the effect of landing position on refixation probability was stronger for children than adults. The pattern was similar for long words, where landing position had a significant effect on refixation probability ($\chi^2 = 50.66$, $p < 0.001$) and children were significantly more likely to refixate a word than adults ($\chi^2 = 100.14$, $p < 0.001$). The interaction between landing position and age group was not significant, possibly due to the large variability of the adult refixation probabilities.

4. Discussion

In the present study we investigated the effects of word length and frequency on the eye movements of children during reading in comparison to skilled adult readers using a silent reading task and age-appropriate word frequencies for children. We found significant effects of word length and frequency for both children and adults while effects were generally stronger for children. The interaction of word length and frequency was significant for children in the eye movement measures of gaze duration and total viewing time but not for adults. The results of the present study thus make

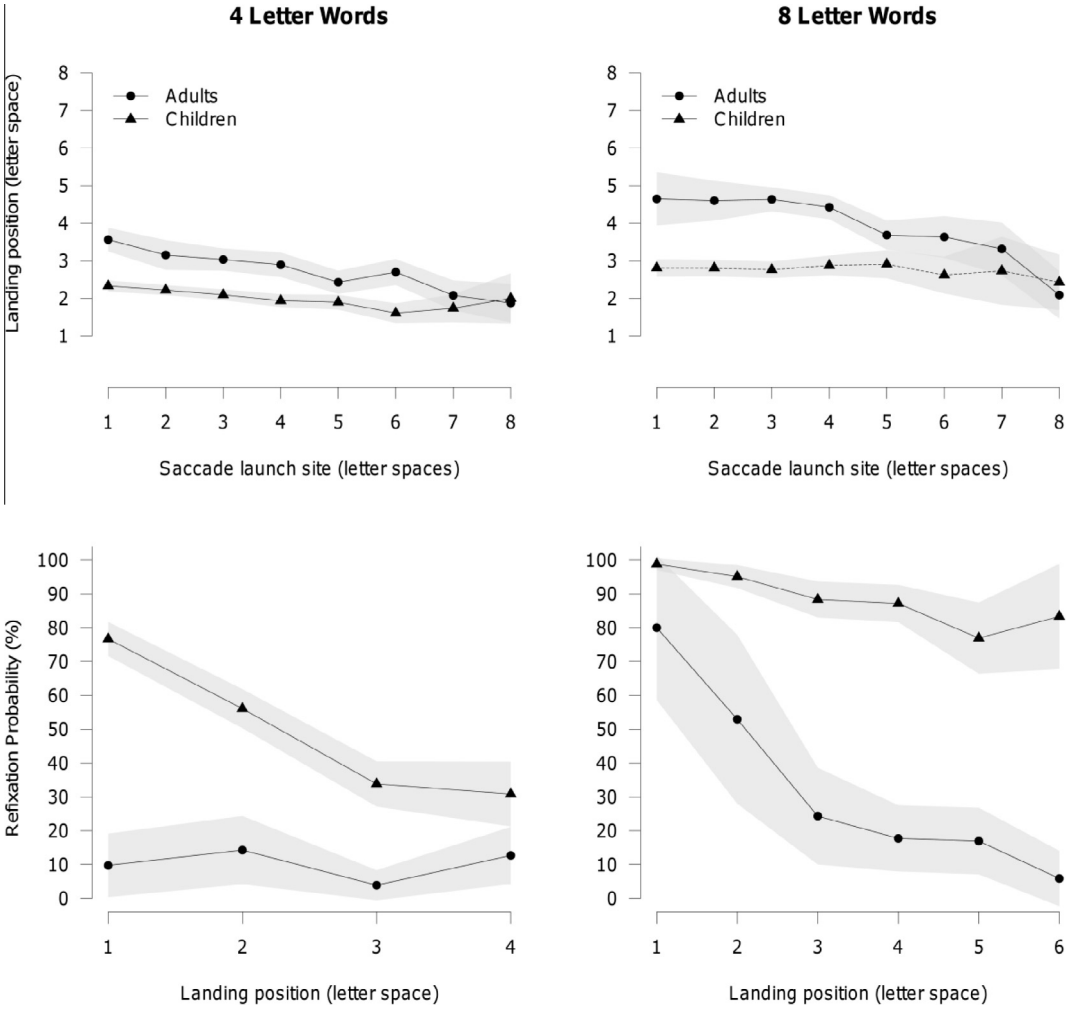

Fig. 1. Mean landing positions by saccade launch site and mean refixation probabilities by landing position for children and adults for short and long target words with 95% confidence intervals.

three general contributions to the sparse literature on the effect of word characteristics on children's eye movements during sentence reading. First, we were able to replicate previous findings that word length and frequency effects can be found in children and adults using the same reading materials in a silent reading task. Second, also consistent with previous studies, we found stronger word length and frequency effects in children than adults. Lastly, we found a stronger length effect for low frequency than high frequency words for children, corresponding to effects reported by Rau, Moeller, and Landerl (2014), Rau, Moll, Snowling, and Landerl (2015) and Hyönä and Olson (1995), indicating that the interaction can be found in both oral and silent reading modalities. This demonstrates the importance for experimental designs to vary both length and frequency word characteristics independently of one another, as keeping one variable constant may affect the measurement of the effects of the second variable.

Longer words were fixated for longer and more often than short words and children showed stronger effects of word length than adults in gaze duration and total viewing time measures. Children also employed a refixation strategy in which longer words were fixated multiple times. Accordingly, we found a trade-off between the number of fixations and the word length effect in first fixation duration in children which was inverse to the effect found in adults. The probability that children fixated a word only once was 31% while they refixated words with a 56% probability. Children's first fixation on short words thus tended to be longer than the first fixation on long words, as long words generally received subsequent first pass fixations. The reverse was true for adults whose probability of a single fixation on a target word was 52% while the refixation probability was only 16%. Accordingly, adults' first fixation on a long target word was longer than on a short target word.

The effect of word frequency also showed a clear overall pattern where infrequent words received longer fixations than frequent words. While children showed frequency effects in all dependent measures, adults were only significantly influenced by word frequency in the measures of single and first fixation duration. Word length was also found to interact with the word frequency effect for children. Long infrequent words hence presented children with the largest reading difficulties which were reflected in longer fixation durations and an increased number of refixations. The greater effect of word length for infrequent words has been found in other eye-tracking studies for children (Rau, Moeller, & Landerl, 2014; Rau, Moll, Snowling, & Landerl, 2015; Hyönä & Olson, 1995) as well as for poor adult readers (Hawelka, Gagl, & Wimmer, 2010). Rau, Moeller, and Landerl (2014) and Hawelka, Gagl, and Wimmer (2010) both interpret their findings with reference to dual route models of word recognition. One reason for the efficiency of the lexical route is that it is theoretically insensitive to word length, as words are processed as whole letter strings, while sublexical processing time increases with the number of graphemes that needed to be decoded. Greater word length effects in children can thus both be interpreted as a greater reliance on sublexical processing, as well as the sublexical route being less efficient than in adults (Rau, Moeller, & Landerl, 2014). According to the self-teaching hypothesis (Share, 1995; Share, 1999), entries in the orthographic lexicon are the result of repeated phonological decoding of words. As more words are encountered and repeatedly decoded, a beginning reader gradually builds up detailed mental representations of more and more words which are necessary for fast lexical word recognition processes. As children are expected to have fewer and possibly poorer representations in their orthographic lexicon, words are more likely to fail to be matched in the lexical route and be decoded using sublexical processes. The consequent sublexical processing, which is serial and sensitive to word length, results in larger length effects for infrequent words. Our results are hence consistent with the assumption that beginning readers are initially more reliant on sublexical phonological recoding (Grainger et al., 2012). However, it should be noted that models such as the DRC were developed to explain effects found in oral single word reading contexts (Coltheart et al., 2001), while computational models of eye movement control such as SWIFT (Engbert, Longtin, & Kliegl, 2002) or EZ-Reader (Reichle et al., 2013) are arguably more appropriate frameworks for modelling reading processes in connected text. Lexical processing in these models is not, however, decomposed into different components. The DRC distinction of lexical and sublexical processes thus retains its usefulness for generating hypotheses for developmental differences in word recognition processes (Hawelka, Gagl, & Wimmer, 2010). The integration of these different kinds of models nevertheless remains a very beneficial future prospect (Rayner & Reichle, 2010).

Due to the difficulties involved in comparing children's and adults' reading processes, we encountered a number of methodological and practical challenges which are relevant beyond the present study. The first challenge was the construction of reading stimuli appropriate for young beginning readers. In this study we opted to use different sentence frames for each target word to maximize flexibility in selecting targets. The alternative of constructing sentence frames for quadruplets of target words of different categories would have provided a more standardized context. However, this standardization comes at the cost of semantic constraints on the selection of quadruplets of target words and we chose the more flexible approach to maximize the manipulation of target word length and frequency. The ratings of our stimulus sentences indicate that children considered the sentences frames plausible and did not have difficulties understanding them, irrespective of target word category. This also suggests that the children knew and understood the infrequent words selected for the study. As the predictability of target words differed slightly between categories, this effect was controlled for in our analyses. The results indicate that predictability affected fixation durations but did not qualitatively influence the overall pattern of word length and frequency effects. This does nevertheless highlight the importance of controlling for predictability in experimental designs such as the one implemented in the present study.

Another practical issue concerned the choice of reported eye movement measures. While single fixations are typically reported in adult studies, young children rarely fixate words just once. In fact, our results suggest that children's refixation strategy for long words as well as infrequent words makes the single fixation measure inappropriate, while gaze duration appears to provide the more reliable comparison between children's and adults' eye movement patterns during reading.

Our results differ from those of earlier studies in a number of ways. First, Rau, Moeller, and Landerl (2014) do not report an interaction of word length and familiarity for their 2nd grade participants. This may be due the use of adult word frequencies for stimulus generation (Joseph, Nation, & Liversedge, 2013) or to the number of participants in the Rau et al. study and the generally large variability of children's eye tracking data. Second, both Rau, Moeller, & Landerl, 2014 and Rau, Moll, Snowling, & Landerl, 2015 report significant interactions of word length and familiarity for their adult participants. Two explanations for the differences between results are plausible. First, these studies used nonword targets as low frequency words, together with medium and high frequency words to provide three levels of differentiation. The inclusion of nonwords targets should require adults and children alike to process these targets serially, leading to the interaction of word length and frequency. It is also possible that using reading materials for children and target words selected on the basis of age-appropriate word frequencies for children could lead to lower

frequency effects for adults due to an under-estimation of the target's frequencies. The disparity between the adult and child appropriate word frequencies in the reading materials used in this study highlights one of the big challenges for reading experiments which compare age groups. As the frequency with which words occur in written language depends on the reading ability and print exposure of the reader, the appropriateness of different word corpora will shift as children progressively become skilled readers. This may also account for the lack of frequency effects in gaze duration and total viewing time for adults in the present study. To shed more light on the effects of using age-appropriate word frequencies and reading materials for different age groups will require further studies and we see the study of eye movement behavior of children and adults while reading texts of differing difficulty as one important area for future research. A possible approach could be to have adults read both child and adult appropriate reading materials. Alternatively, having children read simple adult appropriate reading material could provide an interesting new point of comparison. However, variations of text difficulty will require validated empirical measures of difficulty generating text characteristics.

As there is currently very little research on the eye movements of beginning readers during reading (see Blythe, 2014; Blythe & Joseph, 2011; Reichle et al., 2013), skilled adult reading behavior is typically used as a starting point and disparities found in children's eye movements are interpreted as developmental differences. This is in part due to the present lack of longitudinal studies of children's eye movement development (see Huestegge, Radach, Corbic, & Huestegge, 2009 for a notable exception). While the present study focused on the comparison of word length and frequency effects in young beginning readers and skilled adults, further studies will need to investigate the development of these effects in children in relationship to chronological age and reading ability.

Author Note

Simon P. Tiffin-Richards, MPRG REaD (Reading Education and Development), Max Planck Institute for Human Development, Berlin, Germany; Sascha Schroeder, MPRG REaD (Reading Education and Development), Max Planck Institute for Human Development, Berlin, Germany.

Appendix A

See Tables A1 and A2

Table A1
Sentence stimuli with embedded target words.

Category	Target	Sentence
Long frequent	Astronaut	Gestern Abend war der berühmte Astronaut im Fernsehen
	Geschenk	Wir haben Lena das eingepackte Geschenk zusammen übergeben
	Gespenst	Nachts traut sich das scheue Gespenst manchmal aus der Gruft
	Kommissar	Alle respektierten den wütenden Kommissar und waren still
	Polizist	Davids Papa ist der freundlichste Polizist auf seiner Wache
	Schatten	Draußen war nur ein dunkler Schatten zu sehen
	Schlange	Im Dunkeln liegt eine giftige Schlange und schläft
	Schokolade	Henrik isst die leckere Schokolade von Oma am liebsten
	Versteck	Nora hat uns das geheime Versteck hinter dem Regal gezeigt
	Zauberer	Im Turm wohnt der bärtige Zauberer mit seinem Lehrling
Long infrequent	Explosion	Am Ende gab es eine gewaltige Explosion in dem Film
	Krawatte	Heute trage ich meine gestreifte Krawatte zu dem großen Fest
	Präsident	Es war der beliebte Präsident in dem schicken Auto
	Salamander	Es sonnt sich ein bunter Salamander im Sonnenschein
	Scheusal	Eigentlich war das haarige Scheusal gar nicht so gruselig
	Schinken	Mama hat den gut riechenden Schinken für Opa gekauft
	Sensation	Wir hatten die große Sensation schon lange erwartet
	Skorpion	Im Sand krabbelt ein kleiner Skorpion durch die Wüste
	Vagabund	Nachts lauert der schäbige Vagabund auf reiche Reisende
	Wanderer	Am Straßenrand sitzt ein müder Wanderer und ruht sich aus
Short frequent	Brot	Auf der Straße ist gebackenes Brot zu riechen
	Burg	Der kürzeste Weg zur berühmten Burg ist die steile Treppe
	Flur	Wir gehen zusammen den langen Flur hinunter zum Lehrerzimmer
	Glas	Julia hat das volle Glas aus Versehen umgestoßen
	Hut	Es fehlt nur noch der passende Hut zu dem Anzug
	Knie	Nele hat sich das rechte Knie am Tisch gestoßen
	Maus	Bisher ist die schnelle Maus der Katze immer entkommen
	Sinn	Der Plan machte keinen richtigen Sinn mehr für Sven
	Spur	Es gab eine neue heiße Spur in dem Fall
	Zaun	Alex hat den langen Zaun grün angestrichen
Short infrequent	Aal	Es lebte ein flinker Aal in dem Kanal
	Floß	Tom will mit dem wackeligen Floß bis zur Insel fahren
	Kalb	Auf der Wiese spielt das junge Kalb mit den anderen Kälbern
	Krug	Marie will den zerbrochenen Krug wieder zusammenkleben
	Laus	Mit der Lupe war die winzige Laus gut zu erkennen
	Lob	Eva hat sich über das verdiente Lob sehr gefreut
	Napf	Der Hund hatte seinen bunten Napf in der Küche stehen
	Obst	Im Laden sah das frische Obst besonders lecker aus
	Pfau	Max war von dem farbigen Pfau sehr beeindruckt
	Zoff	Ich hatte gestern mächtigen Zoff mit meinem Bruder

Table A2
Literal English translations of original sentence stimuli with embedded target words and comprehension questions.

German sentence and comprehension question	Literal English translation
Gestern Abend *war* der **berühmte Astronaut** im Fernsehen	Yesterday evening *was* the **famous astronaut** on television
Q: War der Astronaut im Fernsehen?	Q: Was the astronaut on television? [yes]
Der kürzeste Weg zur **berühmten Burg** *ist* die steile Treppe	The shortest way to the **famous castle** *is* the steep staircase
Q: Ist die Treppe der längste Weg zur Burg?	Q: Is the staircase the longest way to the castle? [no]
Im Sand *krabbelt* ein **kleiner Skorpion** durch die Wüste	In the sand *crawled* a **little scorpion** through the desert
Q: Krabbelt der Skorpion im Sand?	Q: Is the scorpion crawling in the sand? [yes]
Max *war* von dem **farbigen Pfau** sehr *beeindruckt*	Max *was* by the **colorful peacock** very *impressed*
Q: War Max von dem Pfau gelangweilt?	Q: Was Max bored by the peacock? [no]

Note: The literal English translations are syntactic equivalents. Verbs are highlighted in italics and adjective/target word bigrams are highlighted in bold.

References

Aghabaian, V., & Nazir, T. A. (2000). Developing normal reading skills: Aspects of the visual processes underlying word recognition. *Journal of Experimental Child Psychology, 76*(2), 123–150.

Ashby, J., Yang, J., Evans, K. H., & Rayner, K. (2012). Eye movements and the perceptual span in silent and oral reading. *Attention, Perception, & Psychophysics, 74*(4), 634–640.

Baayan, H., Piepenbrock, R., & Gulikers, L. (1995). *The CELEX lexical database*. University of Pennsylvania, Philadelphia: Linguistic Data Consortium.

Bates, D., Maechler, M., & Bolker, B. (2012). lme4: Linear mixed-effects models using S4 classes.

Blythe, H. I. (2014). Developmental changes in eye movements and visual information encoding associated with learning to read. *Current Directions in Psychological Science, 23*(3), 201–207.

Blythe, H. I., & Joseph, H. (2011). Children's eye movements during reading. In S. Liversedge, I. Gilchrist, & S. Everling (Eds.), *The Oxford handbook of eye movements* (pp. 643–662). Oxford University Press.

Blythe, H. I., Liversedge, S. P., Joseph, H. S., White, S. J., Findlay, J. M., & Rayner, K. (2006). The binocular coordination of eye movements during reading in children and adults. *Vision Research, 46*(22), 3898–3908.

Blythe, H. I., Liversedge, S. P., Joseph, H. S., White, S. J., & Rayner, K. (2009). Visual information capture during fixations in reading for children and adults. *Vision Research, 49*(12), 1583–1591.

Blythe, H. I., Häikiö, T., Bertam, R., Liversedge, S. P., & Hyönä, J. (2011). Reading disappearing text: Why do children refixate words? *Vision Research, 51*(1), 84–92.

Brown, G. D., & Deavers, R. P. (1999). Units of analysis in nonword reading: Evidence from children and adults. *Journal of Experimental Child Psychology, 73*(3), 208–242.

Brysbaert, M., & Vitu, F. (1998). Word skipping: Implications for theories of eye movement control in reading. *Eye Guidance in Reading and Scene Perception*, 125–147.

Coltheart, M., Curtis, B., Atkins, P., & Haller, M. (1993). Models of reading aloud: Dual-route and parallel-distributed-processing approaches. *Psychological Review, 100*(4), 589.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108*(1), 204.

Engbert, R., Longtin, A., & Kliegl, R. (2002). A dynamical model of saccade generation in reading based on spatially distributed lexical processing. *Vision Research, 42*(5), 621–636.

Feng, G., Miller, K., Shu, H., & Zhang, H. (2009). Orthography and the development of reading processes: An eye-movement study of Chinese and English. *Child Development, 80*(3), 720–735.

Grainger, J., Lété, B., Bertand, D., Dufau, S., & Ziegler, J. C. (2012). Evidence for multiple routes in learning to read. *Cognition, 123*(2), 280–292.

Hawelka, S., Gagl, B., & Wimmer, H. (2010). A dual-route perspective on eye movements of dyslexic readers. *Cognition, 115*(3), 367–379.

Heister, J., Würzner, K. M., Bubenzer, J., Pohl, E., Hanneforth, T., Geyken, A., et al. (2011). DlexDB–eine lexikalische Datenbank für die psychologische und linguistische Forschung. *Psychologische Rundschau, 62*(1), 10–20.

Hothorn, T., Bretz, F., & Hothorn, M. T. (2013). Package 'multicomp'.

Huestegge, L. (2010). Effects of vowel length on gaze durations in silent and oral reading. *Journal of Eye Movement Research, 3*(5), 1–18.

Huestegge, L., Pieczykolan, A., & Koch, I. (2014). Talking while looking: On the encapsulation of output system representations. *Cognitive Psychology, 73*, 72–91.

Huestegge, L., Radach, R., Corbic, D., & Huestegge, S. M. (2009). Oculomotor and linguistic determinants of reading development: A longitudinal study. *Vision Research, 49*(24), 2948–2959.

Hutzler, F., & Wimmer, H. (2004). Eye movements of dyslexic children when reading in a regular orthography. *Brain and Language, 89*(1), 235–242.

Hyönä, J., & Olson, R. K. (1995). Eye fixation patterns among dyslexic and normal readers: Effects of word length and word frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*(6), 1430.

Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics, 40*(6), 431–439.

Inhoff, A. W., Solomon, M., Radach, R., & Seymour, B. A. (2011). Temporal dynamics of the eye-voice span and eye movement control during oral reading. *Journal of Cognitive Psychology, 23*(5), 543–558.

Joseph, H. S., Liversedge, S. P., Blythe, H. I., White, S. J., & Rayner, K. (2009). Word length and landing position effects during reading in children and adults. *Vision Research, 49*(16), 2078–2086.

Joseph, H. S., Nation, K., & Liversedge, S. P. (2013). Using eye movements to investigate word frequency effects in children's sentence reading. *School Psychology Review, 42*(2), 207–222.

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87*(4), 329.

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology, 16*(1–2), 262–284.

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: the influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology: General, 135*(1), 12.

Liversedge, S. P., Rayner, K., White, S. J., Vergilino-Perez, D., Findlay, J. M., & Kentridge, R. W. (2004). Eye movements when reading disappearing text: Is there a gap effect in reading? *Vision Research, 44*(10), 1013–1024.

McConkie, G. W., & Rayner, K. (1976). Identifying the span of the effective stimulus of reading: Literature review and theories of reading. In H. Singer & R. B. Ruddell (Eds.), *Theoretical models and processes in reading* (pp. 137–162). Newark, DE: International Reading Association.

McConkie, G. W., Zola, D., Grimes, J., Kerr, P. W., Bryant, N. R., & Wolff, P. M. (1991). Children's eye movements during reading. In J. E. Stein (Ed.), *Vision and visual dyslexia* (pp. 251–262). London: Macmillan Press.

Moll, K., & Landerl, K. (2010). *SLRT-II: Lese-und Rechtschreibtest; Weiterentwicklung des Salzburger Lese-und Rechtschreibtests (SLRT)*. Huber.

Perfetti, C. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading, 11*(4), 357–383.

Perry, C., Ziegler, J. C., & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: the CDP+ model of reading aloud. *Psychological Review, 114*(2), 273.

Rau, A. K., Moeller, K., & Landerl, K. (2014). The transition from sublexical to lexical processing in a consistent orthography: An eye-tracking study. *Scientific Studies of Reading, 18*, 224–233.

Rau, A. K., Moll, K., Snowling, M. J., & Landerl, K. (2015). Effects of orthographic consistency on eye movement behavior: German and English children and adults process the same words differently. *Journal of Experimental Child Psychology, 130*, 92–105.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*(3), 372.

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *The Quarterly Journal of Experimental Psychology, 62*(8), 1457–1506.

Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition, 14*(3), 191–201.

Rayner, K., & Fischer, M. H. (1996). Mindless reading revisited: Eye movements during reading and scanning are different. *Perception & Psychophysics, 58*(5), 734–747.

Rayner, K., & Liversedge, S. (2011). Linguistic and cognitive influences on eye movements during reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *The oxford handbook of eye movements* (pp. 751–766). England: Oxford.

Rayner, K., Liversedge, S. P., White, S. J., & Vergilino-Perez, D. (2003). Reading disappearing text cognitive control of eye movements. *Psychological Science, 14*(4), 385–388.

Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research, 16*(8), 829–837.

Rayner, K., & Reichle, E. D. (2010). Models of the reading process. *Wiley Interdisciplinary Reviews: Cognitive Science, 1*(6), 787–799.

Reichle, E. D., Liversedge, S. P., Drieghe, D., Blythe, H. I., Joseph, H. S., White, S. J., et al. (2013). Using EZ Reader to examine the concurrent development of eye-movement control and reading skill. *Developmental Review, 33*(2), 110–149.

Schroeder, S., Würzner, K. M., Heister, J., Geyken, A., & Kliegl, R. (2014). ChildLex: A lexical database of German read by children. *Behavior Research Methods*, 1–10.

Share, D. L. (1995). Phonological recoding and self-teaching: Sine qua non of reading acquisition. *Cognition, 55*(2), 151–218.

Share, D. L. (1999). Phonological recoding and orthographic learning: A direct test of the self-teaching hypothesis. *Journal of Experimental Child Psychology, 72*(2), 95–129.

Stracuzzi, D., & Kinsey, J. (2006). EyeTrack (Version 0.6. x).
Stuart, M., Dixon, M., Masterson, J., & Gray, B. (2003). Children's early reading vocabulary: Description and word frequency lists. *British Journal of Educational Psychology, 73*(4), 585–598.
Vitu, F., McConkie, G. W., Kerr, P., & O'Regan, J. K. (2001). Fixation location effects on fixation durations during reading: An inverted optimal viewing position effect. *Vision Research, 41*(25), 3513–3533.
Vorstius, C., Radach, R., & Lonigan, C. J. (2014). Eye movements in developing readers: A comparison of silent and oral sentence reading. *Visual Cognition, 22*(3), 458–485.
Zeno, S. M., Ivens, S. H., Millard, R. T., & Duvvuri, R. (1995). *The educator's word frequency guide*. Brewster: Touchstone Applied Science Associates., Inc..
Zorzi, M. (2010). The connectionist dual process (CDP) approach to modelling reading aloud. *European Journal of Cognitive Psychology, 22*(5), 836–860.