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Context Facilitation in Text Reading: A Study of Children's Eye Movements

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Words are seldom read in isolation. Predicting or anticipating upcoming words in a text, based on the context in which they are read, is an important aspect of efficient language processing. In sentence reading, words with congruent preceding context have been shown to be processed faster than words read in neutral or incongruous contexts. The onset of contextual facilitation effects is found very early in the first-pass-reading eye-movement and electroencephalogram (EEG) measures of skilled adult readers. However, the effect of contextual facilitation on children's eye movements during reading remains largely unexplored. To fill this gap, we tracked children's and adults' eye movements while reading stories with embedded words that were either strongly or weakly related to a clear narrative theme. Our central finding is that children showed late contextual facilitation effects during text reading as opposed to both early and late facilitation effects found in skilled adult readers. Contextual constraint had a similar effect on children's and adults' initiation of regressive saccades, whereas children invested more time in rereading relative to adults after encountering weakly contextually constrained words. Quantile regression analyses revealed that contextual facilitation effects had an early onset in adults' first-pass reading, whereas they only had a late onset in children's gaze durations.

Keywords: text reading, contextual facilitation, children, eye movements

When we read written prose, words are processed not just individually but in relation to their syntactic and semantic context as well as our world knowledge (Castles, Rastle, & Nation, 2018). The combination of bottom-up processes of word recognition and top-down processes of integration and inference building allows a reader to form an increasingly elaborate mental representation of a text, which is widely accepted to be synonymous with successful comprehension (Graesser, Singer, & Trabasso, 1994; van Dijk & Kintsch, 1983; Zwaan & Radvansky, 1998). The context in which a word is embedded further enables a reader to generate expectations about how a discourse or text may plausibly continue, which is regarded as a hallmark of efficient online language processing (Ferreira & Chantavarin, 2018; Kuperberg & Jaeger, 2016; Levy, 2008; Norris, 2006). Studies of moment-to-moment cognitive processes during reading have indeed shown that eye movements (Rayner, 1998, 2009) are not only influenced by the characteristics of a word, such as its length and frequency (Kliegl, Nuthmann, & Engbert, 2006), but also by the nature of its context (Ehrlich & Rayner, 1981; Morris, 1994; Rayner & Well, 1996). If a sentence

is constrained toward a particular continuation, such as “The cat caught the . . .” readers typically need less time to process that next word (e.g., “mouse”), presumably because it is both predictable from its context and easy to integrate into the current understanding of the sentence (Luke & Christianson, 2016).

For readers with inefficient word-recognition processes, the use of context information may represent an important compensatory mechanism in which top-down processes facilitate word recognition by narrowing the plausible continuations of a sentence, given previous syntactic and semantic information and relevant world knowledge (Perfetti, 1985; Stanovich, 1980, 1984). Context may therefore be particularly useful for beginning readers in situations where clear contextual constraints are provided, for instance, when reading narrative texts structured around well-established, age-appropriate themes and content. However, with few exceptions, eye-movement studies generally employ single-sentence stimuli when investigating context effects in, predominantly, skilled adult readers. It is consequently largely unclear whether beginning readers use context to facilitate their word reading and comprehension while reading narrative texts. We therefore provide two important extensions to the present literature on contextual facilitation effects in reading. First, we compare context effects in beginning and skilled readers while taking into account that effects may emerge at different stages of reading processes, suggesting either facilitation through early prelexical prediction or late postlexical integration processes (Staub, 2015). Second, we operationalized our contextual constraint manipulation using short texts with strong narrative themes in which target nouns were either strongly or weakly related to global story themes. We hence present the first study of contextual facilitation effects in children and adults using

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a controlled design with target words embedded in short narrative texts with strong themes primed by informative titles.

Prediction in Reading

Predicting candidates for upcoming words in an ongoing discourse is an important aspect of efficient language processing (Levy, 2008; Norris, 2006). In sentence-reading research, the degree to which a word can be predicted from context (word predictability) is typically operationalized as the likelihood of guessing the next word of a sentence, given only the words preceding it (Taylor, 1953). This measure is also conceptualized as contextual activation because the preceding context preactivates plausible candidates for the continuation of a sentence or text, thereby constraining readers' expectations (Staub, Grant, Astheimer, & Cohen, 2015). In adults, words that are predictable in a strongly constrained context reliably elicit shorter fixation durations (Ehrlich & Rayner, 1981; Rayner & Well, 1996), as well as higher skipping rates (Rayner, Slattery, Drieghe, & Liversedge, 2011), fewer regressions (Ashby, Rayner, & Clifton, 2005; Staub, 2011), and reduced and delayed N400 effects in event-related potentials (Kutas & Federmeier, 2011), compared with words read in a weakly constrained context. Only one recent study has, to our knowledge, demonstrated similar contextual facilitation effects on children's fixation durations and regression probability (Johnson, Oehrlein, & Roche, 2018). The scarcity of developmental studies is surprising (see Rayner, Ardoin, & Binder, 2013) because influential reading theories such as the interactive-compensatory model (Stanovich, 1980, 1984) and the verbal efficiency theory (Perfetti, 1985) explicitly predict context to be particularly important for comprehension processes in less skilled readers. Additionally, only a few aspects of beginning readers' eye movements have been investigated in text reading (Khelifi, Sparrow, & Casalis, 2019; Tiffin-Richards & Schroeder, 2018). Text reading may, however, be particularly interesting in relation to context effects because there is more scope for context facilitation than in single sentences. As readers create a mental model of a text, they construct an increasingly complex situational model by integrating new information with the previously read text and their relevant world knowledge (van den Broek, 1994), thus expanding the context used to integrate each new word and proposition or predict upcoming content. However, by focusing almost exclusively on predictability effects in single-sentence experimental designs, the influence of more global thematic context effects, such as narrative coherence (Ferstl & Cramon, 2001) and informative story titles (Kaakinen, Lehtola, & Paatlammi, 2015), is necessarily limited.

Lexical and Graded Prediction

Facilitation through language prediction in reading can be conceived in very different ways. According to the lexical-prediction account, prediction is an all-or-nothing process of activating a specific word before any perceptual input is available (DeLong, Troyer, & Kutas, 2014). This mechanism assumes facilitation when the prediction is correct and a cost when incorrect, corresponding to a slow, conscious-attention-processing route that selects a lexical candidate while inhibiting the activation of other lexical entries (Stanovich & West, 1979). However, because there are many more unpredictable than predictable words in connected

text (Luke & Christianson, 2016), lexical prediction would be largely ineffective (Huettig & Mani, 2016). A plausible alternative is the graded-prediction account, involving a passive, diffuse activation of multiple candidates providing partial predictions about upcoming words, including semantic and part-of-speech information but not their full word forms (Staub, 2015). The lack of a prediction cost when a word has a more predictable alternative candidate supports this view. Frisson, Harvey, and Staub (2017) clearly demonstrated that an unpredictable word in a sentence that is constrained toward a different highly predictable word does not result in a processing cost compared with the same unpredictable word in an unconstrained sentence, where there is no high-predictability competitor. Put simply, if a word is predictable from its context, its preactivation is helpful for later processing, even if a different word is a much more likely continuation of the sentence. Importantly, context preactivates a number of semantically related lexical entries, and the strength and spread of activation are likely to depend on how strongly a text is centered around a specific topic or coherent theme.

Early Contextual Facilitation Effects

Contextual facilitation effects can be viewed as the result of a spreading of activation from the current information being processed to semantically related lexical entries, which is automatic and does not require directed attentional resources (Stanovich & West, 1979). Indeed, contextual facilitation effects have been shown to occur very early in the time course of fixation durations during skilled adult reading, which suggests that context facilitates the preactivation of upcoming words (Staub, 2015). Contextual facilitation effects are reliably found in first-pass reading times (Ehrlich & Rayner, 1981; Frisson et al., 2017; Luke & Christianson, 2016; Morris, 1994; Rayner & Well, 1996; Staub, 2011). However, contextual constraint also influences reading before a word is fixated directly. Veldre and Andrews (2017) showed that the benefit of reading a word with a valid parafoveal preview is greater if the target word is preceded by congruent context, suggesting that predictable upcoming words are processed more efficiently in the parafovea than unpredictable words. Similar findings have been reported for children. Johnson et al. (2018) found a greater facilitating effect of a valid preview in children's late-eye-movement measures when the previewed word's context was highly constrained. Nevertheless, contextual facilitation effects are also found when no preview is available (Parker, Kirkby, & Slattery, 2017), as well as when invalid, nonword parafoveal previews are presented (Sereno, Hand, Shahid, Yao, & O'Donnell, 2018). Contextual facilitation effects cannot, therefore, be solely due to more efficient parafoveal preview. Further studies have demonstrated that the entire distribution of first-fixation durations is shifted toward shorter average fixation durations for words in highly constrained contexts (Sheridan & Reingold, 2012; Staub, 2011; Staub & Benatar, 2013), suggesting an influence of context from a very early stage of processing. Studies point toward the onset of contextual facilitation effects in event-related potentials (ERPs) at 132 ms (Sereno, Brewer, & O'Donnell, 2003) and at 140 ms in fixation durations (Sheridan & Reingold, 2012). This is earlier than the onset of phonological effects in eye movements, reported at around 160–173 ms (Leininger, 2019).

Late Effects of Integration

Contextual facilitation effects are, however, also evident in late processing stages during reading, suggesting a facilitation of postlexical integration processes that rely on semantic information. Although Staub (2015) cited a lack of studies supporting his finding of predictability effects in late-eye-movement measures, since then, contextual facilitation effects have reliably been found in regression probability and total viewing time (Frisson et al., 2017; Johnson et al., 2018; Luke & Christianson, 2016; Sereno et al., 2018), supporting his observation. Another important finding is that the semantic relatedness of words interacts with context effects. Luke and Christianson (2016) found contextual facilitation effects for unpredictable words that were semantically related to a more predictable alternative continuation of a sentence in total viewing time and regression probability compared with unpredictable words with no semantic relation to a more predictable continuation (see also Schotter, Lee, Reiderman, & Rayner, 2015). This again suggests contextual facilitation in late postlexical integration processes.

Regressive saccades that initiate rereading of text passages are another important measure of late processing during reading and evidently contribute to comprehension building because denying readers the ability to regress adversely affects their comprehension (Schotter, Tran, & Rayner, 2014). Regressions are thought to represent the reader's attempt to repair comprehension failures (Booth & Weger, 2013; Rayner, 2009; Rayner, Kambe, & Duffy, 2000). Indeed, the more difficult the text, the more regressions readers typically make (Rayner, 1998). Both skilled adult (Ashby et al., 2005; Staub, 2011) and beginning readers (Johnson et al., 2018) make fewer regressions back to words in a constrained context compared with words read in neutral context. This suggests that these words are more easily integrated into the reader's mental model on first-pass reading and are therefore less likely to create comprehension difficulties that would elicit reinspection. Children have, however, also been shown to be less strategic than adults in their initiation of regressive saccades and rereading (Tiffin-Richards & Schroeder, 2018), which might lead to less directed rereading of unpredictable words. Because there are currently no direct comparisons of contextual facilitation effects in beginning and skilled adult readers, it remains unclear whether children target words with weak contextual links for rereading as adults do.

Context in Sentences and Longer Texts

Although there is clear evidence of contextual facilitation in lexical processing, there is a continuing debate about the relative importance of integration and prediction processes in text reading (Luke & Christianson, 2016). It is plausible that a graded prediction of possible sentence continuations can be considered as an anticipatory rather than predictive process in which readers use their current situational model to prepare themselves for new information (Ferreira & Chantavarin, 2018). According to this view, the efficiency of anticipatory processes relies on the richness of the reader's current situational model. The postlexical benefit of context in text reading is thus clearly dependent on the congruence of the word being read with its preceding context and the integration of the reader's relevant world knowledge into the reader's mental model of the text content (van den Broek, 1994). A word

can, for instance, be contextually constrained because of the reader's knowledge of the relationship between two actors in a typical narrative, such as in the sentence, "The cat caught the mouse running around the kitchen." A word may also be contextually constrained because of its use in a phrase stored in memory, such as in the proverb, "A bird in the hand is worth two in the bush" (Fernández, Shalom, Kliegl, & Sigman, 2014).

A word embedded in a longer text can therefore be constrained by context on multiple levels, including local interword associations and more global discourse coherence (Pynte, New, & Kennedy, 2008). Using latent-semantic-analysis (LSA) associations between adjacent words and between a word and its preceding sentence fragment, Pynte et al. (2008) demonstrated the simultaneous influence of the contextual constraint of word-level and sentence-level associations on the inspection time of target words in the Dundee eye-tracking corpus (Kennedy, Hill, & Pynte, 2003). Word-level constraint was found to decrease inspection time in single fixations and gaze duration, whereas sentence-level constraint decreased gaze durations. This finding provides clear evidence that contextual constraint effects found in longer texts, such as newspaper articles (Kennedy et al., 2003), are the result of a composition of local and global predictive processes. These combined processes create an expectancy for upcoming words based on the semantic content of both preceding sentence fragments and directly neighboring words.

Contextual constraint can, however, also extend beyond sentence boundaries. Schustack, Ehrlich, and Rayner (1987) showed that inspection time for target nouns embedded in longer passages was affected by both the contextual constraint of the immediately preceding verb (*hung* [restrictive] vs. *put* [general], *picture* [target]) and the proximity of a previous mention of the target. A restrictive preceding verb and recent mention of the target had independent facilitation effects on gaze durations on the target nouns. The authors interpreted their findings as evidence for independent facilitation of word-identification processes through local semantic associations and facilitation of integration processes through repetition in the reader's internal discourse representation (Schustack et al., 1987).

Another source of global contextual information is provided by informative story titles. Wiley and Rayner (2000), for instance, found that when stories with informative titles were read, readers were more accurate in their recall of the text content, made fewer fixations and regressions, and spent less time with wrap-up processing at sentence endings than when the same texts were read without informative titles. The authors concluded that titles facilitate the integration of propositions into readers' mental representation of the text, thus reducing the need for regressions and rereading and increasing reading speed. On a lexical level, titles have also been shown to constrain the understanding of ambiguous nouns (Kambe, Rayner, & Duffy, 2001), suggesting that global context can influence word-level processing. With respect to predictive processing, story titles may also have a facilitating effect through the activation of relevant background knowledge. Titles that explicitly prepare for a comprehension task (e.g., "Why Are Forests Important?") have been shown to influence both adults' and children's reading of science texts (Kaakinen et al., 2015); compared with titles that only state the text's content (e.g., "Forests Are Important"), adults and older children tended to reread more of the text and spend less time on first-pass reading. The

authors interpreted these findings as an indication that the combination of task instruction and title prompt increased the readers' standards of coherence and facilitated their first-pass reading through the activation of relevant background knowledge.

Taken together, eye-movement studies of text reading suggest that contextual facilitation can work on multiple levels, including local semantic word associations, sentence-level semantic associations, and global constraint through the activation of relevant background information by informative titles. It follows that contextual facilitation effects studied in single-sentence frames may not capture the full breadth of possible constraints that readers routinely use when navigating longer text passages.

The Present Study

The present study was designed to extend previous investigations of sentence-predictability effects to contextual facilitation effects in children's text reading. It could be argued that children are unlikely to make use of contextual information, due to lexical processing consuming most of their attentional resources (Just & Carpenter, 1980). However, children, despite poorer overall comprehension skills compared with adults, routinely use prediction during language comprehension. Children are entirely capable of anticipating upcoming spoken language input, and studies have shown that individual differences in children's predictive processing are related to their verbal production skills (Mani & Huettig, 2012) and word-reading ability (Mani & Huettig, 2014).

Joseph et al. (2008) demonstrated that children can detect semantic anomalies in sentence reading, although such detection is somewhat delayed compared with skilled adult readers. This suggests that children use context to form expectations during reading and stumble when their expectations are not met. To our knowledge, there is presently only one published study that investigated contextual facilitation effects in children's sentence reading (Johnson et al., 2018). In their study, Johnson et al. (2018) found evidence of predictability effects mainly in late-eye-movement measures and not, for instance, in beginning reader's first fixations. Our expectation was hence that we would find contextual facilitation effects in children's fixation durations during text reading. Specifically, the use of context should aid beginning readers' integration processes, which are a prerequisite for successful reading comprehension. Conversely, preactivation of upcoming words may play a lesser role, due to constraints on cognitive-processing resources (Just & Carpenter, 1980) and poorer parafoveal processing (Marx, Hutzler, Schuster, & Hawelka, 2016) compared with adult readers. This should result in a late effect of contextual constraint in children's eye movements. To test these hypotheses, we recorded children's eye movements while they read age-appropriate and thematically constrained narrative texts with embedded target nouns that were either strongly or weakly related to the explicit narrative theme. A group of adults provided a point of comparison with contextual facilitation effects in skilled reading.

We pursued two avenues of analysis. First, we assessed the prevalence of the contextual facilitation effect in first-pass fixation measures, which are generally considered to be early processes because they represent the first contact with a word (Clifton, Staub, & Rayner, 2007). We contrasted these with the contextual facilitation effects found in measures of rereading and regression

probability, which are considered to be measures of late processes triggered by integration difficulties (Clifton et al., 2007). We expected to find strong late contextual facilitation effects in children's eye movements compared with early effects in adults, consistent with the hypothesis that poor readers use context to facilitate discourse integration.

Our second approach was to test the strength of the contextual facilitation effect for fixations of different durations using quantile regression. Numerous statistical analysis methods have been used to investigate the time course of effects in adult reading. Survival analysis can be employed to determine the earliest point at which two distributions diverge, for instance, for fixation-duration distributions for high-predictability versus low-predictability targets (Sheridan & Reingold, 2012). Alternatively, ex-Gaussian analysis can specify the shape of the distributions in terms of their mean (μ), standard deviation (SD), and (for response-time analyses) exponential left-hand tail (τ), which can be compared between distributions of high- and low-predictability targets (Staub, 2011). Although these methods provide estimates of differences in the shape of the distribution of fixation durations under different conditions, quantile regression presents an alternative method that allows the estimation of the impact of a predictor along the entire distribution of an outcome variable while holding all other covariates constant (Koenker & Hallock, 2001). Quantile regression does not subdivide the sample but uses all available data points to estimate the relationship between predictor and outcome variables at each specified quantile of the distribution of the outcome variable (e.g., 25th, 50th, and 75th) by weighting their proximity to the quantile. This provides information about the relationship that is otherwise not available in ordinary linear regression, which estimates the average effect of the predictor. In the present case, we tested the contextual facilitation effect at different quantiles of the distribution of first-pass fixation durations. A strong influence of contextual constraint in the low quantiles, representing the left-hand tail of the distribution, would suggest early effects. The earliest effects of contextual facilitation in electroencephalogram (EEG) studies suggest that evidence for early influences can be expected between 132 ms (Serenio et al., 2003) and 140 ms (Sheridan & Reingold, 2012) from the start of a fixation. Conversely, strong effects in later quantiles, representing the right-hand tail, without significant effects in the lower quantiles would suggest late effects. We expected to find early effects of contextual constraint in adults' fixation measures and later context effects in children, consistent with the hypothesis that skilled readers use context for the preactivation of upcoming word candidates, whereas poor readers use contextual constraint to facilitate late integration processes.

Method

Participants

We recruited 21 children (12 girls; age: mean [M] = 8.75 years, SD = 1.25) and 16 adults (9 women; age: M = 26, SD = 4) from the participant database of the Max Planck Institute for Human Development in Berlin, Germany. All participants were native German speakers, had normal or corrected vision, and no record of a reading disability. Children's average word-reading fluency on the SLRT-II (Moll & Landerl, 2010) was slightly above average

(63rd percentile, $t = 2.48$, p value = 0.023), whereas adults' word-reading fluency was average (54th percentile). The ethics board of the Max Planck Institute for Human Development approved the study.

Materials

Texts. The stories used in this study were written with age-appropriate themes for children, such as pirates, animals, birthday parties, and hobbies (see the Appendix for an example story). Each story comprised 3 to 5 sentences ($M = 3.5$) and 33 to 59 words ($M = 45$) and included a brief 1- to 3-word title describing a simple setting (e.g., "The Bee Hive" or "The King"). Six target words were embedded in each story. Three of these were directly related to the theme of the story, and three were not (e.g., title: "The Wizard," related: *tower*, *books*, *staff*; unrelated: *cup*, *noise*, *turtle*), resulting in 72 related and 72 unrelated target words in total. The average word length did not differ significantly ($t = .34$, $p = .735$) between theme-related ($M = 6.45$, $SD = 1.99$) and theme-unrelated target words ($M = 6.59$, $SD = 1.93$). The average lemma frequency also did not differ significantly ($t = 1.39$, degrees of freedom [df] = 138, $p = .665$) between theme-related ($M = 77.69$, $SD = 87.56$) and theme-unrelated target words ($M = 70.78$, $SD = 102.73$). All word frequencies were derived from the German childLex corpus (Schroeder, Würzner, Heister, Geyken, & Kliegl, 2015). Each target word appeared only once in each story and did not occur in the story title. Target words never appeared at the beginning of a sentence or line of text. However, in four cases, targets did appear at the end of a sentence. Whether these items were included or not had no effect on the reported analyses. The sequence of strongly and weakly constrained targets varied across texts such that strongly constrained targets tended to appear earlier (median = fourth position in target sequence) compared to weakly constrained targets (median = third position).

Cloze predictability. To validate that the theme-related target words were indeed easier to predict in the stories than theme-unrelated target words, we collected cloze-predictability ratings of the stories from an independent sample of 36 Grade 4 children (18 girls; age: $M = 9$ years 4 months, $SD = 6$ months) and 12 adults (9 women; age $M = 26$ years, $SD = 4$). Each participant was first presented with a blank screen and asked to guess the title of the story. Adult participants typed their responses on a laptop keyboard, whereas the responses were typed by the test instructor for the children. The title of the story was then presented on the screen, and the participant was asked to guess the first word of the story, upon which the first word was revealed and the next word was predicted. This continued for the entire story. Adults completed between 12 and 24 stories, and children completed between 3 and 8, resulting in 15 to 24 cloze responses for each word. The overall average cloze predictability was 30% ($SD = 34\%$) for adults and 22% ($SD = 29\%$) for children. Because the correlation between the children's and adults' cloze predictability was very high ($r = .81$), these were combined. The mean cloze predictability of target words related to the story theme was 49%, and it was 5% for unrelated target words. Theme-related words are therefore further referred to as strongly contextually constrained, whereas theme-unrelated words are considered as weakly contextually constrained.

Readability. A separate sample of 41 Grade 4 children rated the fit of each title to its story, the difficulty of the story, their interest in the story topic, and their knowledge of the story topic on a 4-point Likert scale of 1 = *not at all*, 2 = *not so much*, 3 = *a little*, and 4 = *a lot*. The average ratings suggest that the titles were a good primer for the content of the story ($M = 3.17$, range = 2.17–3.60), that the stories were of average difficulty ($M = 2.28$, range = 1.17–3.60), and that the children were generally interested in ($M = 2.28$, range = 2.37–3.33) and knowledgeable about ($M = 2.53$, range = 1.89–3.14) the story themes.

Procedure

A 5-dot calibration of the EyeLink 1000 eye tracker (SR Research, Ontario, Canada) was conducted with each participant until a calibration accuracy of at least 0.5 was achieved. The eye tracker was recalibrated after practice trials and as necessary. Reading was binocular, and the right eye was tracked at a rate of 1,000 Hz and spatial resolution of 0.5°. A practice story was followed by 24 stories in random order. Each story was preceded by a fixation cross in the top left-hand corner that triggered the trial on fixation, and participants ended the trial by pressing a gamepad button. Stories were followed by a yes–no comprehension question. Adult participants were compensated with 10€, and children received a small gift.

Analysis

We analyzed first-fixation duration (the only fixation or the first of multiple fixations on a target word) and gaze duration (all fixations on a target before the first saccade leaves a target) as early processing measures. We also analyzed the late measures of total viewing time (all fixations on a target), go-past time (sum of all fixations after first-pass reading of a word up to but not including the first fixation to the right of the word), regression probability (likelihood of initiating a regression from the target on first pass), and reinspection probability (likelihood of regressing back to the target after first-pass reading). To eliminate outliers, durations 2.5 SD above the mean for each participant and item were discarded, removing less than 2% of the data for each measure.

Linear mixed models were used to analyze the data for adults and children for each dependent measure in the R environment (R Development Core Team, 2012) with the lme4 package (Bates, Mächler, Bolker, & Walker, 2015). Participants and items were treated as crossed random effects, and all fixation-duration measures were log-transformed. Context constraint was effect coded (weak vs. strong contextual constraint) and included as a fixed effect, together with a random slope for each participant. Age group was included as an effect-coded factor. Contrasts between predictability conditions and age groups were estimated using cell-mean coding. Word length and frequency were added as centered continuous variables to reduce unexplained error variance and are not further reported.

In addition, linear quantile regression was used to investigate the strength of the contextual facilitation effect at different quantiles of the first-pass fixation measures with the R package quantreg (Koenker, 2007). In analyses of adults' fixation-duration distributions, first-fixation duration is the common measure (Staub, 2011;

Staub & Benatar, 2013). However, gaze duration is a more common measure for children's first-pass reading because they typically refixate on words multiple times (Blythe, Häikiö, Bertam, Liversedge, & Hyönä, 2011). We therefore included analyses of both first fixations and gaze duration. The strength of the contextual facilitation effect was estimated between the 10th to 90th percentiles in steps of 10 percentage points.

Attentiveness was assessed by comprehension questions following each story. Children answered 88% (minimum = 75%) of the comprehension questions correctly, whereas adults answered 91% correctly. There was no significant difference between the comprehension scores of children and adults, $t(34.69) = 1.395$, $p = .172$.

Power Analysis

To test whether any detected developmental differences in contextual facilitation effects in our study could be expected to be replicable, we ran a power study using a simulated mixed-effects modeling approach (Green & MacLeod, 2016). Data were drawn from an unpublished study in which 15 children and 16 adults read 48 sentences selected from the Potsdam Sentence Corpus (PSC; Kliegl et al., 2006). We ran the same mixed-effect models described in the present study with contextual constraint and age group as effect-coded factors and target-word length and frequency as centered control variables. We used the estimated fixed and random effects to generate simulated data sets with varying group sizes, using the `makeLmer()` function of the R `simr` package (Green & MacLeod, 2016). Statistical power of at least 80% (Brysbaert & Stevens, 2018) was reached for the interaction effect of age group and contextual constraint for group sizes of 18 participants and 144 observations per participant in first fixation and gaze duration.

Results

The mean observed fixation measures on target words in weak and strong contextual constraint conditions are provided in Table 1. The results of the analysis of variance (ANOVA) omnibus tests for the fixed effects of contextual constraint are reported in Table 2. The simple main effects reported were calculated using cell-mean coding with the `multcomp` R package and are presented in the following paragraphs. Reported effect sizes are back-

transformed from model estimates. We ran a number of complementary post hoc analyses to check whether properties of the target words or pretarget words or the reading ability of our participants moderated the contextual facilitation effect.

Linear Mixed-Effects Analysis

There were no simple main effects of contextual constraint in the first-fixation durations of children ($b = -0.003$, $t = -0.21$, $p = .830$) or adults ($b = 0.014$, $t = 0.75$, $p = .451$). There was, however, a significant 26-ms simple main effect of contextual constraint in gaze duration for children ($b = 0.074$, $t = 3.04$, $p = .002$) and a significant 15-ms effect for adults ($b = 0.071$, $t = 2.75$, $p = .006$), which did not differ significantly in effect size ($b = -0.003$, $t = -0.12$, $p = .909$).

In the late-eye-movement measures, effects were clearly stronger for children. In total reading times, there was a significant 124-ms contextual facilitation effect for children ($b = 0.24$, $t = 7.67$, $p < .001$) and a significant 28-ms contextual facilitation effect for adults ($b = 0.10$, $t = 3.10$, $p = .002$). The effect was significantly stronger for children ($b = -0.13$, $t = -4.17$, $p < .001$). There was also a significant 108-ms contextual facilitation effect in go-past time for children ($b = 0.19$, $t = 5.92$, $p < .001$), as well as a 29-ms effect for adults ($b = 0.11$, $t = 3.11$, $p = .002$), which was, however, significantly stronger for children ($b = 0.04$, $t = -2.24$, $p = .025$).

Children were 7.1% more likely to initiate a regression on first pass from a weakly contextually constrained word ($b = 0.35$, $t = 2.38$, $p = .017$), whereas the simple main effect of 4.5% was only marginal for adults ($b = 0.26$, $t = 1.64$, $p = .10$). The difference in effect size was not, however, significantly greater for children than adults ($b = -0.8$, $t = -0.46$, $p = .646$). Children were 6.2% more likely to regress back to and reinspect a weakly contextually constrained word ($b = 0.58$, $t = 4.40$, $p < .001$), whereas adults were only marginally more likely to regress back to weakly contextually constrained words ($b = 0.22$, $t = 1.51$, $p = .131$). There was, however, no significant difference in effect size for children and adults ($b = -0.37$, $t = -2.34$, $p = .018$).

Our results show a clear contextual facilitation effect in the first-pass reading of longer gaze durations on weakly contextually constrained words compared with strongly contextually constrained words for both children and adults. However, children showed significantly stronger late effects of contextual facilitation

Table 1
Observed Mean Fixation and Regression Measures for Strong- and Weak-Context Targets With Standard Errors

Measure	Children		Adults	
	Context condition		Context condition	
	Strong	Weak	Strong	Weak
First-pass fixations	1.54 (.03)	1.74 (.04)	1.10 (.01)	1.18 (.01)
First-fixation duration	244 (3)	247 (3)	197 (2)	200 (2)
Gaze duration	371 (8)	411 (10)	213 (3)	231 (3)
Total viewing time	524 (13)	701 (17)	295 (6)	333 (6)
Go-past time	693 (35)	802 (24)	300 (10)	354 (12)
Regression in (%)	10.88 (0.93)	17.67 (1.15)	13.30 (1.20)	17.29 (1.33)
First-pass regression out (%)	26.26 (1.32)	32.38 (1.41)	22.51 (1.41)	26.54 (1.46)

Table 2
ANOVA Omnibus Tests for the Main Effects and Interactions of Contextual Constraint and Age Group as Well as Control Variables

Measure	Effect			Control variables			
	Contextual constraint	Group	Constraint × Group	Word length	Word frequency	Length × Group	Frequency × Group
First-fixation duration							
<i>F</i>	0.12	29.54	0.76	1.39	1.81	0.13	0.78
<i>p</i> value	0.732	<.001	0.387	0.240	0.181	0.724	0.378
Gaze duration							
<i>F</i>	12.35	26.81	0.01	60.22	2.22	37.91	4.13
<i>p</i> value	<.001	<.001	0.909	<.001	0.139	<.001	0.042
Total viewing time							
<i>F</i>	38.21	20.47	17.34	49.30	7.43	35.37	7.64
<i>p</i> value	<.001	<.001	<.001	<.001	0.007	<.001	0.005
Go-past time							
<i>F</i>	28.86	24.07	5.01	39.38	5.67	22.87	3.72
<i>p</i> value	<.001	<.001	0.032	<.001	0.019	<.001	0.053
Regression-in probability							
χ^2	12.30	0.31	5.52	2.57	3.61	0.43	0.36
<i>p</i> value	<.001	0.576	0.019	0.109	0.057	0.513	0.548
Regression-out probability							
χ^2	6.13	1.98	0.18	0.75	1.87	0.43	0.03
<i>p</i> value	0.013	0.159	0.673	0.387	0.171	0.512	0.861

Note. ANOVA = analysis of variance.

in total reading time and go-past time than adults. Children and adults showed similar contextual facilitation effects in the likelihood of regressions into and out of weakly contextually constrained words. This suggests that the lack of strong contextual constraint triggers rereading in children as it does in adults, whereas children generally spend longer rereading weakly contextually constrained words and preceding text compared with adults.

Quantile Regression Analysis

The quantile regression approach allowed us to further tease apart the onset of early and late components of the contextual facilitation effect in first-pass reading. Figure 1 displays children's and adults' average first fixations and gaze durations for words in weak- versus strong-context conditions at the 10th to 90th percentiles of their distributions. Figure 2 further illustrates the strength and confidence interval of the contextual constraint effect at each quantile for children (right panels) and adults (left panels). The grayed area in Figure 2 represents the confidence intervals around the average regression coefficient. Clearly, the effect of contextual constraint was not constant and deviated considerably from the average effect across the quantiles of the fixation-duration distribution. The exact estimates, *t* values, and *p* values for the contextual facilitation effect at each quantile are reported in Table 3. Adults showed an effect of contextual constraint at the 10th–20th percentiles of the first-fixation-duration distribution, corresponding to an early effect between 131 and 151 ms after fixation onset, whereas no such effect was found in children. This suggests that there was a strong effect for adults very early in the time course of their first-fixation durations, even though the effect did not reach significance in the overall analysis. This early effect was not apparent for children. The early contextual facilitation effect carried over into adults' gaze durations up to the 90th percentile. In contrast, the contextual facilitation effect in children's gaze durations was only significant at the 80th–90th percentiles, correspond-

ing to 512–739 ms after the onset of first-pass reading, again suggesting that contextual facilitation effects in children manifest in the late processing stages of first-pass reading.

Moderation of Contextual Facilitation

Reading skill. To assess whether the developmental difference in the expression of the contextual facilitation effect could be explained by individual differences in the speed of lexical processing, we conducted a separate mixed-effects analysis including the participants' centered scores on the 1-min SLRT-II reading test (Moll & Landerl, 2010). We included both the main effect of lexical processing speed and the three-way interaction between contextual constraint, age group, and speed of lexical processing. Word-reading speed decreased target-word inspection time but did not influence contextual constraint or the interaction of contextual constraint and age group.

Target-word length, frequency, and position. The target words used in this study varied in their length and frequency, which was accounted for in all analyses by including their main effects as centered continuous control variables. However, we also ran additional analyses including the interaction between the control variables and the contextual constraint effect and the age-group variable (see Table 2). These analyses found only one significant interaction with contextual constraint. The frequency effect in first fixations was significantly stronger for weakly constrained target words than for strongly constrained targets. The significant interactions of the control variables word length and frequency with age group in gaze duration, total viewing time, and go-past time indicated stronger effects for beginning compared with skilled readers.

We also assessed whether the position of target words within each story influenced the contextual facilitation effect. It is plausible that contextual facilitation should increase for words toward the end of a story because the reader accumulates a richer dis-

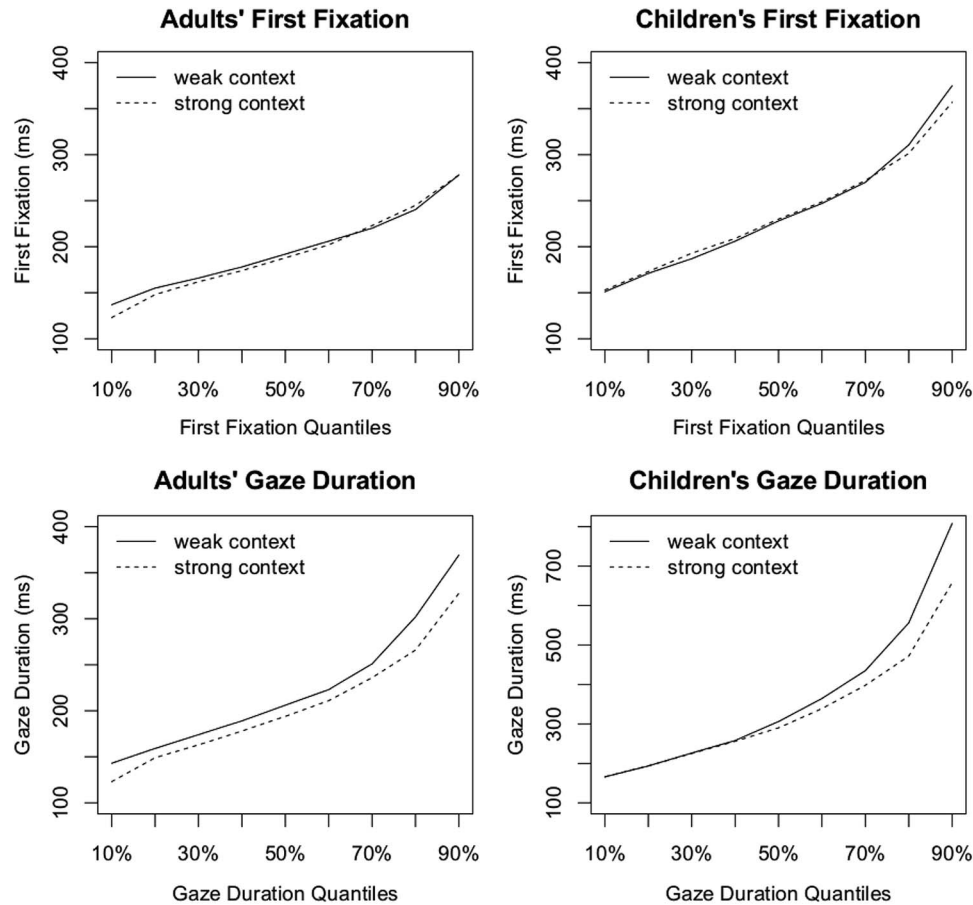


Figure 1. Children's and adults' first-fixation and gaze-duration quantiles for target words in strong- versus weak-context conditions.

course model of the story as it develops. We therefore tested whether target-word position interacted with contextual constraint but found no significant effects.

Pretarget-word length and frequency. The words immediately preceding the target words were not controlled for their length or frequency. To rule out any differential effects on parafoveal preprocessing of the target words, we conducted a final set of complementary analyses in which we included the length and frequency of pretarget words as centered continuous variables as main effects and interactions with contextual constraint. Our results were clear: Pretarget-word length and frequency had no influence on fixation measures on target words, and there were no interactions between pretarget-word characteristics and the contextual constraint effect on the target word.

Discussion

We investigated the prevalence and time course of contextual facilitation effects in children's eye movements during text reading, thus addressing a prominent gap in eye-movement research (Rayner et al., 2013). Our central finding was that children showed contextual facilitation in late-eye-movement measures during text reading as opposed to both the early and late facilitation found in skilled adult readers. Strikingly, quantile regression revealed that

contextual facilitation effects had an early onset in adults' first-pass reading, which was not evident in the overall analysis, whereas contextual facilitation had a late onset in children. Contextual constraint had a similar effect on the pattern of regressions in both children and adults. However, children invested more extra time in rereading weakly constrained target words and the text preceding weakly constrained words compared with adults. Our results thus suggest that context is a highly relevant factor in children's reading of written prose and that the contextual facilitation effect in beginning readers is driven by the facilitation of late integration processes. In contrast, we also replicated the finding of very early contextual facilitation effects in adults that indicate facilitation through preactivation processes or prediction of candidates for upcoming words.

The results of our study suggest a difference in the use of context between beginning and skilled readers, which is consistent with more general developmental differences observed in eye movements between children and adults. Skilled adult readers use contextual constraint to preactivate candidates for upcoming words, probably in combination with parafoveal preprocessing (Kliegl et al., 2006), to facilitate the early processing stages of word recognition. We found evidence of this in the very early onset of the contextual facilitation effect in first fixations in adults.

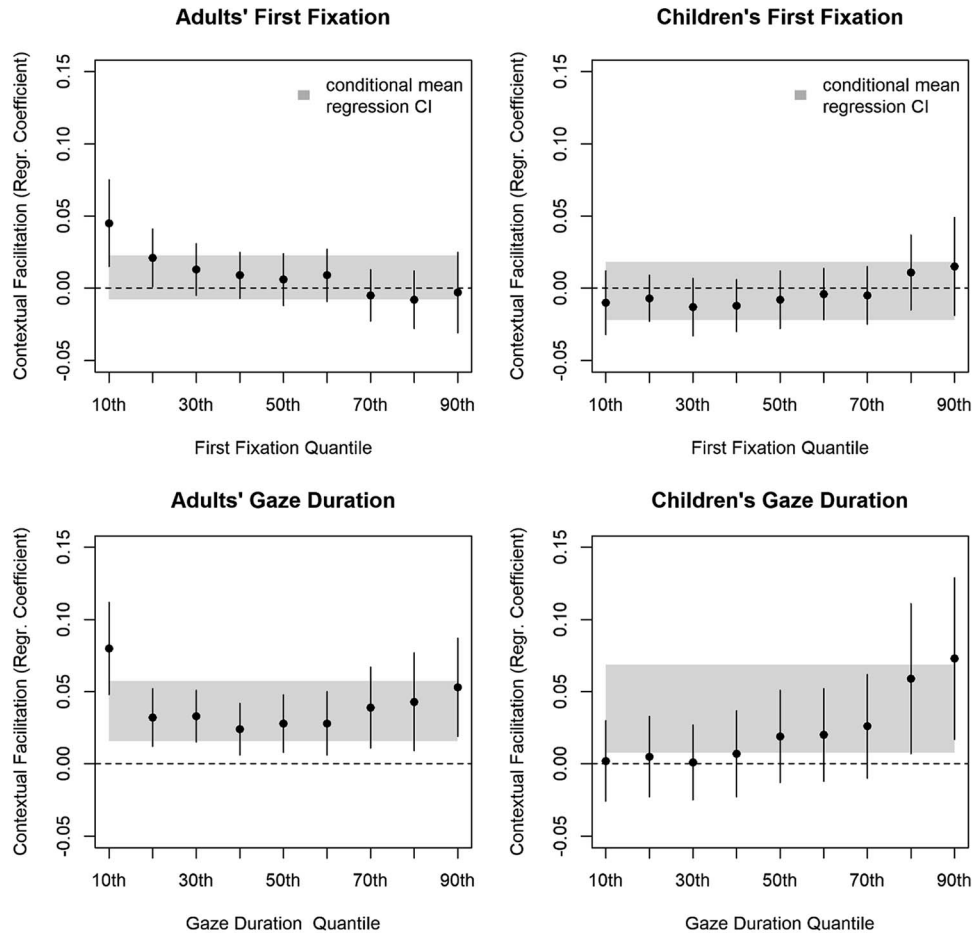


Figure 2. Quantile regression results for the contextual facilitation effect of weak versus strong context in first fixations and gaze durations with the conditional mean regression confidence interval (shaded area).

Children do not have the same lexical processing efficiency (Blythe, 2014; Schroeder, Hyönä, & Liversedge, 2015) and extract less parafoveal information (Marx et al., 2016; Tiffin-Richards & Schroeder, 2015), greatly reducing their capacity to use predictive processing during reading. Children experienced the largest facilitation through contextual constraint in late integration processes, which is evident in the late onset of the contextual facilitation effect in children's first-pass reading and the lack of any effect in first fixations. It is also apparent in children's rereading behavior. Although children and adults both regressed out of and into weakly constrained words more often than strongly constrained words, children invested more time rereading both weakly constrained words and previous text compared with adults. This suggests that story elements, which are not clearly linked to their preceding narrative context, are more likely to trigger a rereading strategy in beginning readers, presumably because they are less easily integrated into the reader's current discourse model of the text.

The difference in the expression of the context facilitation effect is likely due to a combination of limitations in cognitive resources and differences in resource allocation during reading. Skilled readers have greater available cognitive-processing capacity, vocabulary knowledge, and prior knowledge to aid top-down predictions

of upcoming words, as well as more efficient bottom-up processing of parafoveal information, compared with less skilled readers. Conversely, less skilled readers struggle with comprehension during reading and may thus profit to a larger extent from the use of contextual information to integrate each new word into their discourse model (Stanovich, 1980). As a developmental trend, it is conceivable that beginning readers thus concentrate their efforts on decoding and integration to achieve a basic level of comprehension, whereas more skilled readers are free to invest further resources into predictive and anticipatory processing to facilitate their reading fluency. Skilled readers may also have gathered more relevant world knowledge, such as knowledge of story grammar or narrative themes, which may aid both in prediction and integration processes.

The relative weight of predictive versus integration facilitation can also be seen as a trade-off between text difficulty and reading ability. If this assumption holds, skilled adult readers should show increased facilitation of integration processes through the use of context information in more challenging texts. Indeed, there is evidence suggesting that skilled readers make more use of contextual constraints when the difficulty of lexical processing increases, for instance, when input is visually degraded (Morris, 1994). The

Table 3

Contextual Facilitation Effect at Different Quantiles of Children's and Adults' First Fixations and Gaze Durations

Quantile	ms	First fixation				Gaze duration				
		<i>b</i>	<i>SE</i>	<i>t</i> value	<i>p</i> value	ms	<i>b</i>	<i>SE</i>	<i>t</i> value	<i>p</i> value
Children										
10th	151	-0.010	0.011	-0.865	0.387	166	0.002	0.014	0.165	0.869
20th	172	-0.007	0.008	-0.943	0.346	194	0.005	0.014	0.345	0.730
30th	190	-0.013	0.010	-1.405	0.16	225	0.001	0.013	0.11	0.913
40th	208	-0.012	0.009	-1.279	0.201	257	0.007	0.015	0.464	0.643
50th	229	-0.008	0.010	-0.831	0.406	298	0.019	0.016	1.207	0.228
60th	248	-0.004	0.009	-0.433	0.665	349	0.020	0.016	1.221	0.222
70th	271	-0.005	0.010	-0.476	0.634	415	0.026	0.018	1.475	0.140
80th	306	0.011	0.013	0.880	0.379	512	0.059	0.026	2.248	0.025
90th	364	0.015	0.017	0.908	0.364	739	0.073	0.028	2.591	0.010
Adults										
10th	131	0.045	0.015	2.945	0.003	132	0.08	0.016	4.949	<.001
20th	152	0.021	0.01	2.205	0.028	155	0.032	0.010	3.160	0.002
30th	164	0.013	0.009	1.511	0.131	169	0.033	0.009	3.528	<.001
40th	176	0.009	0.008	1.099	0.272	184	0.024	0.009	2.571	0.010
50th	190	0.006	0.009	0.664	0.507	200	0.028	0.01	2.856	0.004
60th	204	0.009	0.009	1.100	0.271	218	0.028	0.011	2.518	0.012
70th	221	-0.005	0.009	-0.545	0.586	243	0.039	0.014	2.818	0.005
80th	242	-0.008	0.01	-0.803	0.422	281	0.043	0.017	2.566	0.010
90th	278	-0.003	0.014	-0.191	0.849	353	0.053	0.017	3.035	0.002

developmental differences reported here should therefore be considered as differences in the relationship of reader ability and reading-task difficulty and ensuing differences in the allocation of processing resources rather than qualitative changes in reading processes themselves.

It is important to emphasize that our study differs in a key aspect from other studies investigating the effects of cloze predictability in single-sentence reading. By using narrative texts with highly constrained content and title themes, we demonstrate that contextual facilitation effects can be achieved by relating target words to the overall theme of a narrative. It is noteworthy that despite this difference in reading materials, our study replicates previously reported predictability effects for adult readers. We were also able to reproduce contextual constraint effects reported in sentence reading in children (Johnson et al., 2018). This has relevance for both experimental design and educational applications. Texts allow the construction of more elaborate context than single sentences and are hence ideal for investigating context effects. Using texts with many words related to a clearly defined narrative theme may also be particularly important for low-skilled readers in educational, foreign language, and remediation contexts. The predictability or theme-relatedness of the vocabulary used in test design and teaching materials thus deserves further attention, particularly in the case of low-skilled and beginning readers.

Our study is the first to report the effect of contextual constraint on children's eye movements and fixation durations during narrative text reading in a controlled experimental design. We provide two important contributions to the current literature on contextual facilitation effects in reading. First, we demonstrate clear differences in the contextual facilitation effect between beginning and skilled readers. Although ordinary linear regression analyses found effects in gaze duration for both children and adults, quantile regression analyses provided further insight into differences in the

time course of the effect. Whereas adult readers showed very early contextual facilitation in their first fixations and strong overall effects in gaze duration, children only showed delayed effects in their gaze durations. We interpret this difference in the time course as an indication of an important difference in the role of context in beginning and skilled readers, suggesting a developmental shift from a focus on lexical and integrative processing in beginning readers to increased parafoveal and anticipatory processing in skilled readers. Our second important contribution is the replication of contextual facilitation effects in children's eye movements during narrative text reading, previously found in single-sentence reading. The use of contextual constraint is likely an important factor in children's text comprehension and vocabulary acquisition when learning from context and is thus directly relevant for educational and remedial settings.

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(Appendix follows)

Appendix

Example Story

Der Fisher (German Version)

Max arbeitet schon lange als Fischer. Er fährt mit seinem BOOT am großen FELS vorbei und wirft sein langes NETZ aus, um Fische zu fangen. In der Ferne sieht er manchmal am ABEND Wale. Das GEHEIMNIS, wo er die Perle in einer MUSCHEL gefunden hat, hat er nie jemanden erzählt.

The Fisherman (English Direct Translation)

Max has worked a long time as a fisherman. He passes in his BOAT [theme related] a large ROCK [theme unrelated] and throws out his NET [theme related] to catch fish. In the distance,

he sometimes sees in the EVENING [theme unrelated] whales. The MYSTERY [theme unrelated] where he found the pearl in the SHELL [theme related] he has never told anyone.

Note. The direct English translation preserves the German syntax as far as possible. Target words are presented in all uppercase in this example for easy identification. The theme-relatedness of the target nouns is indicated in brackets.

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