How do children read words? A focus on reading processes

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We shouldn't teach great books; we should teach a love of reading.

- B. F. Skinner -

Chapter 4
Modeling the length effect: Specifying the relation with visual and phonological correlates of reading

Beginning readers' reading latencies increase as words become longer. This length effect is believed to be a marker of a serial reading process. We examined the effects of visual and phonological skills on the length effect. Participants were 184 second-grade children who read 3- to 5-letter words and nonwords. Results indicated that reading latencies could be decomposed into a length effect and an overall reading speed. Individual differences in the length effect were predicted by phonological awareness and visual attention span. Rapid naming accounted only for differences in overall reading speed.

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INTRODUCTION

In the early stages of reading development, the speed of word reading is closely related to the number of letters in a word. Reading latencies tend to increase as a function of word length. This length effect is strong for both words and nonwords in young beginning readers and poor readers but becomes restricted to longer words (i.e., more than six or eight letters) and nonwords in advanced readers (e.g., de Luca, Barca, Burani, & Zoccolotti, 2008; Hawelka, Gagl, & Wimmer, 2010; Marinus & de Jong, 2010b; Spinelli et al., 2005; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003; Zoccolotti et al., 2005). Generally, a length effect is presumed to occur when words are processed sequentially, whereas the absence of a length effect (i.e., reading latencies that are independent of word length) is considered to indicate that words are processed in parallel. The decrease in the length effect over the course of development is taken to reflect a gradual shift from serial (e.g., letter-by-letter) word reading, toward the parallel processing of increasingly larger parts of words. Therefore, the length effect can be seen as a marker of the reading process (e.g., Ziegler et al., 2003).

The explanation of length effects has been a major focus in several computational models of reading (Ans, Carbonnel, & Valdois, 1998; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Perry, Ziegler, & Zorzi, 2007). For example, in the Dual Route Cascaded model (DRC; Coltheart et al., 2001), two reading routes are distinguished: the nonlexical route and the lexical route. In the lexical route, all letters in a string are activated in parallel, and these letters activate a word’s entry in the orthographic lexicon. In the nonlexical route, the letters are serially decoded into phonemes according to grapheme-phoneme conversion rules. Length effects arise when words are not in the orthographic lexicon and therefore are predominantly read through the nonlexical route. Thus, in the DRC model, and other computational models as well (e.g., Ans et al., 1998; Perry et al., 2007), the length effect reflects the type of reading process that occurs between the visual presentation of a word and its identification. Although most of these computational models have not been designed to model the development of reading, individual differences in the length effect might be regarded as an indication of the development of the reading system (Jackson & Coltheart, 2001).

Currently, there is ample evidence about the cognitive abilities that underlie individual differences in reading development, but the majority of this evidence is based on the outcome of the reading system, the accuracy, or speed of word reading (e.g., de Jong & van der Leij, 1999; Lervåg, Bråten, & Hulme, 2009; Parrila, Kirby, & McQuarrie, 2004; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997). There are very few studies, however, that considered the relation between these cognitive abilities and individual differences in parameters that reflect the process of word identification (for important exceptions, see Hawelka & Wimmer, 2005, and Ziegler et al., 2008). In the current study, we examined the relation between cognitive abilities and individual differences in the sensitivity to word length.

Phonological processing skills have been found to be among the major factors underlying individual differences in reading ability (e.g., Vellutino, Fletcher, Snowling, & Scanlon, 2004). Three phonological processing skills have been distinguished: phonological awareness, rapid naming, and verbal short-term memory (e.g., Wagner & Torgesen, 1987). Phonological awareness and rapid naming have repeatedly been reported to predict concurrent (e.g., Vaessen & Blomert, 2010; Ziegler et al., 2010) as well as future reading skills in all primary school grades (e.g., de Jong & van der Leij, 1999; Kirby, Parrila, & Pfeiffer, 2003; Landerl & Wimmer, 2008; Lervåg et al., 2009; McCallum et al., 2006; Parrila et al., 2004; Torgesen et al., 1997). In addition, studies focusing on reading impairment have shown that reading difficulties tend to be associated with poor naming speed, poor phonological awareness, or both (e.g., Compton, DeFries, & Olson, 2001; de Jong & van der Leij, 2003; Lovett, Steinbach, & Frijters, 2000; McBride-Chang & Manis, 1996; Wimmer, Mayringer, & Landerl, 2002; Wolf & Bowers, 1999; Wolf et al., 2002). The results concerning verbal short-term memory have been less consistent. Some studies showed that short-term memory contributed in predicting reading performance, over and above phonological awareness and rapid naming (e.g., McCallum et al., 2006; Ziegler et al., 2010), whereas in others it was found that the relation between short-term memory and reading overlapped entirely with the effect of phonological awareness (e.g., de Jong & van der Leij, 1999; Lervåg et al., 2009; Parrila et al., 2004).

In short, there is ample evidence that phonological awareness and rapid naming are related to reading. However, their relation with the length effect is less clear.

Phonological awareness might be related to the length effect through its relation with phonological recoding. According to the self-teaching hypothesis (e.g., Share, 1995, 1999) beginning readers rely on print-to-sound translation, or phonological recoding, to read words. Every time a printed word is successfully translated into a phonological code, the orthographic representation of the word, necessary for parallel processing, is built and strengthened. However, phonological recoding cannot be successful without a basic awareness of phonemes. If phonological awareness is poor, phonological recoding will be slow and fallible and the connection between a word's phonological and orthographic representation will not be established. Accordingly, poor phonological awareness results in poor buildup of orthographic representations, and therefore in continued reliance on a serial processing strategy, and a remaining sensitivity to word length.

The relation between the rapid naming of letters or digits and the length effect is more speculative. Rapid naming could relate to the activation of letter sounds. To process a word in parallel, all letters in a word need to be activated within a short timeframe. Although the activation of the letters itself could be either serial or parallel, it has been suggested by Wolf and Bowers (1999) among others, that if a reader is slow in identifying letters, all letters in a word would not be activated fast enough for the integration of individual letters into a whole word representation enabling parallel processing. As a result, the reader would continue to rely on serial processing.

More recently, it has been suggested that in addition to phonological processing skills, the visual attention span, the number of orthographic units (e.g., letters or syllables) that can be processed in parallel, also contributes to reading performance (Valdois et al., 2003; Valdois, Bosse, & Tainturier, 2004). Theoretically, the visual attention span hypothesis has been grounded in the Multiple-Trace Memory model (Ans et al., 1998; Bosse, Tainturier, & Valdois, 2007). In this model, two reading procedures are distinguished that work successively. Through the global procedure words are read as a whole, based on knowledge of entire words. If identification of a word cannot be accomplished through the global procedure, the analytic procedure is activated. This procedure is based on the successive activation of smaller orthographic units, such as syllables or letters, resulting in length effects. These two reading procedures differ in the type of visual attention required; the global procedure requires the visual attention span to extend over the whole letter string, whereas in the analytic procedure visual attention is focused successively on parts of the input string. Thus, global processing requires a larger visual attention span. If the visual attention span is too small to cover entire words, these words cannot be processed in parallel, and serial analysis of the letter string remains the only available reading strategy.

The visual attention span has been shown to contribute to reading performance, independent from IQ, vocabulary, and phonological processing in typically developing children across primary school grades (Bosse & Valdois, 2009), as well as in children with reading impairments (Bosse et al., 2007). Although visual attention span is most often measured as the number of letters that can be processed in parallel, the same relation with reading has been found for the parallel processing of nonverbal symbol strings (Lobier, Zoubrinetzky, & Valdois, 2012; Pammer, Lavis, Hansen, & Cornelissen, 2004, but see Ziegler, Pech-Georgel, Dufau, & Grainger, 2010). In addition, there is some evidence that visual attention span is related specifically to serial processing. Valdois et al. (2006), for example, reported increased activation of visual attentional brain areas during nonword reading through the analytic procedure. Furthermore, visual attention span related to the number of eye movements during word reading (Hawelka & Wimmer, 2005), more specifically to the number of rightward fixations (Prado, Dubois, & Valdois, 2007). The number of eye movements can be regarded as a parameter of the reading process, similar to the length effect, as the number of fixations per word indicates whether processing is serial (multiple fixations within a word) or parallel (a single fixation per word).

From the aforementioned studies it becomes clear that there is ample evidence that both phonological processing skills and visual attention span are related to reading ability. However, to our knowledge, it has not been studied whether phonological and/or visual processing skills explain variance in the length effect found in reading latencies for words and nonwords. In the current study we aim to present a model for the length effect that enables us to examine how the main phonological processing skills, phonological awareness, and rapid naming, as well as visual attention span, are related to the length effect as a parameter of the reading process.

METHOD

PARTICIPANTS

One hundred eighty-four Dutch children (93 boys, 91 girls) from seven second-grade classes participated in the study. The children had a mean age of 7 years, 11 months (*SD* = 5.66 months). At the time of testing, the children had received approximately 1 year 5 months of reading instruction. On the One Minute Reading Test (*Eén Minuut Test*; Brus & Voeten, 1995), a standardized test of word reading fluency with an average of 10 and a standard deviation of 3, the children scored slightly above average (*M* = 11.66), with a somewhat smaller standard deviation (*SD* = 2.53), indicating that fewer extreme scores were included than in the overall population. All children had normal or corrected to normal vision.

MATERIALS

Word and nonword reading. The reading task consisted of 45 words and 45 nonwords varying in length from three to five letters. For each length, 15 monosyllabic words were selected from a corpus of child literature (Schrooten & Vermeer, 1994). Across lengths the words were matched on onset (i.e., the first phoneme) and frequency. The words ranged in frequency to reflect the variation in the words children encounter (*Mdn* = 23, range: 1-148). In comparison, for all monosyllabic words in the database the median frequency was 22, with a range of 1 to 591 (excluding 10% extremely high-frequent words).

Nonwords were created by interchanging onsets and rhymes of the words. For example, the words *drift*, *front*, and *kramp* (meaning *urge, front* and *cramp* respectively) were used to create the nonwords 'dront', 'framp', and 'krift'. Therefore, words and nonwords of each length were matched on onset and consonant-vowel structure. When the created nonword was unpronounceable or also a Dutch word, one letter was changed in the rhyme.

The reading task (as well as the verbal short-term memory task and the visual attention span task mentioned next) was programmed in E-prime Version 1.0 (Schneider, Eschman, & Zuccolotto, 2002). Words and nonwords were presented one by one in the middle of a laptop screen (14.1 in.; 35.8 cm) in 72-point Arial font. A plus sign presented for 750 ms focused attention. Then the word or nonword appeared, and children were asked to read it aloud as quickly and accurately as possible. A voice key registered naming latencies from the onset of stimulus presentation until the onset of the response. The experimenter registered for each trial whether the response was correct and the latency was valid, by pressing the corresponding button on a response box (correct and valid, incorrect, or invalid). Words and nonwords were presented in blocks separated by a fixed break of 1.5 min. The order of word and nonword reading was counterbalanced across the children.

Vocabulary. The Vocabulary subtest from the RAKIT intelligence test battery (Bleichrodt, Drenth, Zaal, & Resing, 1984) was used to assess children's vocabulary. The experimenter read aloud a word and children were instructed to choose from among four alternatives the picture that best matched the word. A total of 45 items were administered. The score consisted of the number of items correct.

Nonverbal IQ. Raven's Standard Progressive Matrices test (Raven, 1960) was used to assess nonverbal IQ. Children were asked to identify out of six or eight alternatives the element that fitted the missing position in a pattern. Children were instructed to work individually for 45 min and complete as many items as possible. The score consisted of the number of items correct.

Verbal short-term memory. To assess verbal short-term memory, a letter memory span task was used (e.g., Johnston, Rugg, & Scott, 1987). Children were presented with letter sequences increasing in length from two to seven letters. Letters were presented visually, one by one on a laptop screen. Each letter was presented for 750 ms in bold 24-point Arial font. Letters were separated by a blank screen presented for 500 ms. When the entire sequence had been presented, children were asked to repeat the letters aloud in the order of presentation. Children were presented with three sequences of each length. The task was discontinued after two consecutive errors within the same sequence length. The score consisted of the number of sequences repeated correctly.

Phonological awareness. An elision task was used to assess phonological awareness (de Jong & van der Leij, 2003). The experimenter read aloud a nonword, and children were asked to repeat the nonword completely. Next, the experimenter repeated the nonword and named a phoneme to be deleted. Children were asked to repeat the nonword without this phoneme. Children completed a total of 27 items. The first 18 items required a single phoneme to be deleted (e.g., 'tral' without 'r'), whereas in the last nine items the phoneme to be deleted was included twice (e.g., 'gepgral' without 'g'). The score consisted of the number of correct responses.

Rapid naming. To assess rapid naming, children were presented with a sheet with five lines of 10 digits each. The digits were a sequence of the digits 1, 3, 5, 6, and 8, each repeated 10 times in random order. Children were asked to name the digits aloud as quickly as possible. The time needed to name all digits on the sheet was recorded. The score consisted of the naming latency in milliseconds per digit.

Visual Attention Span. Following Valdois et al. (2003) the whole report task was used to assess children's visual attention span. Stimuli consisted of 20 five-letter strings (e.g., R H S D M). The strings were created from the consonants B, D, F, H, L, M, P, R, S, and T. Each consonant was repeated in 10 strings, twice in each of the five letter positions. Letters were presented in bold 24-point Arial font. The strings were presented for 200 ms. Children were asked to repeat as many letters of the string as possible. Trials were preceded by a plus sign presented for 1000 ms to focus attention. The score consisted of the number of letters repeated correctly (from a total of 100), in its proper position within the string. For example, if a child would answer 'R H S M' in response to 'R H S D M', this child would score 3 on this particular item, because M was the fifth, not the fourth letter in the string[1].

PROCEDURE

The vocabulary and nonverbal IQ tasks were administered during a classroom session of about 45 min each. The other tasks were administered in a fixed order to each child individually in two sessions of approximately 30 min.

[1] In this score both identity and location of the reported letters were taken into account. This score differs from the score used in previous studies (for example Valdois et al., 2003), which was based on the total number of letters that was identified correctly. In our score it was also taken into account whether order of the letters was correct, because in reading it is important to perceive letters in the correct order in which they appear. However, the correlation between the score with and without taking order into account was .88, and the use of identity only scores in our analyses gave similar results.

DATA ANALYSIS

Structural equation modeling was used to model the relation between the length effect and the cognitive correlates of reading. The model was specified in two steps. First, the relation between the number of letters in a word or nonword and its reading latency was specified as a latent growth model. Such a model consists of an intercept, or initial status, and a slope, or growth rate over time (Kline, 2011). In our model, however, we estimated the slope not over time, but over word length. The intercept was specified as the reading speed at the first measurement point, namely three-letter words or nonwords, and the slope as the additional time needed to read words and nonwords that contain one or two more letter(s). Because an intercept and slope were estimated simultaneously but separately for words and nonwords, the resulting model can be considered a parallel latent 'growth' model, with two intercepts and two slopes (Kaplan, 2009). In the second step, the correlates of reading were added as concurrent predictors of the length effect. Direct effects were specified from each correlate to the intercepts and slopes in the length effect model.

Analyses were conducted within Mplus version 5.21 (Muthén & Muthén, 2009). Parameter estimates were obtained by full information maximum likelihood estimation. To evaluate model fit we used the chi-square statistic of overall goodness of fit, the root mean square error of approximation (RMSEA), the comparative fit index (CFI), and the standardized root mean square residual (SRMR; Kline, 2011). A significant chi-square indicates that the model does not fit the data, whereas *p* values considerably larger than .05 indicate exact fit (Hayduk, 1996). For the RMSEA, values below .05 indicate close fit, values below .08 indicate satisfactory fit, and values over .10 indicate poor fit (Browne & Cudeck, 1993). A CFI larger than .95 in combination with an SRMR below .08 indicates good fit (Hu & Bentler, 1999). To test the difference in model fit between two hierarchical models, a chi-square test of the difference in chi-squares and the difference in degrees of freedom was used (Kline, 2011).

RESULTS

DATA CLEANING

For the word and nonword latencies, analyses were conducted on correct and valid trials only. Trials were excluded from analysis if the response was incorrect (8.8%) or if the voice key was not validly triggered (6.2%). In addition, latencies of less than 350 ms or more than 6000 ms (1.3%), as well as latencies 3 standard deviations below or above a participant's mean (0.9%) were considered invalid and removed. For each child valid and correct trials were averaged for each of the six Lexicality x Length conditions. Mean scores were coded as missing when less than 60% of the trials for that condition were valid. Three children were excluded from further analysis due to missing scores in more than two of the six conditions.

Scores on the nonverbal IQ task were recalculated. Due to a mistake of one of the experimenters 67 children completed only the first 36 items of the test. However, for the children that completed as many items as possible, the score over the first 36 items correlated highly with the total score ($r = .925$, $p < .01$). Therefore, for all children the nonverbal IQ score was calculated over the first 36 items, and this score was used in the analyses reported in the following sections.

Scores on the correlates of reading were all normally distributed. One univariate outlier (i.e., a score of more than 3 standard deviations above or below the mean) was identified for the verbal short-term memory task, and one for the vocabulary task. Furthermore, based on their score pattern, six children were identified as a multivariate outlier, using Mahalanobis distance with a significance level of .001 (Tabachnick & Fidell, 2001). These children were excluded from further analysis. Taken together, the reported analyses were based on data from 175 children (90 boys, 85 girls) with a mean age of 7 years, 11 months (*SD* = 5.62 months).

LENGTH EFFECTS

The mean latencies and error rates for the words and nonwords of each length are reported in Table 1. The error rates were below 10% in all conditions and were therefore not analyzed. The distributions of the latencies were positively skewed. To normalize the data, a log transformation was used. This transformation also corrects for proportional increases in naming latencies for words and nonwords of increasing length (Keene, 1995). Differences in the length effect are affected by the mean latency, because initial differences in latencies for three-letter words and nonwords become larger at four- and five-letter words and nonwords. In other words, a larger increase in latencies from three- to four-letter words and nonwords when latencies to three-letter words and nonwords are long might be proportionally equal to a smaller increase with shorter mean latencies. Our main interest, however, is in length effects that are disproportionate to the mean latencies. Log-transformed scores control for proportional increases and provide a purer estimate of the length effect. The means after this transformation are also presented in Table 1.

The log-transformed scores were subjected to an analysis of variance (ANOVA). The main effects of lexicality, $F(1,155) = 125.89$, $p < .001$, $\eta_p^2 = 0.45$, and length, $F(2,154) = 88.40$, $p < .001$, $\eta_p^2 = 0.53$, were significant. For both words and nonwords the length effect was significant from three to four letters, $F(1,155) = 82.24$ $p < .001$, $\eta_p^2 = 0.35$, and $F(1,155) = 103.02$, $p < .001$, $\eta_p^2 = 0.40$, respectively, and from four to five letters, $F(1,155) = 87.90$, $p < .001$, $\eta_p^2 = 0.36$, and $F(1,155) = 37.21$, $p < .001$, $\eta_p^2 = 0.19$, respectively. The interaction between lexicality and length did not reach significance.

Table 1
Mean Reaction Times (RT) in Milliseconds, Mean RT's after Log Transformation, and Mean Error Rates in Percentages (and Standard Deviations)

	RT (in ms)	Error rates	RT (log transformed)
Words			
3 letters	828 (377)	4.7 (7.6)	6.65 (.34)
4 letters	982 (571)	8.5 (10.2)	6.78 (.44)
5 letters	1106 (726)	7.7 (9.7)	6.87 (.48)
Nonwords			
3 letters	963 (443)	5.9 (8.2)	6.79 (.38)
4 letters	1152 (658)	10.0 (10.9)	6.93 (.47)
5 letters	1242 (744)	9.9 (10.7)	6.99 (.50)

MODELING THE LENGTH EFFECT

To describe the relation between word and nonword length and reading latency, a parallel latent growth model was fitted to the variance-covariance matrix of three-, four-, and five-letter word and nonword latencies. The length effect was modeled as a linear process, with increases in latencies from three- to four-, and from four- to five-letter words and nonwords constrained to be equal. This model provided a poor fit to the data, $\chi^2(7) = 27.10$, $p = .000$, RMSEA = .128 [.079-.181], CFI = .990, SRMR = .128. To improve model fit, nonlinear length effects were considered by allowing the loadings of the four-letter words and nonwords on the slope factors to be freely estimated. This model provided a good fit to the data, $\chi^2(5) = 2.46$, $p = .782$, RMSEA = .000 [.000-.069], CFI = 1.000, SRMR = .045, and was also a significant improvement over the previous model, $\Delta\ \chi^2(2) = 24.64$, $p < .001$.

For all four factors, the variances (intercept words = .111, slope words = .011, intercept nonwords = .140, slope nonwords = .010) differed significantly from zero ($p < .001$), indicating that there was individual variation in both intercepts and slopes. Correlations between the intercept and slope for words ($r = .608$) and nonwords ($r = .477$) were moderate. The intercepts for words and nonwords were strongly correlated ($r = .904$), as were the slopes ($r = .757$). The correlations between the intercept for words and the slope for nonwords ($r = .704$) and between the intercept for nonwords and the slope for words ($r = .503$) were also moderate to high.

COGNITIVE CORRELATES OF THE LENGTH EFFECT

The means, standard deviations, and range of the scores on the cognitive correlates are presented in Table 2, as well as the correlations with word and nonword reading. Rapid naming latencies were log transformed in the same way as the word and nonword latencies. The relations between the cognitive correlates of reading and the intercepts and slopes were examined. Direct effects were specified for each predictor on each of the four factors in the length effect model. The model provided a good fit to the data, $\chi^2(17) = 15.43$, $p = .565$, RMSEA = .000 [.000-.062], CFI = 1.000, SRMR = .025. A graphical representation of the model, including standardized parameter estimates of the significant direct effects, is presented in Figure 1. The standardized direct effects of the control variables vocabulary, nonverbal IQ, and verbal short-term memory were not significant (range = -.11 to .05).

Individual differences in the intercepts, representing the reading speed for three-letter words and nonwords, were related to rapid naming, phonological awareness, and visual attention span. Individual differences in the slopes for words and nonwords, representing the length effect, were associated with phonological awareness and visual attention span, but not with rapid naming. Nonverbal intelligence, vocabulary, and verbal short-term memory did not explain any additional variance in any of the factors. Taken together, the visual and phonological abilities explained 27.6% of the variance in the intercept for words, 28.9% in the intercept for nonwords, 20.9% in the slope for words, and 15.9% in the slope for nonwords.

Of interest, the direct effects of these cognitive correlates on the length effect factors looked quite similar. Therefore, we examined whether the effects on words and nonwords, and the effects on intercepts and slopes, respectively, were equal. First, the effects of the cognitive correlates on the intercepts for words and nonwords were constrained to be equal, as were the effects on the slopes. This model provided a good fit to the data, $\chi^2(29) = 27.13$, $p = .565$, RMSEA = .000 [.000-.053], CFI = 1.000, SRMR = .082, and did not differ significantly from the previous model, $\Delta\ \chi^2(12) = 11.70$, $p = .470$). Second, the effects of the cognitive correlates on the intercept and slope for words were constrained to be equal, as were the effects on the intercept and slope for nonwords. This model provided a poor fit to the data, $\chi^2(29) = 71.88$, $p < .001$, RMSEA = .092 [.065-.119], CFI = .979, SRMR = .225, and was significantly worse than the previous model, $\Delta\ \chi^2(12) = 56.45$, df = 12, $p < .001$. Even with rapid naming, which had an effect on the intercepts only, excluded from the equality constraints, the model remained significantly worse than the previous model, $\Delta\ \chi^2(10) = 23.14$, $p < .05$). In sum, the direct effects of the predictors of reading differed between intercepts and slopes but did not differ between words and nonwords.

Table 2[2]

Means, Standard Deviations and Correlations for Reading Variables and Cognitive Correlates of Reading

	1	2	3	4	5	6	7	8
Reading Speed								
1 Words	1							
2 Nonwords	.937**	1						
Cognitive correlates								
3 Vocabulary	-.020	.001	1					
4 Nonverbal IQ	-.130	-.087	.184*	1				
5 Short-term memory	-.272**	-.233**	.044	.226**	1			
6 Phonological awareness	-.418**	-.409**	-.008	.252**	.359**	1		
7 Rapid naming	.364**	.380**	.125	.126	-.115	-.303**	1	
8 Visual attention span	-.353**	-.354**	.010	.168*	.335**	.306**	-.203**	1
Mean	6.78	6.91	27.35	24.11	6.89	15.75	6.42	53.90
SD	.42	.44	3.81	5.47	1.65	5.40	.22	12.11
Range	6.15-8.19	6.16-8.12	18-36	7-34	3-11	1-27	5.94-7.07	31-95

Note. * $p < .05$, ** $p < .01$

[2] The full correlation matrix (i.e., the input for the structural equation models) can be obtained from the author.

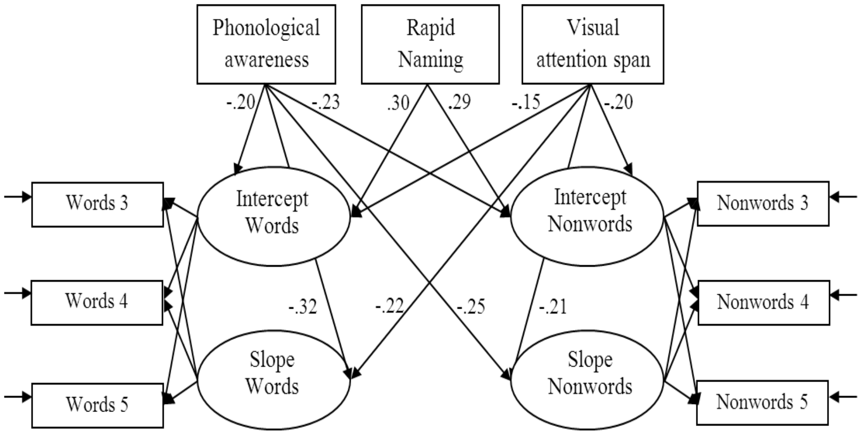

Figure 1. Model of the length effect for words and nonwords. This figure contains only the significant effects (α = .05) on the intercepts and slopes.

DISCUSSION

In the current study we examined how visual and phonological correlates of reading ability are related to the length effect, a marker of the reading process. As expected, we found that second-grade beginning readers showed a length effect for both words and nonwords. This result, in line with previous studies (e.g., Marinus & de Jong, 2010b; Zoccolotti et al., 2005), indicates that these readers do not process letter strings in parallel but predominantly rely on a serial processing strategy. Nonwords were read more slowly than words, but the interaction between length and lexicality did not reach significance. Although larger length effects for nonwords than for words are predicted by several models of reading (e.g., Ans et al., 1998; Coltheart et al., 2001), the absence of this interaction in children has been reported previously (e.g., Ziegler et al., 2003). The detection of the interaction could depend on the frequency of the words. High-frequency words will most likely be in the orthographic lexicon of children, enabling parallel processing. For words of lower frequency, orthographic representations may not have been built yet, resulting in a length effect.

The main aim of this study was to model the length effect and its relations with phonological and visual correlates of reading. Our results indicated that reading latencies of words and nonwords could be decomposed into an intercept and a slope. If the intercepts and slopes would reflect similar aspects of the reading process, the correlation between the word and nonword intercept and slope would be close to one. However, we found that these factors were only moderately related, which indicates that the intercepts and slopes reflect partly different processes.

The slopes represent the length effect, or the degree of serial processing. If processing is serial, there is an increase in reading latencies with each additional letter, whereas the slope will be close to zero if words are mainly processed in parallel. Interpretation of the intercepts, however, is not as straightforward. Because the intercepts were estimated based on reading latencies to three-letter words and nonwords, which consist of multiple letters, the intercepts may partly reflect a serial reading process. If readers rely on a serial processing strategy, this type of processing can also be expected for three-letter words and nonwords. However, the intercepts also represent overall reading speed of words and nonwords, irrespective of length. These findings are consistent with the developmental trends described by Spinelli et al. (2005), and Zoccolotti et al. (2005), who showed that over the course of development, children's word reading is characterized by a decrease in the length effect, but also by an increase in overall reading speed, regardless of word length. Our model indicates that although, in general, slower reading times are associated with a greater reliance on serial processing, these aspects are distinguishable, and represent different aspects of the reading process.

The relations of the intercepts and slopes with the correlates of reading further support the dissociation between overall reading speed and the degree of serial processing. The overall reading speed of words and nonwords, the intercept, was predicted by phonological awareness, rapid naming, and visual attention span. This is in line with previous studies (e.g., Bosse & Valdois, 2009; Vaessen & Blomert, 2010; Ziegler et al., 2010), that showed concurrent relations of these cognitive skills with reading ability. The length effect, the slope, however, was also predicted by phonological awareness and visual attention span, but not by rapid naming. The relation of phonological awareness and visual attention span with the slopes is in line with the results reported by Hawelka and Wimmer (2005), who found that these skills relate to the degree to which words and nonwords are processed serially.

As in previous studies (e.g., Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007), the effect of rapid naming on reading was largely independent from the effect of phonological awareness. A novel finding was, however, that rapid naming and phonological awareness affected different aspects of reading. Rapid naming accounted for individual differences in the intercepts only, which indicates that rapid naming, in contrast to phonological awareness, is specifically related to overall reading speed. The effect of rapid naming was the same for words and nonwords. A similar finding was reported by Moll, Fussenegger, Willburger, and Landerl (2009), suggesting that rapid naming cannot be particularly involved in the acquisition of orthographic knowledge. The current results suggest that rapid naming is related to an aspect of reading that is shared in the processing of all letter strings, irrespective of length or lexicality.

The effects of rapid naming are especially interesting, because our results suggest that children with poor phonological awareness and/or visual attention span can be expected to be slow readers who continue to rely on serial processing, whereas children with poor rapid naming skills are most likely slow readers who do shift toward a parallel-processing strategy and who thus show a different kind of reading impairment. This finding could be interesting in light of the double-deficit hypothesis (e.g., Wolf & Bowers, 1999). According to this hypothesis, phonological awareness and rapid naming represent two separate deficits underlying reading impairment. Our results also indicate this unique contribution of phonological awareness and rapid naming to reading (dis)ability, and suggest that these skills might be associated with different types of reading problems.

As predicted, visual attention span had an effect on the degree of serial processing for both words and nonwords. It has been argued by Bosse and Valdois (2009) that visual attention span should not be perceived as a measure of verbal short-term memory. To examine this argument, we included the letter memory span task. Both the form of presentation and the stimuli of this task were very similar to the visual attention span. However, we found that verbal short-term memory did not have an independent effect on the intercepts or on the slopes. This finding is in accordance with studies that indicated that the relation between short-term memory and reading is shared with the other phonological-processing variables (e.g., de Jong & van der Leij, 1999; Parrila et al., 2004). Visual attention span, however, even with verbal short-term memory included in the model, had a significant effect on all aspects of the reading process. These results support the claim made by Bosse and Valdois (2009), that the visual attention span does not reflect general or verbal short-term memory, but rather multi-element parallel visual processing. Although it is still debated whether visual attention span concerns a purely visual skill (Lobier et al., 2012), or visual to phonological mapping (Ziegler et al., 2010), our results clearly indicate that visual attention span predicts reading latencies independent from phonological processing skills. If visual attention span reflects visual to phonological mapping, a stronger relation might have been expected with rapid naming, a skill that is also associated with orthography to phonology mappings. Therefore, our results are more in favor of a purely visual interpretation of visual attention span.

The amount of variance in overall reading speed and length effects explained by the model ranged from 15.9 to 28.9%, which is in line with previous studies that included similar predictors of reading (e.g., Bosse & Valdois, 2009; de Jong & van der Leij, 1999). Although a substantial amount of variance is explained, a large part remains unexplained. It should be noted, however, that a discrete naming task, as used in the current study, differs from most standardized tests, in which words are presented in a list. For example, recent findings of de Jong (2011) indicate that discrete rather than serial rapid naming could explain additional variance in a discrete naming task.

We explicitly modeled individual differences in the length effect to investigate the relation between cognitive correlates of reading and this specific marker of the developing reading process. Phonological awareness and visual attention span were both related to the length effect and therefore to a serial processing strategy. Rapid naming, in contrast, was not related to the length effect but to aspects of reading that are independent of word length. Future studies could further specify the relations between reading and cognitive correlates by determining the specific relations of visual and phonological skills with parameters of the reading system.