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Parallel and Serial Reading Processes in Children's Word and Nonword Reading

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Fluent reading is characterized by rapid and accurate identification of words. It is commonly accepted that such identification relies on the availability of orthographic knowledge. However, whether this orthographic knowledge should be seen as an accumulation of word-specific knowledge in a lexicon acquired through decoding or as a well-developed associative network of sublexical units is still under debate. We studied this key issue in reading research by looking at the serial and/or parallel reading processes underlying word and nonword reading. Participants were 314 Dutch 2nd, 3rd, and 5th graders. The children were administered digit, word, and nonword naming tasks. We used latent class analyses to distinguish between readers who processed the letter strings serially or in parallel, based on the correlation patterns of word and nonword reading with serial and discrete digit naming. The 2 classes of readers were distinguished for both word and nonword reading. The validity of these classes was supported by differences in sensitivity to word and nonword length. Interestingly, the different classes seemed to reflect a developmental shift from reading all letter strings serially toward parallel processing of words, and later of nonwords. The results are not fully in line with current theories on the representation of orthographic knowledge. Implications in terms of models of the reading process are discussed.

Keywords: decoding, sight word reading, parallel processing, reading development, nonwords

Fluent reading is characterized by rapid and accurate identification of words. Such identification is commonly believed to depend on the availability of orthographic knowledge (e.g., Ehri, 2005; Share, 2008). However, the proper representation of orthographic knowledge in a model of reading is still under debate. On the one hand, it has been proposed that readers acquire word-specific knowledge and store this knowledge in a lexicon (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Jackson & Coltheart, 2001). Upon encountering familiar words in written form, pronunciation and meaning can immediately and automatically be retrieved from memory (Ehri, 2005). On the other hand, it has been proposed that the reading system is an associative network of interconnected sublexical units, without lexical memory for words (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989). First, we discuss these two approaches and their implications in more detail. Next, we consider methods to determine whether word identification is based on the retrieval of pronunciations from memory.

According to the first or word-specific approach, fluent reading means reading by sight. For a word to be read by sight, a connection must be made between the orthographic form of a word and its previously acquired phonological counterpart (Ehri, 2005). According to the self-teaching hypothesis (Share, 1995, 1999), a reader can acquire the detailed orthographic representations necessary for fast and efficient reading through phonological recoding of novel letter strings. Every time a reader successfully decodes a printed word into a phonological code, an orthographic representation of that word is built or strengthened. Therefore, beginning readers initially rely on decoding skills to read words, but read more fluently when previous encounters with words have accumulated in well-established orthographic representations.

This development of the reading system, from heavy reliance on decoding toward reading an increasing number of words by sight, fits well with the dual route cascaded (DRC) model of reading (Coltheart et al., 2001; Jackson & Coltheart, 2001). Therefore, the DRC model provides a useful framework in studying reading development, although it should be noted that the model is intended to model reading aloud of monosyllabic letter strings by adult fluent readers. Within the DRC model, two routes are distinguished that are simultaneously active. Initial parallel identification of letter identities is common to both routes. Subsequently, phonology is activated through the lexical and nonlexical routes. Sight word reading is represented as reading through the lexical route. In the lexical route, word identification is achieved in parallel by successive activation of the word's entry in the orthographic and phonological lexicon. Decoding, dominating the processing of unfamiliar words or nonwords, is modeled with the nonlexical route. This route works in parallel to the lexical route, but graphemes are serially decoded into phonemes according to grapheme-phoneme conversion rules. As a result of reading experience, one could expect a gradual shift in dominance from the

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nonlexical route, when many words are decoded early in development, toward the lexical route, when an increasing number of words become represented in the orthographic lexicon and can be quickly recognized by sight.

An important characteristic of the DRC model is that words can only be read by sight if a word-specific representation is present in the orthographic lexicon (e.g., Coltheart et al., 2001). In other words, reading development is item specific. Orthographic representations can exist only if words have previously been encountered and decoded successfully. And words can be processed in parallel only if orthographic representations exist that are connected to the representations of the same words in the phonological lexicon.

This idea of word-specific orthographic knowledge, however, stands in sharp contrast to the second approach in modeling the reading system. According to the parallel distributed processing model (PDP; e.g., Plaut et al., 1996), for example, word-specific representations do not exist. Rather, letter strings are read by a reading system based on parallel activation of interconnected orthographic, phonological, and semantic units. The interactions among these units are governed by connection weights that represent the system's knowledge of spelling–sound correspondences in the language input. Within this associative network of sublexical units, there is no orthographic or phonological lexicon for words.

As a result of the different representations of orthographic knowledge as either word-specific or sublexical, the DRC and PDP models of reading also have different definitions of fluent reading. Fluent reading, in the DRC model (e.g., Coltheart et al., 2001), entails reading by sight, which occurs through parallel activation of phonology of a letter string by accessing representations in the orthographic and phonological lexicon. In contrast, fluent reading in the PDP model (e.g., Plaut et al., 1996) entails parallel activation of phonology from print via sublexical units. Both models, however, predict that fluent word reading is achieved through parallel computation of phonology from the letter string.

The models differ greatly in how they account for the reading of nonwords. According to the DRC model (e.g., Coltheart et al., 2001), nonwords cannot be represented in the orthographic lexicon, and as a result always require involvement of the nonlexical route. In contrast, PDP models do not presume a separate mechanism for the reading of unfamiliar words and nonwords. According to the PDP model (e.g., Plaut et al., 1996), all letter strings are read by the same reading system through parallel activation of the interconnected units. Nonwords, especially those that adhere to regular orthographic and phonological patterns, are not processed differently from words.

A key issue in distinguishing between these two models of reading is whether phonological codes of words and nonwords are activated in parallel. Within the DRC framework, length effects have been studied as indicators of whether phonology is activated predominantly serially or in parallel. In the early stages of reading development, the speed of single word and nonword reading increases as a function of the number of letters, whereas in advanced readers this length effect becomes restricted to longer words (i.e., more than six letters) and nonwords (e.g., Marinus & de Jong, 2010; Spinelli et al., 2005; van den Boer, de Jong, & Haentjens-van Meeteren, 2013; Weekes, 1997; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003; Zoccolotti et al., 2005). A length effect is presumed to occur when words are identified through serial activation of phonology, whereas the absence of a length effect indicates that phonology is activated in parallel. In line with the DRC model, length effects remain for nonwords, which are supposed to be read predominantly through the nonlexical route.

However, although a length effect is indeed expected when letter strings are decoded, the reverse—that an observed length effect is the result of decoding—is not necessarily true. In fact, length effects have been found that could not be ascribed to serial processing through the nonlexical route (Risko, Lanthier, & Besner, 2011; van den Boer, de Jong, & Haentjens-van Meeteren, 2012). Risko et al. (2011), for example, found that increased spacing between letters resulted in increased effects of item length. These effects, however, were found at the level of letter identification, not serial activation of phonology. Similarly, Van den Boer et al. (2012) found length effects in the lexical decisions of children, while independent evidence suggested that items were processed in parallel through the lexical route. Together, these findings indicate that a length effect in and of itself does not prove that serial processes underlie word identification. Moreover, in PDP models, length effects are not interpreted in terms of decoding but are ascribed to other factors, such as visual and articulatory factors or differences in orthographic neighborhood size (Seidenberg & Plaut, 1998; but see Plaut, 1999, for an attempt to model length effects within a PDP framework). Thus, length effects are expected when words are decoded, but a length effect in itself does not prove that words have been identified through serial decoding. Additional independent evidence for a serial or parallel reading strategy is called for.

As an alternative, it has been proposed that parallel processing can be detected by the speed with which single words are read. Ehri and Wilce (1983) compared how quickly beginning readers could identify highly familiar, overlearned symbols (i.e., digits) with the readers' word recognition speed. In skilled readers, response latencies to both digits and words were equal as early as first grade. In less skilled readers, however, similar response rates were obtained later, around third or fourth grade. These results indicated that even in the first years of reading development, words are no longer decoded but are processed in parallel and elicit the same routinized naming responses as overlearned symbols. Interestingly, Ehri and Wilce (1983) also included three-letter nonwords in their study and found that skilled readers also identified these nonwords as quickly as digits. Less skilled readers, however, identified nonwords slower than digits at least up to fourth grade. These findings suggest that nonword phonology could potentially be activated in parallel.

In line with Ehri and Wilce (1983); Aaron et al. (1999) showed that if a word is processed in parallel, the speed of reading this word is close to the speed of naming letters. Similar results have also been reported by van den Bos, Zijlstra, and Van den Broeck (2003), who showed that naming speed of alphanumeric symbols (i.e., letters and digits) was closely related to monosyllabic word naming speed. However, naming speed is greatly influenced by word frequency (e.g., Forster & Chambers, 1973; Frederiksen & Kroll, 1976). The phonological codes of digits are very frequent, which results in relatively short naming latencies. Therefore, similar reading latencies to digits and words are probably only found when high frequency words are studied. Reading latencies to words of lower frequency might not be equal to reading latencies of digits, even though these words might be processed in parallel.

To get around this problem, de Jong (2011) argued that if word reading relies on a parallel retrieval process, individual differences in word reading and digit naming speed should be similar. Therefore, a high correlation should be found between word and digit naming, despite possible differences in absolute naming speed. More specifically, de Jong proposed to consider the relations of serial and discrete digit naming with word reading to determine whether a particular set of words is read by sight. Digit naming concerns the rapid naming of digits. Whereas in serial naming the digits are presented in rows, in discrete naming digits are presented one by one, on a computer screen. Naming latencies of digits presented in a discrete format were assumed to reflect lexical access speed, the retrieval of known phonological codes from memory. If words, also presented in a discrete format, are processed in parallel, a high correlation is expected with discrete digit naming. If, however, words are read through decoding, a stronger relation could be expected with a serial format of digit naming, because both activation of phonology and serial digit naming reflect a serial process. The correlation patterns were in line with both of these expectations in showing that for beginning readers (Grade 1), who are expected to rely predominantly on decoding, word reading was most strongly related to serial digit naming, whereas discrete digit naming was the stronger correlate for more advanced readers, who are expected to processes short words in parallel (Grades 2 and 4).

As a next step, de Jong (2011) showed through latent class analyses that the children from the three grades could be assigned to two classes of readers. For a large class of readers, single word reading related strongly to discrete digit naming. For a second, smaller class of readers, however, single word reading related more strongly to serial digit naming. This suggested that the first class of readers processed the words in parallel, similar to naming a digit. The second class of readers, however, was not processing the words in parallel but predominantly relied on a serial decoding strategy instead. De Jong argued that this classification is fully compatible with an item-specific view of reading development, such as the DRC model (e.g., Coltheart et al., 2001). Whether a reader processed the words in parallel or serially depended on whether the words in the set were represented in the lexicon or not. If the words were represented in the lexicon, the words were read by sight. If the majority of the words in the set were not represented in the lexicon, the main reading strategy would be serial decoding. In other words, the classifications depend on the words that were presented. The number of classes would vary with the number of word sets used, and the sizes of the classes with the difficulty of the words included.

In the current study we focused on word and nonword reading in Grades 2, 3, and 5. For word reading, we expected to find two classes of readers, namely, serial and parallel processors. More importantly, we studied whether these results are tied to a particular set of words by studying whether similar classes of readers could be distinguished for nonword reading. According to an item-specific view of reading development, and in line with the DRC model, all readers should have a predominantly serial reading strategy for nonwords; thus, only one class of serial nonword readers should be identified. These predictions are tested against the predictions of the PDP model (e.g., Plaut et al., 1996), which states that both words and nonwords are processed in parallel by all readers. Thus, a single class of parallel processors would be expected for both word and nonword reading. If nonwords, like words, can be processed in parallel, this would indicate that serial and parallel reading processes were not tied to particular sets of words but could potentially be generalized to all short words and nonwords. A second novel aspect in the current study is the focus on validating the interpretation of the different classes of readers by examining length effects. Reading latencies of serial processors are expected to be affected by word length, whereas the reading latencies of parallel processors are hypothesized to be independent of length.

Method

Participants

A total of 314 Dutch children participated in the study. One hundred seventeen children attended second grade (52 boys, 65 girls), 86 third grade (44 boys, 42 girls), and 111 fifth grade (51 boys, 60 girls). The mean ages of the children were 8 years (SD = 5.70 months) in Grade 2, 9 years 4 months (SD = 6.58 months) in Grade 3, and 11 years (SD = 5.86 months) in Grade 5. All children attended mainstream primary education. Scores 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, showed that the sample included a representative range of reading abilities (Grade 2: M = 10.66, SD = 2.93; Grade 3: M = 10.54, SD = 2.52; Grade 5: M = 9.25, SD = 2.58). All children had normal or corrected to normal vision.

Measures

A word and nonword reading task was administered to all children, as well as serial and discrete measures of digit naming.

Discrete 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 of two million tokens (Schrooten & Vermeer, 1994). Across lengths, words were matched on onset (i.e., the first letter) and frequency. The words ranged in frequency to reflect the variation in words children encounter (Mdn = 23, range: 1–148). 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 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 discrete digit-naming task described below) 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 naming accuracy 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.

Digit naming. Naming of digits (1, 3, 5, 6, and 8) was administered in serial and discrete format.

Serial digit naming. The five digits were presented 10 times in a random order on a sheet with five lines of 10 digits each (see Denckla & Rudel, 1976). Children were asked to name aloud all digits as quickly as possible. The time needed to name all 50 digits was converted to the number of digits named per second.

Discrete digit naming. The 50 digits were also presented in a discrete naming task, in the same order as in the serial task. The digits were presented one by one in the middle of a laptop screen (14.1 in.; 35.8 cm) in 72-point Arial font. Each trial started with a plus sign, presented for 750 ms, to focus attention. Then the digit was presented and remained on the screen until the child made a response. A voice key registered response latencies from the onset of presentation until the onset of the response. The experimenter registered naming accuracy on a response box (correct and valid, incorrect, or invalid). The score consisted of the mean naming latency per digit, converted to the number of digits named per second.

Procedure

Children in second and fifth grade were tested in January/February, when they had received approximately 1 year 5 months and 4 years 5 months of reading instruction, respectively. Third graders were tested in June/July, after approximately 3 years of reading instruction, meaning that the reading age of these children lay exactly between the reading ages of second and fifth graders. The word and nonword reading task and the digit naming tasks were administered during two waves of more extensive data collection. Second and fifth graders participated in a classroom session of about 1 hr 30 min and two individual sessions of approximately 30 min each. Third graders completed the experimental tasks during one individual session of approximately 40 min.

Results

Clustering Readers Based on Reading Processes

As to be expected in a transparent orthography, mean accuracy across grades was high for both words ($M = 0.95$, $SD = 0.07$) and nonwords ($M = 0.92$, $SD = 0.09$). Reading latencies were excluded from analysis if the voice key was not validly triggered (5.9%), if latencies were less than 250 ms or more than 6,000 ms (0.9%), and if latencies were more than 3 standard deviations from a participant's mean (1.6%). Similar to de Jong (2011), word and nonword reading latencies were converted into fluency scores reflecting the number of items read correctly per second. First, average word and nonword latencies were calculated for each child and transformed to the number of items read per second to normalize scores. Then, the proportion of words and nonwords read correctly was calculated over valid trials. Finally, word and nonword fluency scores were calculated by multiplying the number of items read per second by the proportion of items correct. For clarity purposes, we use the terms *word reading fluency* and *nonword reading fluency* to refer to these reading scores. However, please note that the measures of reading fluency are based on discrete word and nonword reading tasks.

Scores on word and nonword reading fluency, as well as on serial and discrete digit naming, were normally distributed in each grade separately and in the entire data set. All variables were inspected for univariate outliers (i.e., a score of more than 3 standard deviations above or below the mean), separately for each grade. Two outliers (one in Grade 3 and one in Grade 5) were identified for word reading, one (in Grade 3) for nonword reading, two (one in Grade 3 and one in Grade 5) for serial digit naming, and two (one in Grade 3 and one in Grade 5) for discrete digit naming. These scores were coded as missing and not included in the analyses. None of the children was identified as a multivariate outlier.

Descriptive statistics. The means and standard deviations on word and nonword reading fluency and serial and discrete digit naming for each grade are shown in Table 1. Overall, growth can be seen across grades. Both reading fluency and digit naming speed increased significantly between Grades 2 and 3. Between Grades 3 and 5, only discrete digit naming speed significantly increased. Across all grades, average reading fluency was lower than average digit naming speed.

Correlations between word and nonword reading fluency and serial and discrete digit naming for each grade are shown in Table 2. In Grade 2, word reading fluency correlated equally strongly with serial and discrete digit naming ($Z = 0.701$, $p = .414$). In Grades 3 and 5, however, word reading was more strongly related to discrete than to serial digit naming (Grade 3: $Z = 2.216$, $p < .05$; Grade 5: $Z = 4.036$, $p < .001$). Interestingly, a similar pattern was found in the correlations between nonword reading fluency and digit naming. In Grade 2, nonword reading fluency was related

Table 1
Means (and Standard Deviations) on Word and Nonword Reading Fluency, and Serial and Discrete Digit Naming in Items per Second in Grades 2, 3, and 5

Variable	Grade 2 ($N = 117$) M (S)	Grade 3 ($N = 86$) M (S)	Grade 5 ($N = 111$) M (S)	t statistics 2 vs. 3	t statistics 3 vs. 5
Word reading fluency	1.13 (.43)	1.62 (.25)	1.68 (.27)	10.284**	1.610
Nonword reading fluency	.99 (.43)	1.44 (.29)	1.46 (.34)	8.780**	0.463
Serial digit naming	1.75 (.39)	2.19 (.42)	2.27 (.45)	7.703**	1.241
Discrete digit naming	1.69 (.26)	1.91 (.25)	2.00 (.31)	6.080**	2.027*

* $p < .05$. ** $p < .01$.

Table 2
Correlations of Word and Nonword Reading Fluency With Serial and Discrete Digit Naming in Grades 2, 3, and 5

Digit naming	Words			Nonwords		
	Grade 2 (N = 117)	Grade 3 (N = 86)	Grade 5 (N = 111)	Grade 2 (N = 117)	Grade 3 (N = 86)	Grade 5 (N = 111)
Serial	.532**	.274*	.232*	.564**	.338**	.343**
Discrete	.467**	.503**	.643**	.454**	.444**	.543**

* $p < .05$. ** $p < .01$.

equally strongly to serial and discrete digit naming (Z = 1.397, p = .163). In contrast to words, equal relations were also found in Grade 3 (Z = 1.024, p = .306). In Grade 5, however, the difference of the correlation of nonword reading with discrete and serial digit naming approached significance, in favor of discrete digit naming (Z = 1.936, p = .053).

A series of stepwise regression analyses was conducted to examine whether serial and discrete digit naming were independent predictors of reading fluency. The analyses were conducted for each grade, with word and nonword reading fluency as dependent variables. In the first set of analyses serial digit naming was entered first, and it was determined whether including discrete digit naming resulted in additional explained variance. In the second set, the order of serial and discrete digit naming was reversed. The (additional) variance explained in each step is presented in Table 3. In Grade 2, both serial and discrete digit naming explained unique variance in word reading fluency. In Grades 3 and 5, however, discrete digit naming was the stronger predictor, and serial digit naming did not explain additional variance. For nonword reading fluency, the results were the same, with the exception of a small independent effect of serial digit naming on nonword reading fluency in Grade 5. Interestingly, the results clearly show an increase in the amount of variance in reading fluency explained by discrete digit naming and a decrease in the amount of variance explained by serial digit naming.

Classes of readers. The correlation patterns and regression results indicate that in the early stages of reading development (i.e., Grade 2) serial digit naming is the stronger correlate and predictor of reading fluency, whereas reading becomes more strongly related to discrete digit naming in the higher grades. This might suggest that two classes of readers could be found: one class for whom word reading is related more strongly to serial digit naming, and one class for whom word reading is related more strongly to discrete digit naming. Alternatively, three classes of readers could be expected, when readers are better classified by grade. Therefore, both two- and three-class models were fitted and compared. Correlation patterns with nonword reading fluency suggest that similar clusters of children could be found based on the relations between nonword reading and digit naming. Therefore, the same models were estimated based on nonword reading, serial digit naming, and discrete digit naming.[1]

Table 3
R^2 Changes in Hierarchical Regression Analyses Using Serial and Discrete Rapid Naming to Predict Word and Nonword Reading Fluency

Digit naming	Words			Nonwords		
	Grade 2	Grade 3	Grade 5	Grade 2	Grade 3	Grade 5
1. Serial	.28**	.08*	.04*	.32**	.11**	.10**
2. Discrete	.06**	.18**	.39**	.05**	.11**	.24**
1. Discrete	.22**	.26**	.42**	.21**	.20**	.30**
2. Serial	.13**	.00	.01	.16**	.02	.04**

* $p < .05$. ** $p < .01$.

If a (categorical) variable is measured that can be the source of heterogeneity within a sample, this variable can be used to split participants into groups, and differences can be analyzed through multiple group analyses. If, however, the source of heterogeneity is hypothesized but unobserved, as are reading strategies in the current study, factor mixture modeling can be used to determine classes within a heterogeneous sample (Lubke & Muthén, 2005). Through factor mixture modeling, participants were clustered into unobserved (latent) classes based on mean scores on and correlations between a set of observed variables. Three variables were input for the current analyses: word or nonword reading, serial digit naming, and discrete digit naming.

Models distinguishing between two classes and three classes were fitted using Mplus (Version 5.21; Muthén & Muthén, 2009). Several statistics can be obtained to evaluate model fit and decide on the number of classes. However, Nylund, Asparouhov, and Muthén (2007) showed that the Bayesian information criterion (BIC) and bootstrap likelihood ratio test (BLRT) should be favored. Models with lower BIC values should be preferred. The BLRT p value indicates whether a model with k classes significantly improves fit over a model with $k - 1$ classes. In addition, entropy was used to evaluate the models, with a value close to 1 indicating low average likelihoods that a child assigned to one class could have been assigned to another (Celeux & Soromenho, 1996).

For the word reading fluency models, the two-class model was favored over the three-class model, according to BIC (two classes: 633.19; three classes: 648.42) and entropy (two classes: .878; three classes: .756). In addition, the BLRT indicated that the two-class model fitted significantly better than a one-class model ($p < .001$), but that a three-class model did not significantly improve fit over a two-class model (p = .92). The results of the two-class solution are presented in Table 4. For a large class of 277 children, word

[1] Including word and nonword reading in one mixture model resulted in classes that did not fit expected correlation patterns and were difficult to interpret. This is possibly due to the high correlation between word and nonword reading.

Table 4
Correlations of Serial and Discrete Digit Naming With Word and Nonword Reading Fluency in Classes of Readers

	Word reading fluency		Nonword reading fluency	
Digit naming	Serial processors ($N = 37$)	Parallel processors ($N = 277$)	Serial processors ($N = 69$)	Parallel processors ($N = 245$)
Serial	.551*	.438*	.545*	.403*
Discrete	.462*	.674*	.483*	.613*

* $p < .01$.

reading correlated more strongly with discrete than with serial digit naming, suggesting that words are processed in parallel or read by sight. Children from each grade were assigned to this class of parallel processors (83 second, 84 third, and 110 fifth graders). However, for a smaller class of 37 children, word reading was most strongly related to serial digit naming, suggesting that words are not (yet) processed in parallel. This class of serial processors consisted mainly of children in Grade 2 (34 second graders, 2 third graders, and 1 fifth grader).

For the nonword reading fluency models, the two-class model was favored over the three-class model according to BIC (two classes: 690.22; three classes: 704.49) but not according to entropy (two classes: .775; three classes: .836). The BLRT, however, indicated that the two-class model fitted significantly better than a one-class model ($p < .001$), but that a three-class model did not significantly improve fit over a two-class model ($p = .89$). Moreover, one of the classes in the three-class solution included only nine children, and the interrelations among the variables within the classes were difficult to interpret. Therefore, the two-class solution seemed best. The results of the two-class solution are presented in Table 4. In line with the result for word reading, nonword reading correlated more strongly with discrete than serial digit naming for a large class of 245 children, suggesting that nonwords were processed in parallel. Parallel processors were identified in each grade (66 second, 79 third, and 100 fifth graders). For a smaller class of 69 children, nonword reading related more strongly to serial digit naming. This class of serial processors, who did not (yet) process nonwords in parallel, consisted mainly of children in Grade 2, although small groups of third and fifth graders were also assigned to this class (51 second graders, 7 third graders, and 11 fifth graders).

Length Effects

If our interpretation of the classes of readers is correct, differences would be expected across classes in length effects. Length effects are expected when letter strings are processed serially. Therefore, length effects were expected in the classes of readers who process words or nonwords serially, but not in the classes of readers who process words or nonwords in parallel. Accuracy rates and correct reading latencies to words and nonwords of three, four and five letters are presented in Table 5.

Multilevel models were used to test differences in length effects (Snijders & Bosker, 1999). Within a multilevel model, random factors from participants and items can be captured within one model, instead of separate analyses (Quené & van den Bergh, 2004). Each response to an item (Level 1) represents one case, but these cases are nested under individuals (Level 2). These models are equivalent to, for instance, the repeated measures analysis of variance but have more statistical power, because analyses are based on responses to all separate items instead of a mean score per participant per condition.

The analyses were conducted with MLwiN 2.24 (Rasbash, Steele, Browne, & Goldstein, 2008). Separate models for words and nonwords were specified. In each model dummy variables for each length (three, four, or five letters) by class (serial, parallel processors) combination were computed, amounting to a total of six variables. To test the interactions of class and length as well as the main effect of length, length effects were split in two contrasts. These contrasts specified the differences between three versus four and four versus five letter items. The contrasts were tested simultaneously in a multivariate test, using a chi-square statistic with two degrees of freedom (Tabachnick & Fidell, 2001). The main effects of class were tested with a single contrast, resulting in a chi-square statistic with one degree of freedom.

First, a model was specified for accuracy rates. Because accuracy was dummy coded (0 is incorrect, 1 is correct), a logistic regression procedure was used, assuming a binomial distribution rather than the normal distribution assumed for reaction latencies. Mean accuracy rates were high for both words ($M = 0.95$, $SD = 0.07$) and nonwords ($M = 0.92$, $SD = 0.09$). However, serial processors were significantly less accurate than parallel processors for both words, $\chi^2(1) = 117.12$, $p < .001$, and nonwords, $\chi^2(1) = 135.03$, $p < .001$. Length effects were found in the accuracy rates of both classes for both words (serial processors: $\chi^2(2) = 19.72$, $p < .001$; parallel processors: $\chi^2(2) = 19.06$, $p < .001$) and

Table 5
Accuracy Rates and Reading Latencies (and Standard Deviations) for 3-, 4-, and 5-Letter Words and Nonwords in Serial and Parallel Processors

	Words				Nonwords			
	Serial processors ($N = 37$)		Parallel processors ($N = 277$)		Serial processors ($N = 69$)		Parallel processors ($N = 245$)	
Length	Acc.	RT	Acc.	RT	Acc.	RT	Acc.	RT
3 letters	.89 (.10)	1,160 (459)	.97 (.05)	607 (109)	.88 (.11)	1,206 (436)	.97 (.05)	638 (102)
4 letters	.78 (.17)	1,590 (704)	.95 (.08)	639 (138)	.77 (.16)	1,572 (671)	.93 (.09)	680 (131)
5 letters	.82 (.16)	1,952 (809)	.96 (.06)	669 (159)	.80 (.18)	1,649 (754)	.94 (.08)	702 (138)

Note. Acc. = accuracy; RT = reaction time.

nonwords (serial processors: $\chi^2(2) = 48.40$, $p < .001$; parallel processors: $\chi^2(2) = 58.15$, $p < .001$). These length effects did not differ significantly between classes. The effects could mainly be ascribed to three-letter words and nonwords, which were read more accurately than both four- and five-letter items.

The same model was specified for reading latencies. As can be seen in Table 5, large differences are found between classes in mean reading latencies. These differences in mean latencies might affect the interpretation of possible differences in length effects across classes. Significant differences can reflect absolute differences in length effects but might also be merely proportional differences. Because we were interested in relative differences in the effect of length, we controlled for the differences in overall reading latencies by calculating within-subject *z*-scores (Faust, Balota, Spieler, & Ferraro, 1999). The subject's overall mean reading latency was subtracted from every item's reading latency. The difference was divided by the standard deviation of the subject's latency score distribution based on all 90 word and nonword items.

As expected, length effects for words were larger in serial processors than in parallel processors, $\chi^2(2) = 64.15$, $p < .001$. Unexpectedly, however, a separate test showed that the effect of length was significant in the parallel processors, $\chi^2(2) = 355.95$, $p < .001$. For nonwords, length effects were also larger in serial processors than in parallel processors, $\chi^2(2) = 32.69$, $p < .001$. Again, however, a significant length effect was also found for parallel processors, $\chi^2(2) = 283.36$, $p < .001$.

Two additional analyses were conducted to control for age and neighborhood size, respectively. The classes of word and nonword parallel processors included more of the older children, whereas the majority of the serial processors were children from Grade 2. To determine whether the differences in length effects between classes could be ascribed to age, we conducted the same analyses including only second graders. These children were more equally divided over the classes (words: serial processors $N = 34$, parallel processors $N = 83$; nonwords: serial processors $N = 51$, parallel processors $N = 66$) and did not differ in age (words: 8 years 1 month versus 8 years; nonwords: 8 years 1 month versus 7 years 11 months). Nevertheless, the results in Grade 2 were the same as for the entire group. Length effects were larger in serial than in parallel processors (words: $\chi^2(2) = 35.01$, $p < .001$; nonwords: $\chi^2(2) = 22.20$, $p < .001$). Again, length effects were found in both classes of readers for both words (serial processors: $\chi^2(2) = 157.75$, $p < .001$; parallel processors: $\chi^2(2) = 234.96$, $p < .001$) and nonwords (serial processors: $\chi^2(2) = 184.90$, $p < .001$; parallel processors: $\chi^2(2) = 110.00$, $p < .001$). Thus, differences in the length effects of serial and parallel processors cannot be ascribed to differences in age between the classes.

According to the PDP model, length effects could be ascribed to orthographic neighborhood size (Seidenberg & Plaut, 1998). Therefore, neighborhood size was added to the model for reading latencies as a covariate. Because the distribution of neighborhood size was skewed, a log-transformation was used and neighborhood size was standardized. As a result the estimates for neighborhood size can be interpreted as beta-coefficients. Four dummy variables were specified and added to the models for words and nonwords; the effect of neighborhood size on words and on nonwords in each class separately. The effect of neighborhood size on words was significant only for the parallel processors, $\beta = -.06$, $\chi^2(1) = 11.19$, $p < .001$. Words with a larger neighborhood size were read faster than words with a smaller neighborhood size. The effect of neighborhood size on nonwords was significant for both serial processors, $\beta = -.20$, $\chi^2(1) = 22.75$, $p < .01$, and parallel processors, $\beta = -.18$, $\chi^2(1) = 67.62$, $p < .001$. Nonwords with a larger neighborhood size yielded shorter response latencies than nonwords with a smaller neighborhood size. Although length effects decreased when neighborhood size was controlled for, all length effects remained significant. Thus, length effects in word and nonword reading latencies could not (fully) be ascribed to neighborhood size.

Cross Classification of Classes for Word and Nonword Reading

We combined the classes that were identified in the separate word and nonword models. Interestingly, of the four possible classes, only three classes of readers emerged. The first class consisted of 36 children, who read both words and nonwords serially. These children relied on decoding for both types of letter strings. A second class of 244 children read both words and nonwords in parallel. Finally, 33 children read words in parallel but relied on serial processing for nonwords. Only one child was identified as a serial processor of words but parallel processor of nonwords, indicating that this fourth class of readers did not exist in the data.

Discussion

In the current study we used serial and discrete digit naming to examine serial and parallel processes in word and nonword reading. In line with the results of de Jong (2011), we found that the pattern in the correlations of discrete word reading with serial and discrete digit naming changes over time. From second to fifth grade the relation of discrete word reading with serial digit naming decreased, whereas its relation with discrete digit naming increased. A novel finding was that a similar pattern was found between the formats of digit naming and nonword reading. Regression analyses revealed that from second to fifth grade the amount of unique variance explained by discrete naming increased in both word and nonword reading. Previous studies have also shown that the relations of serial digit naming with word and nonword reading are similar, at least in more transparent orthographies (Greek: Georgiou, Papadopoulos, Fella, & Parrila, 2012; German: Moll, Fussenegger, Willburger, & Landerl, 2009; Dutch: van den Boer et al., 2013). The current results indicate that the development of the relations with both discrete and serial naming over time is similar for words and nonwords.

Next, as predicted, we identified two classes of readers for word reading based on the correlations with serial and discrete digit naming. In line with de Jong (2011), for a large class of readers, single word reading was strongly related to discrete digit naming. For these readers, the process of reading a single word mirrored naming of single overlearned symbols. Words, like digits, were read through parallel retrieval of phonological codes. For a second class of readers, however, single word reading was more strongly related to serial digit naming. For these readers, the process of reading a single word more closely resembled the serial naming of multiple overlearned symbols, suggesting that word reading in this class relies on a serial process. As argued by de Jong (2011), these results for word reading are compatible with a word-specific view of reading development, as assumed for example in the DRC model (e.g., Coltheart et al., 2001), but cannot be explained within a PDP model (e.g., Plaut et al., 1996).

A novel and unexpected finding was that the same classes were found for nonword reading. Strong correlations between nonword reading and serial digit naming were found for one class of readers, suggesting that nonwords were identified through serial reading processes. For a second and larger class of readers, however, nonword reading related most strongly to discrete digit naming, which suggests that the nonwords were processed in parallel. At first sight, these findings seem to be at odds with both the DRC model (e.g., Coltheart et al., 2001) and the PDP model (e.g., Plaut et al., 1996). For nonwords, both models predict one specific, although different, reading strategy. Whereas nonwords should be processed serially according to the DRC model, the PDP model predicts parallel processing of all letter strings, words and nonwords alike.

Moreover, a clear developmental pattern could be seen, although we were unable to study individuals' stability of class assignment or transition across classes in the current cross-sectional study. First, although in latent class analysis, as opposed to group-wise comparisons, no assumptions have to be made about equal development of all children within an age group (see Bouwmeester & Verkoeijen, 2010), grade level was found to be a good proxy of the class assignments. The classes of serial processors of both words and nonwords consisted mainly of younger children from Grade 2. With just a few exceptions, all the older children in Grades 3 and 5 were able to process the words and nonwords in parallel. These results are in line with de Jong (2011), who identified serial decoders among first and second graders, but not fourth graders. On the other hand, like Ehri and Wilce (1983), we also found parallel processing in young readers with limited reading experience. Even the poorer readers eventually read all words in parallel, since hardly any serial processors were identified past Grade 2.

Second, when class assignments for word and nonword reading were combined, three classes of readers were identified: readers who processed both words and nonwords in parallel, readers who processed only words in parallel, and readers who relied on serial decoding for both words and nonwords. Importantly, the fourth possible group of readers, who process words serially but nonwords in parallel, was not found. Together, these results suggest a developmental path. With increasing reading experience, a shift seems to occur from a serial decoding strategy to identify every letter string toward parallel processing of only words, and later on, even nonwords.

An alternative interpretation of the classes and patterns of correlations in the current study could be the increasing differentiation of abilities over time. In other words, our discrete reading task becomes more strongly related to discrete digit naming because of similar format and task demands. However, if this interpretation is valid, a drop in the relation between serial and discrete digit naming would be expected. Our data do not show a difference in the relation between serial and discrete digit naming across classes of readers: .47 for serial word readers, and .44 for parallel word readers. A similar pattern was found by de Jong (2011), who reported correlations of .50 and .45 for serial and parallel processors, respectively. In comparison, in that same study the relation between serial and discrete reading dropped from .80 to .32. In addition, increasing differentiation of abilities is most likely a gradual process. In light of a gradual differentiation process, it would not follow that at a certain point in time two classes could be distinguished for whom the tasks either are or are not differentiated. Probably, more than two classes would be found.

To further support our interpretation of the classes of readers, length effects were examined. As predicted, for both words and nonwords we found that length effects were much larger in the classes denoted as serial processors than in the classes of parallel processors. This pattern of results was found both in the entire sample and in a separate analysis of second grade children (i.e., controlling for age differences).

The larger sensitivity to word and nonword length in the class of serial decoders supports our interpretation of the reading strategy used. However, the small length effects in the classes denoted as parallel processors are not in accordance with the general idea that parallel processing of letter strings would result in the absence of a length effect. These findings could imply many different things. Of course, the results could indicate that our interpretation of the difference in reading strategies across the classes is incorrect. For several reasons, however, we think it safe to assume that small length effects can be observed in parallel processors. First, similar small length effects have been regularly reported in advanced adult readers (e.g., Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; Bates, Burani, d'Amico, & Barca, 2001; Ziegler, Perry, Jacobs, & Braun, 2001) and children (Ziegler et al., 2003), all of whom are assumed to use parallel processing. Such small length effects could reflect the involvement of the nonlexical route. Although parallel activation of phonology is the dominant reading strategy, letter strings are simultaneously processed through the nonlexical route. Possibly, the nonlexical route contributed to the identification of at least some of the items. In addition, a small percentage of serial decoders could have been erroneously assigned to the class of parallel processors, which could also result in small length effects. Alternatively, the findings could add to previous indications that length effects cannot be uniformly ascribed to serial decoding of letters into phonological codes (e.g., Risko et al., 2011; van den Boer et al., 2012). In several computational models, length effects are also not ascribed to serial activation of phonology. Within PDP models, for example, length effects are assumed to reflect visual and articulatory factors or neighborhood size (Seidenberg & Plaut, 1998). Alternatively, in more recent connectionist dual process models (CDP^{+}: Perry, Ziegler, & Zorzi, 2007; CDP^{++}: Perry, Ziegler, & Zorzi, 2010), graphemes are serially connected to the onset, vowel, or coda position in a graphemic buffer. Subsequently, phonology for the input in the graphemic buffer is activated in parallel, either through the lexical route or through a sublexical parallel network of orthographic and phonological units.

In line with this final point, our results do raise the more general question of what is initially processed serially. In line with the DRC framework (e.g., Coltheart et al., 2001; Pritchard, 2012), we have interpreted serial processing as serial activation of phonology through grapheme-phoneme conversion along the nonlexical route. However, serial processing could also occur at the preceding level of letter identification.[2] Within the DRC model, as a model of skilled reading, letter features and identities are always identified in parallel. In their work on the causes of letter-by-letter dyslexia, however, Fiset and colleagues (e.g., Fiset, Arguin, Bub, Humphreys, & Riddoch, 2005; Fiset, Arguin, & McCabe, 2006; Fiset, Gosselin, Blais, & Arguin, 2006) highlight that serial reading processes can also occur at the level of letter encoding. When presented with words, readers who suffer from letter-by-letter dyslexia experience an abnormally low signal-to-noise ratio. As a result, these readers present with an impairment at the letter encoding level because visual features of individual letters cannot be registered with enough precision to activate the corresponding letter identities in parallel. Consequently, readers rely on a compensatory sequential letter processing strategy, and focus on each letter separately to achieve the increase in the resolution of the visual system necessary to encode the letter. Possibly, our younger readers, similar to readers who suffer from letter-by-letter dyslexia, were unable to encode the letter strings in parallel and instead processed letters sequentially, irrespective of how phonology was subsequently activated. With increasing reading experience, readers might develop the skills necessary for parallel letter identification, as seen in adults.

This alternative interpretation could account for several of our findings, such as the fact that even among beginning readers, relatively few children were identified as serial processors. It would also be less surprising that similar shifts from serial toward parallel processing were seen in both word and nonword reading. Letter identification should be similar for both types of letter strings. Interestingly, interpreting our results in terms of development in letter processing skills would mean that our findings could be in line with the DRC model. Our idea that nonword phonology could be activated in parallel would be at odds with the DRC model, according to which nonwords are predominately processed through the nonlexical route. If, however, our findings on reading development in children should be interpreted in terms of development in letter identification processes, they could easily be accommodated within the DRC model with the addition of a developmental process in the initial stage of letter identification.

Some of our findings, however, appear difficult to explain through increases in parallel letter encoding, such as the developmental trends indicating parallel processing of words before nonwords. A specific group of children was identified who appeared to process words in parallel, but nonwords serially. If it is letter features and identities that are increasingly processed in parallel, no differences should be expected in the way words and nonwords are processed, given that the initial stage of visual feature and letter encoding is the same for all letter strings. Furthermore, the correlation of word reading with discrete digit naming seems difficult to interpret. This relation was significant for both serial and parallel processors and appeared to increase when words are processed in parallel. Since only a single digit is presented in a discrete naming task, the task cannot reflect parallel identification of multiple items. It could be argued, however, that it is not the number of items that is essential in this relation but rather parallel activation of all the features of an item, be that a single digit or multiple letters. Nevertheless, although visual feature identification could account for some individual differences in discrete digit naming, it is unlikely to account for the relatively high correlation with reading, given the general agreement that discrete digit naming reflects the retrieval of phonological codes from memory (Bowers & Swanson, 1991; Jones, Branigan, & Kelly, 2009; Logan & Schatschneider, 2014). Taken together, it seems difficult to determine exactly what is initially processed serially. Future studies could help to examine whether it is mainly letters, mainly phonological codes, or both that are increasingly activated in parallel.

Admittedly, the approach taken in the current study adopts assumptions and has limitations that should be mentioned. First, we have to acknowledge that in the current study only short, regular monosyllabic words were studied. The focus on monosyllabic words fits well with the models of the reading system that were studied. Both the DRC (e.g., Coltheart et al., 2001) and PDP (e.g., Plaut et al., 1996) models focus on monosyllabic word reading. The question remains, however, whether the shift from serial toward parallel processing can only be found in short words or could also be seen in longer monosyllabic or in polysyllabic words. In addition, the nonwords in the current study were constructed by interchanging onsets and rhymes of the words. Possibly, nonwords were processed like words, because of their high resemblance to words. Future studies might include multiple sets of nonwords, varying in their similarity to words.

Another limitation lies in the tasks used in the current study. We included only a discrete reading task. Thus, our results cannot be generalized to serial reading tasks. We also made specific choices in the scoring of the discrete naming and reading tasks. The reaction latencies obtained in the naming tasks, which are a measure of time, were converted to fluency scores, a measure of speed. This transformation was chosen to correct for the skewed distributions of reading latencies (Ratcliff, 1993). Our results are not expected to be different, however, if reaction latencies are used, since a high correlation ($r > .80$) was found between fluency scores and reaction latencies for both word and nonword reading. Moreover, the fluency scores as obtained from the discrete word reading task mainly reflect accuracy and automaticity in sublexical and lexical processes, which could also be referred to as reading rate. Our definition therefore differs from fluency measures based on text reading, when for example prosody or comprehension can also be taken into account (e.g., Kuhn, Schwanenflugel, & Meisinger, 2010; Wolf & Katzir-Cohen, 2001). Furthermore, the discrete reading and digit naming task were presented on a computer screen, but the serial naming task was not. However, we do not think this had a major effect on our results. Protopapas, Altani, and Georgiou (2013) administered both serial and discrete naming tasks on a computer and found similar relations with word reading as in the current study.

Finally, we chose to include naming of digits rather than letters. When studying word reading, letter naming might seem the more obvious choice. Digits were chosen, however, because digit names were expected to be even more well known by the children, especially in second grade. In the Netherlands, the names of letters are learned after letter sounds. Digit names are acquired earlier. Moreover, in Dutch, digit names are monosyllabic words, similar to the items in the reading task. However, results are not expected to be different if letters are used. De Jong (2011) presented correlations of discrete word reading with both digit and letter

[2] We thank an anonymous reviewer for bringing this alternative explanation to our attention.

naming and showed that past Grade 1, relations of letter and digit naming with word reading were found to be almost identical.

Taken together, the results suggest that readers can be sorted into latent classes of serial and parallel processors in reading single monosyllabic words and nonwords based on the relations with serial and discrete digit naming. The different classes were validated by large differences in sensitivity to word and nonword length. Together, the different classes identified suggest a developmental shift from reading all letter strings serially toward parallel processing of words, and later on nonwords. These findings possibly challenge current models of the reading system (e.g., Coltheart et al., 2001; Plaut et al., 1996) and highlight the need for models of the reading system that can accommodate developmental changes from initial serial processing, toward later parallel processing of all letter strings.

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