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Shifting Reading Processes and the Development of Word Reading Fluency

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ABSTRACT

Theories of reading state that the development of word reading fluency is dependent on a shift from a slow letter-by-letter decoding process to the faster parallel processing of the letters in a word. We examined developmental changes in these reading processes based on the accuracy and speed of the reading of isolated words. We also investigated to what extent changes in these within-word reading processes account for individual differences in word reading fluency, conceived as the reading of a series of words. Data from de Jong (2011) were analyzed. Participants were 70 Grade 1 (52.9% boys), 73 Grade 2 (53.4% boys) and 127 Grade 4 Dutch-speaking children (47.2% boys) learning to read in Dutch. Children read sets of one-syllable and two-syllable words. Reading accuracy and reaction time per word were registered. Response mixture modeling was used to separate slow and fast reading times at the word level. Also, measures of word reading fluency and serial rapid naming were included. The proportion of words read in parallel across grades increased for both one- and two-syllable words. Unexpectedly, within grades a clear separation was observed into groups of children reading most words through decoding or in parallel. These changes in reading processes only partly captured differences in word reading fluency development. Independent contributions of the speeding up of each within-word process and the growing importance of serial rapid naming were found. These results suggest the need for a further specification and refinement of theories of reading development.

A major assumption in developmental models of reading is that reading development entails the acquisition of an orthographic lexicon, a store for the orthographic knowledge of words (Ehri, 2005; Share, 2008; Steinhilber et al., 2023; Ziegler et al., 2014; but see; Harm & Seidenberg, 1999). In turn, the availability of orthographic knowledge is assumed to determine how words are read. Words with an entry in this lexicon are believed to be read by a process denoted in various ways, such as reading words by sight (Ehri, 2005), memory-based retrieval of words (Perfetti & Helder, 2022) or mapping a word's spelling directly onto its meaning (Castles et al., 2018). Here, we use the more generic-term reading words in parallel by which we mean the direct mapping of the written form of a word onto a pronunciation or, put differently, the parallel activation of a pronunciation from print. For words without an entry in the orthographic lexicon, these models of reading have presumed an effortful and time-consuming decoding procedure in which the letters of the written form are serially converted into sounds to reach the spoken form (e.g., Ans et al., 1998; Coltheart et al., 2001; Perry et al., 2007; Share, 2008). Changes in the process of reading words are deemed to underlie the development of reading accuracy and speed.

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There is abundant evidence for the acquisition of orthographic knowledge and its importance for reading development (Georgiou et al., 2008; Georgiou et al., 2021; Giazitzidou et al., 2025; Li & Wang, 2023). However, there is currently a lack of evidence for a concurrent word-specific shift in reading processes as reading acquisition proceeds. Therefore, the first aim of this study was to examine whether there is a developmental shift in the reading process of words from a slow and effortful decoding process to the rapid process of reading words in parallel.

This shift can be regarded as a within-word change in the reading process as reading acquisition proceeds. Typically, however, reading fluency is conceived as the accurate and rapid reading of *a series* of words either in word lists or connected text (Altani et al., 2020a; Protopapas et al., 2018; van Viersen et al., 2024). Recent evidence shows that individual differences in the fluent reading of series of unconnected words (henceforth “serial word reading fluency” or “word reading fluency”) are only moderately related to differences in the rapid and accurate reading of single words, that is words presented one by one (henceforth “discrete word reading fluency”) (Altani et al., 2018, 2020a; de Jong, 2011; Protopapas et al., 2013). It follows that changes in within-word reading processes are probably not sufficient to explain the development of (serial) word reading fluency.

Protopapas et al. (2013) were the first to propose that the processing of a series of words, in contrast to a discrete presentation format, enables cascaded processing, the processing of multiple words or symbols at the same time but each being at a different stage of processing. For example, a reader might already process the visual features of an upcoming word while accessing the phonological representation of a target word and at the same time execute the articulation of a preceding word. Protopapas and colleagues (Altani et al., 2020a; Georgiou et al., 2023; Protopapas et al., 2013) suggested that efficient programming of such between-word processes requires additional skills that are acquired during reading development. Therefore, changes in within-word processes cannot fully explain the development of (serial) word reading fluency. Accordingly, the second aim of this study was to examine the extent to which changes in within- and between-word processes can account for the development of word reading fluency in its typical format, the serial reading of words.

A developmental shift in reading process

A decrease in the effect of word length is often regarded as a major marker for a developmental shift in reading processes (Hawelka et al., 2010; Marinus & de Jong, 2010; Ziegler et al., 2003; Zoccolotti et al., 2005). When words are decoded, reading speed will become slower as the number of letters in a word increases. The effect of word length on reading speed is absent if words are read in parallel. Evidence clearly shows that sensitivity to word length decreases as children learn to read. Several studies suggest that the effect of word length in the reading of high frequency one-syllable words even tends to disappear by the end of fourth grade indicating that children read these words in parallel (Marinus & de Jong, 2010; Ziegler et al., 2003; Zoccolotti et al., 2005).

Although a length effect is to be expected when serial decoding is used, the observation of a length effect does not necessarily reflect decoding (e.g., van den Boer et al., 2012). Length effects have been ascribed to other factors, such as sensitivity to orthographic neighbors or articulation (Seidenberg & Plaut, 1998). Moreover, the length effect cannot be used as an individual marker of a developing reading system. Word length usually varies from 3 to 6 letters in one-syllable words and this number of letters is insufficient for a reliable estimate of the sensitivity to word length of a particular individual. Therefore, the basis of a length effect in a group of children is hard to determine. It could be the result of a length effect in all children or, alternatively, it might be due to a mixture of two groups of children, a group that reads a particular set of words by decoding, and a group that reads them in parallel, and it could even be the result of a speeding up of the decoding process as demonstrated for example, in the domain of arithmetic, by the increase in calculation speed of simple operations (e.g., Chen et al., 2020). Therefore, the importance of the length effect as an indicator of age-related individual differences in reading processes is limited.

de Jong (2011) proposed an alternative method to examine developmental shifts in reading processes. The method assumes a gradual change toward “format-specific relations” between word reading fluency and the rapid naming of alphanumeric symbols. The latter is often referred to as Rapid Automated Naming and commonly requires the rapid serial naming of an array of highly familiar symbols (usually 4–5 rows of 8–10 digits, letters or colors). Here, we will refer to this format as serial rapid naming. Alternatively, symbols can be presented in a discrete format in which the symbols are presented one by one, denoted here as discrete rapid naming (Jones et al., 2009; Logan et al., 2011). Discrete rapid naming can be regarded as a pure measure of individual differences in access to verbal codes stored in memory (e.g., Bowers & Swanson, 1991). The serial format of rapid naming additionally reflects the ability to generate codes sequentially, which requires inhibiting preceding codes while processing current codes and looking ahead to the next (Jones et al., 2009), that is cascaded processing (Protopapas et al., 2013).

de Jong (2011) reasoned that a change in the word reading process can be revealed by changes in the pattern of relations of discrete and serial rapid naming with discrete and serial word reading fluency. Beginning readers will read most words by the process of serial decoding. Consequently, both discrete word reading and serial word reading fluency involve sequential processing and therefore are more similar to a serial rapid naming task than to a discrete rapid naming task which involves only the immediate retrieval of a verbal code from memory. Put differently, when words are read by serial decoding both task formats of word reading fluency are dominated by sequential processing and therefore the relationship of word reading fluency, irrespective of format, with serial rapid naming will be higher than with discrete rapid naming. However, the rapid naming-reading relationship changes when words are read in parallel, as in advanced readers. Then, the pronunciation of a word is immediately retrieved from memory and as a result, a discrete reading fluency task will be very similar to a discrete rapid naming task in which names of symbols are also immediately retrieved from memory. It follows that in advanced readers the relation of discrete word reading fluency with discrete rapid naming is higher than its relation with serial rapid naming. Similarly, when words are read in parallel, a serial word reading fluency task will resemble a serial rapid naming task as the sequential retrieval of the pronunciation of words is highly similar to the sequential retrieval of the names of symbols. Therefore, in advanced readers the relation of serial word reading fluency with serial rapid naming will be higher than with discrete rapid naming. Put differently, de Jong (2011) hypothesized that in advanced readers the relationship between rapid naming and word reading fluency will be format-specific as words are read in parallel (e.g., van den Boer et al., 2016). Following a similar reasoning, de Jong (2011) also hypothesized that serial and discrete word reading fluency would be more alike in beginning readers, whereas their relation would decrease as an increasing number of words are read in parallel. When words are read through parallel processing then discrete and serial word reading fluency are only moderately related because only the latter task requires sequential processing. In contrast, the relationship between both presentation formats of reading is high when words are read through decoding.

Indeed, as predicted, de Jong (2011) found format-specific relations between the reading of high-frequency words and rapid naming in second- and fourth-grade readers but not in a group of first-grade readers. In this group consistently higher relations of serial rapid naming with both formats of word reading were found. The emergence of format-specific relations between rapid naming and word reading fluency during reading development for words that presumably are read in parallel by advanced readers was replicated in subsequent Dutch studies (van den Boer & de Jong, 2015; van den Boer et al., 2016) and in studies in Chinese (Georgiou et al., 2023), English (Altani et al., 2018; van den Boer et al., 2016), and Greek (Protopapas et al., 2013, 2018). Also, a decrease in the relationship between serial and discrete word reading fluency was found as children advanced in reading acquisition (Altani et al., 2018, 2020a; de Jong, 2011; Protopapas et al., 2013).

Both changes in the length effect and in format-specific relations of rapid naming and reading support a shift in word reading processes, but only at the level of groups of children differing in age and thereby reading ability. Which process a particular individual reader uses to read words has hardly

ever been determined. As an exception, de Jong (2011) used changes in format-specific rapid naming–reading relations to sort readers into two groups. With factor mixture modeling, groups of readers could be distinguished that were presumed to read a set of one-syllable words in parallel and a group that relied more on a decoding process. The solution with two classes had a good fit to the data and fitted significantly better than solutions with one or three classes. As expected, the proportion of readers who processed words in parallel increased from first to fourth grade. By fourth grade, the overall majority of children read a particular set of high-frequency words in parallel. These findings were replicated with Dutch, English and Greek children (Altani et al., 2018; van den Boer & de Jong, 2015) and support the hypothesis that the development of word reading fluency is, at least at the group level, accompanied by a gradual shift from decoding to the parallel processing of words.

de Jong (2011) suggested that the group of parallel word processors read almost all words in the set in parallel because only then format-specific relations between rapid naming and reading could emerge. However, it is unclear whether readers that were classified as decoders used a decoding process to identify each word or, as predicted by the word-specific account, differed in the number of words that were decoded. What hinders further understanding of word reading fluency development is the absence of research on individual differences in word-to-word reading processes. To our knowledge, there is no study in which developmental shifts in word reading processes are supported by direct evidence, that is changes in the number of words that are read in parallel. The primary aim of this study was to fill this gap by applying a psychometric method with which slow decoding and fast parallel word reading processes can be separated in a discrete reading task within persons, at the level of individual words (Molenaar et al., 2016, 2019).

Reading processes and the development of word reading fluency

Current understanding suggests that the development of word reading fluency, the reading of a series of words, depends on changes in both within- and between-word processes (e.g., Protopapas et al., 2013; van Viersen et al., 2022, 2024). Within-word changes concern the transition from a decoding to a parallel reading process. Beyond these within-word changes there is also an increase in the amount of cascaded processing. Younger readers read words or name symbols mostly one by one, whereas older readers start to benefit from the serial format of the reading fluency task (Protopapas et al., 2013).

Two types of evidence suggest an increase in cascaded processing during reading development. Central to both types of evidence is that the serial rapid naming of alphanumeric symbols, in particular of digits, can be regarded as a pure measure of cascaded or sequential processing. This seems to be a reasonable assumption as the naming of a symbol does not involve a “within-word-process” (e.g., Altani et al., 2020b; van Viersen et al., 2024). The first type of evidence is the observation that during reading development the speed of serial rapid naming tends to increase more rapidly than the speed of discrete rapid naming (Altani et al., 2017, 2020b) suggesting that readers benefit more from a serial presentation format as reading acquisition proceeds. Also, better readers tend to have a larger serial advantage than poor readers (Jones et al., 2008; Zoccolotti et al., 2013). Interestingly, also a serial advantage effect has been observed for words that are likely to be read in parallel (e.g., Altani et al., 2017).

In addition to studies revealing a serial advantage effect, further evidence for an increase in cascaded processing are findings on the association between serial rapid naming and word reading fluency. A number of studies have shown that serial rapid naming described extra variance in serial word reading fluency after discrete word reading fluency was controlled (Altani et al., 2020a; G. K. Georgiou et al., 2022; Protopapas et al., 2013; van Viersen et al., 2022). Note here that discrete word reading fluency was taken into account to control for within-word reading processes. In advanced readers, the contribution of serial rapid naming was larger than in beginning readers in which serial rapid naming hardly explained any additional variance (Altani et al., 2020a; Protopapas et al., 2013; van Viersen et al., 2024). These studies support the view that as reading acquisition proceeds, the ability to handle between-word processes during reading, as indexed by serial rapid

naming, tends to become more important in explaining individual differences in word reading fluency.

Thus, the development of word reading fluency is likely to depend on changes in within and between-word processes. However, the extent to which changes in these processes contribute to word reading fluency is not yet clear. First, it is currently unknown how much of the performance of discrete word reading can be ascribed to differences in the particular underlying word reading processes, that is decoding or parallel processing. Recent models on skill acquisition, often derived from studies on the acquisition of arithmetic, suggest that an increase in fluency might only partly be due to a change in process as there is also a speeding up of each process (Chen et al., 2020; Tenison & Anderson, 2016).

Secondly, the relationship between the development of within- and between-word reading processes is not yet clear. One hypothesis is that cascaded processing only becomes available when individual words are read in parallel (Protopapas et al., 2018). This hypothesis is in accordance with the finding of an increasingly larger association of serial rapid naming with word reading fluency as reading acquisition proceeds. A corollary of this hypothesis would be that the association of serial rapid naming with word reading fluency will decrease as words become longer and are less likely to be processed in parallel. Currently, however, most studies on the role of between-word processes have involved short high-frequency one-syllable words. Only one study examined the contribution of between-word processes to shorter and longer words controlling for within-word processes (van Viersen et al., 2024). van Viersen et al. (2024) found that in fifth graders the contribution of serial digit naming to the reading fluency of shorter words was higher than to the reading fluency of longer words, whereas this contribution was similar, and lower, in third-grade readers. In the present study, we aim to extend this result to a wider age range.

Present study

In this study, we re-analyzed the data of the study by de Jong (2011). Participants of the study were children in first, second and fourth grades learning to read in Dutch orthography. The children read one and two-syllable words in discrete and serial format. de Jong (2011) reported only the results for one-syllable words because the cluster technique used to separate decoders and parallel word readers was not deemed feasible for two-syllable words. In this study, we use a different statistical technique. As an exploration and extension of de Jong (2011), we will also analyze the data of the two-syllable words in order to separate slow and fast response times. For matters of convenience, we will maintain here the labels decoding and parallel processing for slow and fast response times, respectively. We are aware that parallel processing of all letters in a two-syllable word might not be possible.

The primary aim of this study was to determine for each reader the process, decoding or parallel processing, underlying the reading of the individual words on the discrete reading task. We use response mixture modeling, a psychometric method which enables, within readers, the separation between slow and fast response times (Molenaar et al., 2016, 2019). The method has been applied in other domains, for example, intelligence (Hauenstein et al., 2024; Molenaar et al., 2016) and personality (Tamimy et al., 2020), but to our knowledge it has not been used in the domain of word reading. The method vastly differs from the factor mixture modeling approach to classify groups of readers used by de Jong (2011). That method was based on the interrelations among discrete and serial formats of rapid naming and reading fluency, the fluency scores on four measures in total, and was applied to the full sample. The response mixture modeling in the current study is based on the individual words in the discrete reading format and is primarily focused on intraindividual differences. Moreover, the method takes both the reading accuracy and speed of a word into account to estimate its underlying word process. Thereby, an often arbitrary criterion on how to combine these two types of data is avoided as well the use of an arbitrary criterion to distinguish between slow and fast reading times.

Based on the word and child-specific estimates of the underlying word process, we will compute per child the proportion of words read in parallel and then consider whether there is, across grades, an increase in the proportion of words that are read in parallel. We will also split the readers into two

groups and examine the similarity of these groups to those reported by de Jong (2011), who used, as said, a completely different statistical technique.

The second major aim of this study concerned the extent to which individual differences in within- and between-word reading processes can account for differences in word reading fluency. We examined the independent and joint contributions of the various components of word reading fluency, that is the number of words read in parallel, discrete reading speed and serial rapid naming, to individual differences in word reading fluency.

Method

Participants

The study included 70 first-grade (37 boys, 33 girls), 73 second-grade (39 boys, 34 girls) and 127 fourth-grade children (60 boys, 67 girls) Dutch-speaking children learning to read in Dutch from seven schools (see also de Jong, 2011).¹ There were no specific inclusion or exclusion criteria. All but four children spoke Dutch at home. Parents gave passive consent for the participation of their child.

Measures

Four word reading tasks were administered differing in format (discrete or serial) and number of syllables (one or two). A serial digit naming task was also administered.

Word reading tasks

The words that were included in the word reading tasks and their frequency in CELEX and number of phonemes are listed in [Appendix A](#). The one-syllable discrete and serial reading task consisted of 20 regular high-frequency words each. The median CELEX frequency of the words in the discrete format was 2478 (range 208 to 182,938) in the serial format frequency 2010 (range 101 to 96,980). Note that within CELEX 50% of the words have a frequency of more than 100. In both discrete and serial reading formats 13 out of the 20 words belonged to the 20% most frequent words. The number of letters in the words varied from 3 to 5. The mean number of letters in discrete and serial format was 3.60 and 3.65, respectively, and the mean number of phonemes was 3.35 for the discrete and 3.45 for the serial format.

The two-syllable word reading tasks consisted of 15 regular two-syllable words of which about half were compounds. The median CELEX frequency of the words in the discrete was 387 (range 89 to 4995). The median frequency in the serial format was 225 (range 11 to 4700). Note, however, that about two-third of the syllables in these 15 words were very high-frequent morphemes, with a median frequency of 11,864 for the discrete and 2415 for the serial reading task. The mean number of letters in the words of the discrete word reading task was 6.55 (range 5 to 9), and in the serial task 6.33 (ranges 5 to 8). For the number of phonemes, the means were 5.9 and 5.6 for the discrete and serial reading tasks, respectively. In all the discrete and serial reading tasks were nicely matched on number of letters and phonemes. The words in both types of tasks were very high frequent but the frequency of the words in the discrete reading tasks was somewhat higher than in the serial reading tasks.

On each of the four tasks accuracy and speed were registered and used to compute a fluency score. For serial reading tasks accuracy and speed (total reading time of the list) were used to compute the number of words read correctly per minute. In discrete reading tasks, speed was registered per word (time to articulation onset). Total time to name all the words and mean accuracy was used to compute

¹There is a small disparity with the number of the children in de Jong (2011). One child in first and one child in second had more than 10 missing scores on the one-syllable task. These children were erroneously included in the study by de Jong (2011).

the number of correctly read words per minute (see de Jong (2011) for an extensive description of the scoring procedure).

Serial rapid naming

The task consisted of 5 digits presented in a random order on a sheet with 5 rows of 10 symbols. Total time to name all 50 symbols was converted to the number of symbols per second.

Statistical analysis

We used response mixture modeling (Molenaar et al., 2016) to separate slow and fast response times to words in the discrete one- and two-syllable reading tasks. We outline this method below.

Response mixture modeling: the model

In response mixture modeling, reading accuracy (the word being correctly or incorrectly read) and reading time (time taken to read the word) are simultaneously analyzed. Figure 1 contains a graphical representation of the response mixture model. A mathematical outline of the model is given in Appendix B. Here, we give a verbal description.

The model consists of a number of latent variables. The first latent variable reflects individual differences in accuracy. All word accuracy variables load on this variable. The second latent variable concerns individual differences in reading speed and is indicated by the observed reading time of the words. Put differently, a two-factor model is specified for accuracy and speed based on all word

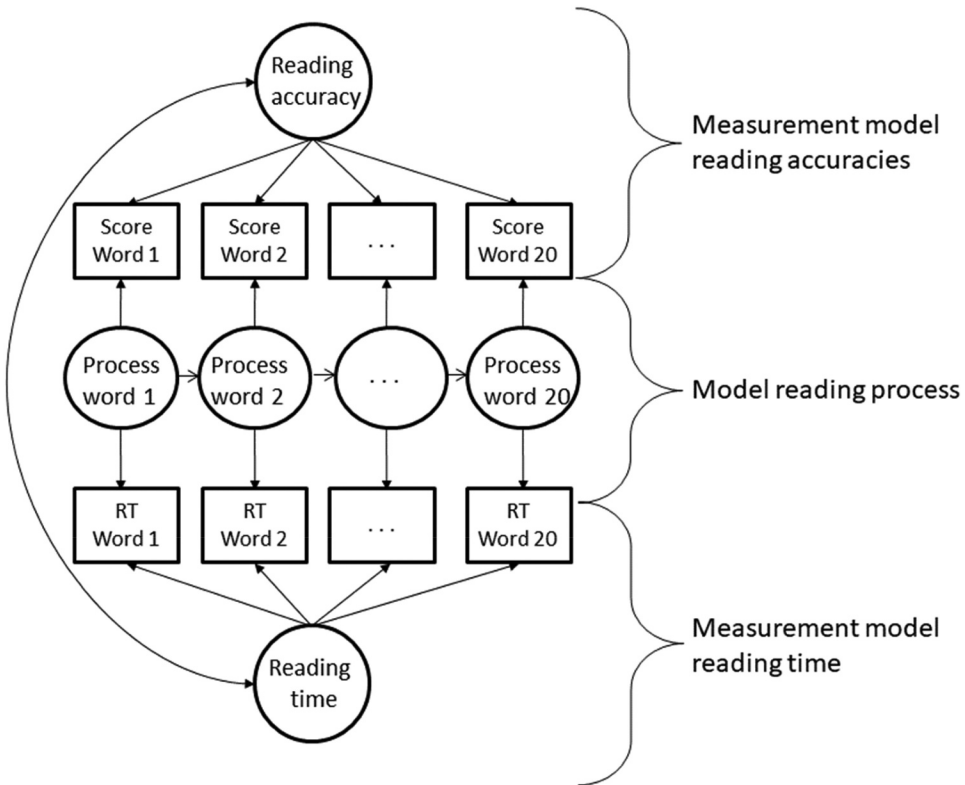


Figure 1. A graphical representation of the response time mixture model used in this study. Circles indicate unobserved (latent) variables, squares indicate observed variables.

accuracy and speed variables, respectively. Finally, for each word, a categorical latent variable is specified with the word's accuracy and speed as indicators. These latent variables, here dichotomous, capture individual differences in word-specific processes. In principle, this parametrization is an alternative way to specify the residual correlation between the accuracy and speed variable related to each word. (Note that the residual of the accuracy and speed variable belonging to each word are not depicted in [Figure 1](#).) The model also shows autoregressive paths between these categorical variables assuming dependencies among reading processes applied to consecutive words. The autoregressive paths thereby reflect the chance that a given process used on a previous word will also be applied in the next word.

The model takes individual differences in reading ability into account. However, also mean differences among words in accuracy and speed are to be expected. These are controlled (see [Appendix B](#)) but are not represented in [Figure 1](#). In all, according to the model the response (accuracy or speed) of a person on a word is determined by the ability of the person (accuracy or speed), the difficulty of the word (mean accuracy or speed), the process that is used and a residual. As a result, for example, differences in the reading speed of a particular word can be expected among persons using the same reading process because they differ in mean reading speed. Similarly, persons differing in the reading process of a word might have a similar reading speed. The same holds for accuracy. A particular response on a word is conditional on the ability of the person and the mean difficulty of a word.

Response mixture modeling: model estimation and model fit

The model used in [Figure 1](#) was implemented in LatentGOLD (Vermunt & Magidson, 2013). Parameters were estimated using Maximum Likelihood. We estimated separate models for the one- and two-syllable words.

With respect to model fit, there is no single standard procedure available yet to establish how well a model like this accounts for the data. Therefore, we examined two aspects of the fit of the model to establish if the model gives an acceptable representation of our data. First, we verified that there are indeed two processes underlying the data by falsifying a single-process model. We did so by comparing the fit of the two-process model with the fit of a model assuming a single word reading process. Fit indexes were commonly used indexes, BIC and AIC, for which lower values indicate a better model fit.

Second, we established model fits for each reading process separately to examine if within a given process, the model fit is acceptable. To this end, for the reading accuracies, we fitted the model in Equation 1 to the reading accuracies of the words read in parallel and to the reading accuracies of the words read by decoding using the ltm package (Rizopoulos, 2007) in statistical computing environment R (R core team, 2022). If this model fits the data, we can conclude that the model reasonably accounts for the data. We used χ^2 -statistics which indicate the discrepancy between the model predictions and the observations. We used bootstrapped p-values. Significant χ^2 values indicate a misfit of the model.

For the reading times, we fitted the model in Equation 2 to the reading times of the words read in parallel and to the reading times of the words read by decoding. To this end, we used the Lavaan package (Rosseel, 2012) in the statistical computing environment R. We used the RMSEA statistic to indicate the discrepancy between the model predicted covariance matrix and the observed data covariance matrix. According to the guidelines by Schermelleh-Engel et al. (2003), values between 0 and 0.05 indicate a good model fit, values between 0.05 and 0.08 indicate an acceptable model fit, and values above 0.08 indicate a poor model fit.

Results

The results are presented in two sections. In the first section, we consider developmental shifts in reading processes. We fit the response mixture model and compare the findings for the one-syllable

words to those reported by de Jong (2011). We also examine whether the proportion of words read in parallel increases across grades. In the second section, we examine the contribution of within- and between-word processes to individual differences in word reading fluency. Within-word processes concerned differences in the type of word reading process and discrete reading fluency, whereas between-word processes were indexed by serial RAN.

Shifting reading processes

We conducted response mixture modeling to separate slow decoding and fast parallel word reading responses on one- and two-syllable words. Both reading accuracy and speed were included in the model, although the proportion of words read correctly was high, ranging from .92 to 1.00 for the one-syllable and from .80 to 1.00 for the two-syllable words. For the one-syllable words a model with two processes fitted the data better than a model assuming one single word reading process (one process: BIC = 2337.10, AIC = 2100.14; two processes: BIC = -196.16, AIC = -615.39). A similar result was found for the two-syllable words (one process: BIC = 3187.37, AIC = 3005.81; two processes: BIC = 1877.47, AIC = 1550.66). Moreover, the chi-square fit statistic for the one-parameter item response model for the reading accuracy data was not significant for both the one- and the two-syllable words for each process type, that is fast decoding or slow parallel processing (one-syllable decoding: $\chi^2 = 50.01$, ns.; one-syllable parallel: $\chi^2 = 101.95$, ns.; two-syllable decoding: $\chi^2 = 9.96$, ns.; two-syllable parallel: $\chi^2 = 19.33$, ns).² The RMSEAs for the reading time part of the model were acceptable for good (one-syllable decoding: 0.084; one-syllable parallel: 0.043; two-syllable decoding: 0.045; two-syllable parallel: 0.049) except for the one-syllable words that were decoded. However, the misfit of this part of the model for the one-syllable words seems to be small as the RMSEA value is close to 0.08. So it is unlikely that the misfit may have distorted our results. Overall, the fit of the model with two processing modes was satisfactory and aligned with the common assumption of two underlying processes of word reading, a slow serial decoding process and a fast(er) parallel process.

Next, we computed per child the proportion of words that were read in parallel, separately for the one-syllable and two-syllable words. Per grade, the distributions of the proportions of words read by sight are displayed in Figure 2. The distributions are clearly not normal. In first and second grades, the distributions for one-syllable words were bimodal. The most frequent outcomes were all words read through decoding (score 0) or all in parallel (score 1). The distribution in fourth grade was heavily skewed to the left. Most children read all words in parallel. Similar distributions of the number of words read in parallel were found for the two syllable words. In first grade, the distribution was skewed to the right, in second grade bimodal and in fourth grade skewed to the left. In all, there seem hardly any shifts in the reading process within persons which is supported by the strong autoregressive paths in the model. The overall probability of the same reading process on two subsequent words was .960 for one-syllable words and .959 for two-syllable words.

de Jong (2011) sorted readers on the basis of RAN–reading relations into groups of parallel word processors and decoders. In this study, we also classified the children into two groups to determine the agreement with the classification of de Jong. However, here the classification was based directly on the proportion of words read in parallel. As said above, de Jong reasoned that the group of parallel word processors read almost all words in parallel. Therefore, we assigned a child to a class of parallel word processors if it had read at least 80% of the words in parallel. The other children were considered as decoders. Note, however, that most of the children in the latter group decoded all words. The results showed that the percentage of readers assigned to the same class by both methods was 85.8% in first grade, 87.7% in second grade and 98.5% in fourth grade.³ Thus,

²Note that as we bootstrapped the p-values, the reported chi-square statistic lacks an explicit degrees of freedom.

³With the more stringent criterion of 90% words read in parallel to qualify as a parallel word processor, we found similar agreement: 81.4% in first grade, 89.0% in second grade and 95.3% in fourth grade.

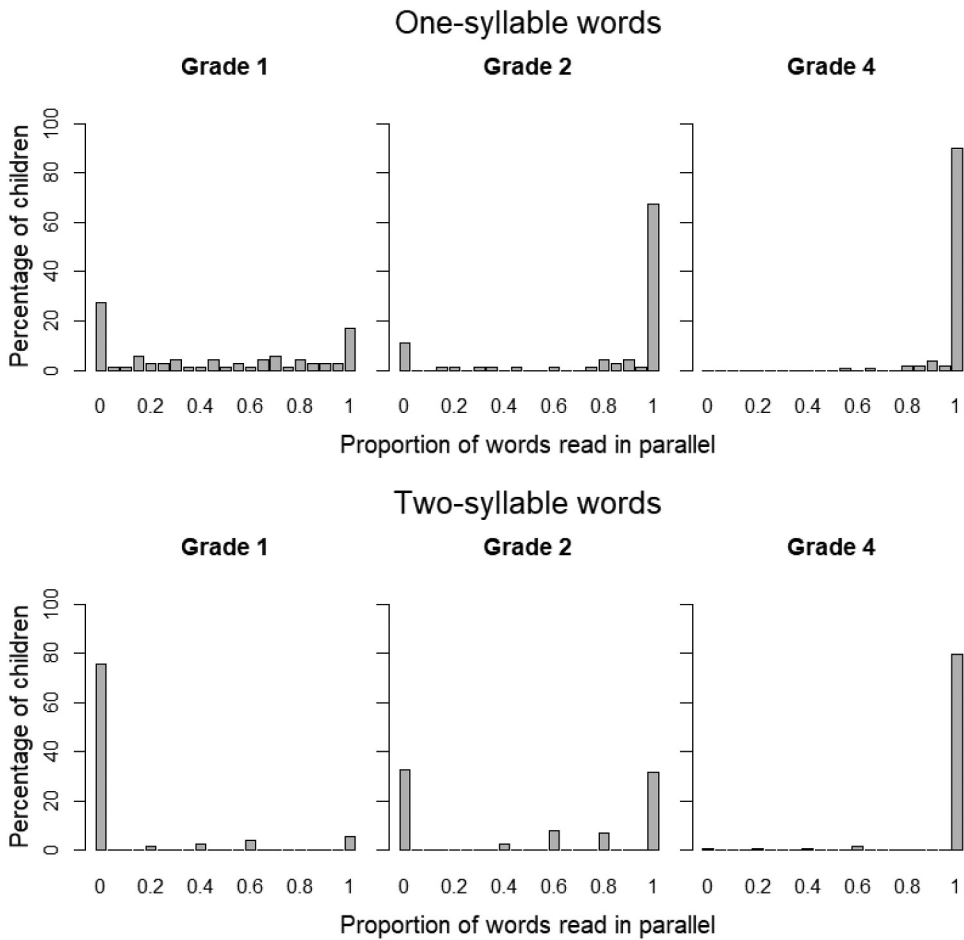


Figure 2. Distribution of proportion of words read in parallel per grade for one-syllable and two-syllable words.

the factor mixture modeling used by de Jong (2011) and the entirely different method applied in this study gave very similar results.

Next, we examined whether the number of words read in parallel increased across grades. Because the distributions of proportions of words read in parallel were either skewed or bimodal, we used the two-group classification described above. In Table 1 we present the percentage of parallel word processors per grade for one- and two-syllable words. As a matter of comparison, we also give the percentage of parallel word processors for one-syllable words based on the factor mixture model of de Jong (2011). As can be seen, these percentages were highly similar to the percentage obtained here. Two findings are noteworthy. First, as expected, we found a clear developmental increase across grades in the percentage of parallel

Table 1. Percentage of children per grade in the group of parallel word processors for one and two-syllable words.

Grade	One-syllable words		Two-syllable words
	Study de Jong (2011)	This study	This study
1	30.0	30.0	7.1
2	72.6	79.5	42.5
4	96.9	98.4	85.0

word processors, both for one- and two-syllable words. Second, there was also a developmental increase across word types. In each grade, the percentage of parallel word processors was higher for the one- than for the two-syllable words. Interestingly, of the 66 children that were classified as decoders on one-syllable words, only 6 (9.1%) were assigned to the class of parallel word processors on the basis of two-syllable words.

Word reading processes and the development of word reading fluency

Our second aim was to determine the extent to which the proportion of words read in parallel, discrete word reading fluency and serial rapid naming contribute to serial word reading fluency. In Table 2, we present the means and standard deviations on the word reading fluency tasks, discrete and serial, and the serial rapid naming task broken down by reader group and grade. The mean proportion of words read correctly on these tasks ranged from .90 to .98 and did hardly differ between decoders and parallel word processors. The results are listed separately for groups based on discrete reading of one-syllable (upper part of the table) and two-syllable words (lower part of the table). In the last column, the effect size, Cohen's d , of the difference between the classes of readers is given for each measure. For these computations, three outlier scores of children in fourth grade were omitted, two on the one-syllable discrete and one on the two-syllable discrete reading task. All outliers had a score that differed by more than 3.3 standard deviations from the mean.

The effect sizes listed in Table 2 clearly show that the differences between decoders and parallel word processors in reading performance are very large. In contrast, the differences between the groups in serial rapid naming, as tested by t -tests, were not significant. The results also showed an increase within reader group across grades in the mean scores on both reading tasks and on the serial rapid naming task. For the one-syllable words, we compared, within groups, children in first and second grades. Effect sizes on the three measures ranged from .72 to .94 in the decoding class and from .43 to 1.04 in the group of parallel word processors. With respect to the two-syllable words, we compared

Table 2. Means and standard deviation of discrete and serial reading fluency and serial rapid naming per grade for groups of decoders and parallel word processors.

Measure	Grade	Decoders			Parallel processors			d
		N	M	SD	N	M	SD	
Groups based on one-syllable words								
DRFS1	1	49	48.32	26.78	21	94.97	13.97	1.97**
	2	15	66.58	19.32	58	101.46	15.44	2.14**
	4	0	^a	^a	125	113.88	14.00	^a
SRFS1	1	49	39.88	20.21	21	75.18	20.68	1.74**
	2	15	61.64	31.12	58	87.82	21.90	1.10**
	4	2	^a	^a	125	104.88	25.46	^a
SRN	1	49	1.37	0.28	21	1.45	0.27	0.29
	2	15	1.63	0.33	58	1.73	0.26	0.34
	4	2	^a	^a	125	2.08	0.40	^a
Groups based on two-syllable words								
DRFS2	1	65	32.18	24.52	5	^a	^a	^a
	2	42	55.18	24.37	31	95.24	15.22	1.91**
	4	18	77.30	15.80	108	104.36	14.64	1.83**
SRFS2	1	65	25.24	15.91	5	^a	^a	^a
	2	42	40.85	15.34	31	63.21	17.98	1.35**
	4	19	64.03	27.67	108	82.19	24.48	0.73**
SRN	1	65	1.39	0.28	5	^a	^a	^a
	2	42	1.66	0.28	31	1.77	0.26	0.41
	4	19	1.94	0.36	108	2.10	0.40	0.39

N = number of children in the group; d = Cohen's d based on pooled SD ; D = discrete; S = Serial; RF = Reading Fluency; S1 = One-syllable words; S2 = Two-syllable words; SRN = Serial Rapid Naming. Reading Fluency in words per minute, Serial Rapid Naming in digits per second.

^aNot enough children in this group.

** $p < .01$.

Table 3. Incremental percentages of variance accounted for in the prediction of the serial reading of one-syllable (upper part) and two-syllable (lower part) words per grade for models without and with group.

Step	Predictor	Grade 1		Grade 2		Grade 4	
		Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
One-syllable words							
1	Group1	-	39.4	-	16.7	-	^a
2	DRFS1	76.2	37.0	32.8	16.2	9.5	^a
3	SRN	0.1	0.2	12.3	12.7	20.7	^a
	<i>R</i> ²	.76	.77	.45	.46	.30	^a
Two-syllable words							
1	Group2	-	^b	-	31.5	-	5.1
2	DRFS2	82.5	^b	58.7	27.4	30.4	26.1
3	SRN	3.4	^b	2.0	2.0	10.3	10.0
	<i>R</i> ²	.86	^b	.61	.61	.41	.40

Group1 = Reader group based on processing of one-syllable words; DRFS1 = Discrete Reading Fluency One-syllable words; SRN = Serial Rapid Naming; Group2 = Reader group based on processing of two-syllable words; DRFS2 = Discrete Reading Fluency Two-syllable words. All percentages above 2% are significant, nonsignificant percentages are underlined.

^aNo children in group of decoders. ^bNot enough children ($n = 5$) in group of parallel word readers.

the second- and fourth-grade groups. We found effect sizes ranging from .87 to 1.16 in decoders and from .62 to .87 in parallel word processors. Overall, reading performance was related to both reading group and grade, with larger effect sizes for reader group than for grade. In contrast, on serial rapid naming clear effects of grade were found, whereas the differences between groups were not significant.

Next, regression analyses were conducted to determine the contribution of reader group (decoders or parallel processors), discrete word reading and serial rapid naming to word reading fluency, that is the serial reading of one and two-syllable words. Reader group and discrete word reading were assumed to reflect within-word processes. Serial rapid naming was taken as an indicator of between-word processes. For each grade and for each word type (one or two-syllables) two regression analyses were done, one analysis without (Model 1) and one including reader group (Model 2). Note that reader group in the analyses of the one- and two-syllable words was based on the discrete reading of the one- and two-syllable words, respectively. In all analyses, serial rapid naming was always included last thereby accounting for all individual differences in within-word processes first.

The percentage of variance in these analyses accounted for by within- and between-word processes is presented in Table 3. Several results are worthy of note. First, according to Model 1, the percentage of variance accounted for by discrete word reading, that is within-words processes, decreases from first to fourth grade for both one- and two-syllable word reading fluency. Second, the results of Model 2 showed that about half of the variance in word reading fluency explained by discrete word reading was captured by reader group when both reader groups contained a substantial number of children, for one-syllable words the children in first and second grades, and for two-syllable words the children in second grade. As expected, the reader group hardly described variance in word reading fluency when one of the reader groups consisted of only a very small minority of the children. Third, irrespective of the model, the percentage of variance described by serial rapid naming, indexing between-word processes, increased from first to fourth grade. For one-syllable word reading fluency, this was a more gradual increase, whereas for two-syllable word reading fluency the increase started after second grade. Finally, serial rapid naming accounted for more additional variance in the reading fluency of one than of two-syllable words, in particular in second and fourth grades.

Discussion

Most developmental theories of reading suggest that growth in reading fluency is largely dependent on word-specific changes in reading processes (Ehri, 2005; Perfetti, 2007; Share, 2008). As reading

acquisition proceeds, a growing number of words are entered into an orthographic lexicon, and thereby for an increasing number of words, the slow letter-by-letter decoding process can be replaced by the faster process of reading words in parallel. The primary aim of this study was to examine this developmental shift in reading processes. Unlike previous studies, we tested this presumed shift directly by considering individual differences among readers in the number of words that were read in parallel. The second aim of the study concerned the extent to which differences in word reading fluency can be accounted for by changes in within- and between-word processes and whether this differs between the reading fluency of one- and two-syllable words.

Shifts in reading processes

Developmental shifts in reading processes have mostly been supported by indirect evidence such as a decrease in sensitivity to word length and changes in the format-specific relations of rapid naming and reading. In this study, we determined which process children used to decipher each individual word. We found, as theoretically expected, that a model which assumed two processes fitted the data well. In accordance with current developmental models, the slow process was denoted as decoding and the fast process as reading in parallel.

In line with current developmental theories of reading, we found in each grade a group of children that read almost all of the high-frequency words by a parallel process. These children had acquired sufficient orthographic knowledge about all of the words in the set and thereby were able to replace the slow decoding process by the faster process of reading words in parallel. Surprisingly, however, there were also fair numbers of children that read almost all words by decoding. About 30% of the first-grade children read all one-syllable words by decoding and 80% decoded all two-syllable words. In second grade, still about 10% of the children fully relied on decoding for the one-syllable words, whereas 30% used decoding for all of the two-syllable words.

Theoretically, the use of a persistent mode of decoding would imply that these children did not have sufficient word-specific orthographic knowledge. But this does not seem very likely. The words in the set were highly frequent, and the majority of the children at the end of first grade will have come across one-syllable words like “stop” [stop], “dag” [day], or “gek” [crazy]. Similarly, it does not seem very likely that a large minority of the children at the end of second grade did not have any orthographic knowledge of completely regular two-syllable words like “zondag” [sunday], gordijn [curtain], or “vandaag” [today].

The observation of a group of persistent decoders in Dutch children has been reported before and could be the result of a strong emphasis on the sounding out of words in Dutch education (van der Schoot & Licht, 2000). Note, however, that the persistence of a decoding mode of reading seems to be affected by the number of syllables, because the percentages of persistent decoders were far larger for the two than for the one-syllable words. Possibly, the persistent decoders wanted to minimize their errors. Indeed, in the current study accuracy was over 90% correct on both one- and two-syllable words. To maintain such a high accuracy, children are more likely to fall back on decoding on the two- than on the one-syllable words.

The finding of a group of persistent decoders points to the broader issue of the relation between the acquisition of orthographic knowledge and changes in reading processes. Current developmental theories have hardly specified this relation (Ehri, 2005; Perfetti, 2007; Share, 2008), whereas computational models of orthographic learning have assumed a “one-shot-approach” in which the word process shifts as soon as an entry is formed in an orthographic lexicon (Pritchard et al., 2018; Ziegler et al., 2014, but see; Steinhilber et al., 2023). Empirically, an abundant number of studies have shown that word-specific orthographic knowledge of novel words is acquired after a few exposures (Nation & Castles, 2017; Share, 2008; see for a review; Li & Wang, 2023). However, there is a lack of studies in which the relationship between orthographic learning and changes in word-specific reading processes is examined. How much orthographic knowledge is sufficient to enable a word-specific change in the word reading process is yet unknown. Moreover, most models of reading

development tend to suggest that the availability of orthographic knowledge is sufficient for the transition from decoding to parallel word reading. It is yet unclear whether other factors also have to be in place to enable a shift in reading process.

In this study, the distributions of the numbers of words read in parallel were either bimodal or highly skewed. Therefore, as in the study by de Jong (2011), children were classified into two groups according to overall reading mode. An important finding is that this classification of children on one-syllable words into decoders and parallel word processors was highly similar to the classification of these children in the study by de Jong (2011). The latter classification was based on changing patterns in the format-specific relations of serial rapid naming and word reading, four fluency measures in total, in the full sample. The current classification was derived only from the discrete reading task using both accuracy and reading time per word and was conditional on children's grade. Despite these large differences in underlying data and statistical technique, the similarity of both classification methods is striking. However, the method of response mixture modeling, used in this study, seems far more flexible and has wider applications (e.g., Molenaar et al., 2016). It also enabled us to analyze the processes underlying the reading of two-syllable words.

As for the one-syllable words (de Jong, 2011), we found a developmental shift from decoding to parallel word reading on the two-syllable words. The percentage of children that could be classified as parallel word processors increased from first to fourth grade. At first sight, parallel processing of all letters in a two-syllable word, especially words of 8–9 letters, seems unlikely. For shorter one-syllable words parallel processing is generally believed to be possible and is often denoted as reading by sight (Ehri, 2005). However, computational models for polysyllabic words show that parallel reading of longer words could be possible (e.g., Ans et al., 1998; Ginestet et al., 2019; Perry et al., 2010). Empirical evidence also suggests that more fluently reading children can process longer polysyllabic words in parallel (Häikiö et al., 2015; Hautala et al., 2022). Moreover, the fact that about two-third of the two-syllable words contained high-frequent morphemes might have facilitated parallel processing. In several instances, a morpheme and an additional letter might have been sufficient to get to the pronunciation. Finally, it should be noted that the parallel processing of a two-syllable word might involve the parallel activation of its phonological representation but possibly not the immediate activation of the entire pronunciation of the word. In all, however, the current results do not show to what extent two-syllable words can be entirely processed in parallel. However, the results do support a clear distinction between children that do and do not use parallel processing during the reading of two-syllable words.

Interestingly, in each grade, the percentage of children that read words in parallel was lower for the longer two-syllable than for the shorter one-syllable words. Note here that the classifications for the one- and two-syllable words were independently computed because the response mixture models were estimated per word type. The results show a developmental trajectory from the decoding of one-syllable words to the parallel processing of two-syllable words as reading acquisition proceeds, suggesting systematic changes in reading mode. This developmental trajectory mostly mirrors Dutch reading instructions starting with high frequency one-syllable words and then moving further to more complex one-syllable words and subsequently polysyllabic words.

Within and between-word processes in reading fluency

We hypothesized that the development of reading fluency would be dependent on changes of within and between-word processes. The separation of groups of decoders and parallel word processors was based on the discrete reading task, assumed to reflect only within-word processing. In contrast, serial word reading, a typical measure of reading fluency, was assumed to involve both within- and between-word processes (e.g., Altani et al., 2020a).

With respect to changes in within-word processes, decoders were less rapid on the discrete reading tasks than parallel word processors. This was to be expected because the separation of these groups was mainly based on discrete reading speed and hardly on reading accuracy. However, we also found an

increase in the speed of within-word processes across grades but within classes. Thus, increases in reading speed of single words do not only reflect changes from a slow serial to a fast parallel within-word reading process but also the speeding up of these separate processes. This finding was further supported by the results of our regression analyses meant to examine the extent to which changes in within-word reading processes contribute to an increase in (serial) reading fluency. Group membership accounted for at the most half of the variance captured by within-word processes, that is discrete word reading, in the prediction of (serial) reading fluency. Taking a look at more general models of skill acquisition, this cannot come as a surprise as several of these models, especially in the area of arithmetic, accommodate both shifts in underlying processes as well as an increase in the processing speed of each process (e.g., Chen et al., 2020; Tenison & Anderson, 2016).

Several possibilities might be raised, which partly independently, might be responsible for an increase in word reading fluency within each mode of reading. With respect to decoding, an obvious possibility is a strengthening of letter-sound connections, a process that might continue to develop until sixth grade (Blomert, 2011), resulting in the more rapid activation of letter-sounds. Another possibility concerns the lexicalization of the decoding process in which, for irregular words, the surrounding letters are used to determine the proper sound of a letter (e.g., Perry et al., 2007; Share, 1995). Related to this possibility, Elbro and colleagues (Elbro & De Jong, 2017; Elbro et al., 2012) suggested that the decoded form, as in the word PIZZA, might differ from the pronunciation of a word stored in memory (see also Steacy et al., Steacy et al., 2023). As a second step in the decoding process, the decoded form, a pronunciation elicited by the spelling of the word, has to be associated with the pronunciation in memory. Decoding might speed up if this association becomes more firmly established (Elbro & De Jong, 2017). Finally, the availability of orthographic knowledge might also affect the decoding process, for example through neighborhood effects (e.g., Coltheart et al., 2001).

There was also a speed-up of reading across grades in the class of parallel word processors as well as large differences within grades. In fourth grade, virtually all children, including the poorest readers, tended to process one-syllable words in parallel, suggesting that orthographic knowledge of these words was available. This result is in line with the findings of Mehlhase et al. (2019) who found that good spellers, presumed to have sufficient orthographic knowledge, could nevertheless have poor reading fluency. Similarly, Hawelka et al. (2010) examined the reading times of German children with dyslexia on one-syllable words that had required only a single eye fixation, suggesting that the children had processed these words in parallel. However, despite the availability of orthographic knowledge, these poor readers remained to be slow. Wimmer and Schurz (2010) hypothesized that poor readers might be slow and inefficient in the processing of phonology from print, including both access to sounds from graphemes and access to pronunciations of words from their written form. Thus, from a developmental perspective, the reading process could speed up because, as with decoding, letters and sounds might gradually become more connected enabling a rapid access to the spoken form of a written word.

The results also revealed a developmental increase in the importance of between-word processes in word reading fluency. Serial rapid naming was taken as a pure reflection of between-word reading processes, in particular sequential processing, on the assumption that the retrieval of the name of a symbol from memory does not require any processing akin to the processing of a word. In accordance with previous studies (Altani et al., 2020a; Georgiou et al., 2022; Protopapas et al., 2013; van Viersen et al., 2024), we found that the percentage of variance described by serial rapid naming increased from first to fourth grade after individual differences in within-word processing fluency were controlled. This increase is probably due to a growing ability to coordinate between-word processes, enabling cascaded processing of words in the serial word reading task. However, a growing ability toward cascaded processing might also have occurred in the serial rapid naming task as the performance on this task also increased across grades (Protopapas et al., 2013). Interestingly, and as an extension to previous studies, serial rapid naming contributed less to the reading fluency of two-syllable words than to the reading fluency of one-syllable words, a difference that was most pronounced in second- and fourth-grade children. A similar finding was recently

reported by van Viersen et al. (2024) between the fluent reading of one-syllable words as compared to the reading fluency for polysyllabic words (one to four syllables) in third and fifth graders.

The smaller association of serial rapid naming with word reading fluency in longer words provides support for the hypothesis that the possibility of cascaded processing is dependent on the efficiency of within-word processes. Indeed, discrete word reading fluency, a measure of within-word reading efficiency, accounted for more variance in the reading fluency of two-syllable words than in the fluent reading of one-syllable words. Especially, in first and second grades, the majority of the children read the two-syllable words through decoding. In these children, the within-word process of decoding seemed to dominate reading fluency, probably at the expense of the contribution of between-word processes. However, it should be noted that the current results do not fully support the hypothesis that the association of serial rapid naming with word reading fluency will decrease as words become longer and are less likely to be processed in parallel. First, in fourth grade, the overall majority of the children processed both one- and two-syllable words in parallel. Nevertheless, serial rapid naming accounted for a substantially larger part of the individual differences in word reading fluency of the one-syllable words than of the two-syllable words. Second, we found an increase in serial rapid naming across grades in the group of decoders as well as in the group of parallel processors but hardly any difference between the two reader groups within grades. The result suggests that the ability of cascaded processing develops with age. Given these findings, we cannot exclude the possibility that within- and between-word processes develop, at least partly, independently and that series of longer words, possibly because of their length, provide fewer opportunities for cascaded processing than shorter words, irrespective of the underlying reading process.

Limitations

This study has some particular limitations. First, we used high-frequency words. Therefore, the observation of a group of readers that read all words in parallel was to be expected. As a consequence, the number of children that could vary in their frequency of decoding was more limited. This does not seem to be such a problem as we find a group of readers that predominantly used a decoding mode. Nevertheless, we cannot exclude the possibility that our sets of one- and two-syllable words were too homogeneous and somehow elicited a decoding mode for a substantial number of children. Future studies need to include more varied sets of words to establish to what extent the current results were confined to these particular sets of one- and two-syllable words.

We also have to note that the one-syllable words were more frequent than the two-syllable words, although both were, as said, highly frequent. Therefore, the larger association of serial rapid naming with one-syllable word reading fluency than with two-syllable word reading fluency might be (partly) due to differences in frequency and not to differences in word length. However, this does not seem very likely. van Viersen et al. (2024) reported that serial naming made a similar contribution to the reading fluency of polysyllabic words and nonwords, suggesting that word frequency can probably not account for the current results,

Another limitation concerns the measurement of reading speed. In this study, we used the onset of articulation and not its offset. Thus, our reaction times did not include the articulation time. If the onset time mostly reflects the processing of the first part of a word, then the use of the onset might not have been very influential in the reading speed of the one-syllable words. However, in the two-syllable words further processing might have continued after the onset. Consequently, we might have missed some serial decoding and overestimated the percentage of parallel word processors. However, we found fairly large differences in the percentages of parallel word processors between the one- and two-syllable words, suggesting that the influence of using only the onset might not have been very large.

Conclusion

We examined the contribution of a shift in reading processes to the development of reading fluency. We determined, for the first time, within children which process was used to read each individual word. As expected, we found that some children read all words in parallel but, unexpectedly, there was also a group of children that read almost all words through decoding. We argued that the latter group of children most likely had orthographic knowledge of the words. Therefore, this finding seems at odds with the common assumption of most developmental theories of reading that orthographic knowledge is word specific and that the availability of this knowledge is sufficient to enable a shift in reading process. In accordance with theories of reading development, we found a clear increase from first to fourth grade in the percentage of children that had shifted their reading process from decoding to parallel processing. This shift occurred earlier in one- than in two-syllable words. A change in the word reading process could only partly account for the development of reading fluency, conceived as the reading of series of words. We also observed a developmental increase in the speed of within-word processes as well as a growing importance of between-word processes, indexed by rapid serial naming. Between-word processes appeared to be more important in one than in two-syllable words, raising the question about the relation between within and between-word reading processes. Together, these findings suggest the need for a further specification of theories of reading development.

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Appendices

Appendix A

Words in the one- and two-syllable discrete and serial reading tasks in their Order of Presentation

Discrete reading task			Serial reading task		
Word	Freq	Pho	Word	Freq	Pho
One-syllable words					
gil [scream]	322	3	gat [hole]	4260	3
taart [pie]	438	4	trein [train]	3436	4
juf [teacher]	208	3	jas [coat]	2091	3
gaan [go]	137590	3	rups [caterpillar]	128	4
mat [mat]	620	3	mus [sparrow]	743	3
rust [rest]	3639	4	gas [gas]	1037	3
gek [crazy]	5822	3	stip [dot]	224	4
stop [stop]	306	4	dun [thin]	1992	3
dag [day]	3989	3	jaar [year]	48453	3
klok [clock]	1573	4	wel [well or true]	96980	3
win [win]	3384	3	rol [role or roll]	8894	3
jeuk [itch]	225	3	dop [cap]	225	3
rat [rat]	995	3	tent [tent]	1142	4
fles [bottle]	4760	4	klas [class]	2028	4
dan [then]	182939	3	snoep [candy]	101	4
trap [stairs]	4901	4	kat [cat]	3040	3
kip [chicken]	1421	3	slak [snail]	227	4
staan [stand]	79617	4	fiets [bike]	2049	4
val [fall]	1498	3	vos [fox]	315	3
stil [quiet]	6996	4	geel [yellow]	2880	3
Two-syllable words					
kiespijn [toothache]	134	6	karton [cardboard]	331	6
zondag [Sunday]	1752	6	zakdoek [handkerchief]	874	6
servet [napkin]	218	6	servies [tableware]	67	6
fontijn [fountain]	387	6	fornuis [stove]	225	6
ballon [balloon]	240	6	bijdoen [add]	11	5
languit [sprawling]	342	6	luiwak [slacker]	26	5
gordijn [curtain]	1909	6	glijbaan [slide]	35	6
kermis [funfair]	456	6	koffie [coffee]	4700	5
soldaat [soldier]	4790	6	sandaal [sandal]	299	6
oppas [babysitter]	89	6	opzij [aside]	2324	4
vandaag [today]	4995	6	voetbal [soccer]	242	6
rijweg [roadway]	142	5	roomijs [ice cream]	23	5
meedoen [join]	717	5	middag [afternoon]	2999	6
kasteel [castle]	1546	6	koprol [rollover]	17	6
spookhuis [hauntedhouse]	79	7	spaarpot [piggy bank]	61	6

Freq = Word frequency in CELEX; Pho = Number of phonemes.

Appendix B

Specification of the response mixture model

The model displayed in Figure 1 consists of three parts: the measurement model for the reading accuracies (correct/incorrect scores), the model for the reading times (time to read the word), and a model for the reading processes. Below we specify each of these models.

For the reading accuracies, we used the following item response theory model for dichotomous scores:

$$\text{logit}\left(P\left(X_{pi} = 1 \mid \eta_p, C_{pi}\right)\right) = \beta_{0i} + \beta_{1i} \times C_{pi} + \eta_p \quad (1)$$

Specifically, the probability that word i is correctly read by subject p (i.e., the probability that $X_{pi} = 1$) is decomposed into an intercept, an effect of the reading process, and a factor score. First, η_p is the position of subject p on the reading accuracy of individual difference dimension (i.e., the dimension of individual differences underlying the reading accuracies of the words). Next, β_{0i} is the general intercept of word i which indicates how difficult the word is to read overall, i.e., irrespective of the reading process that is used (higher β_{0i} indicates that the word is overall easier to read). Then, C_{pi} indicates the process subject p is using to read item i , where $C_{pi} = 0$ is a decoding process, and $C_{pi} = 1$ is the reading by sight process. As a result, β_{1i} accounts for the difference in the difficulty of word i if it is read in parallel instead of by decoding. That is, β_{1i} indicates how much easier or more difficult it becomes if you use reading by sight on word i .

For the reading times we used a factor model for continuous scores with equal factor loadings for the reading times (denoted T_{pi}), that is:

$$\log\left(T_{pi} \mid \tau_p, C_{pi}\right) = \nu_i - \delta \times C_{pi} + \tau_p + \varepsilon_{pi} \quad (2)$$

Specifically, the reading time of word i is decomposed into an intercept, an effect of the reading process, a factor score, and a residual. First, τ_p is the position of subject p on the reading time of individual difference dimension (i.e., the dimension of individual differences underlying the reading times of the words). Next, ν_i is the general intercept of word i which indicates how much time it takes in general to read word i , i.e., irrespective of the reading process used (higher ν_i indicates slower reading overall), and ε_{pi} is a residual. Then finally, δ accounts for the overall difference in reading speed across the two processes, that is, how much faster are subjects if they use reading by sight? Parameter δ is constrained to be positive, so that $C_{pi} = 1$ is the faster process (which we subsequently interpret as reading in parallel). This choice is arbitrary and does not affect the results (i.e., if we would have constraint δ to be negative, $C_{pi} = 1$ would be the slower process). In the model above, the reading times are assumed to be log-normally distributed for each reading process with a separate residual variance for each reading process.

The reading process variable C_{pi} can readily be estimated using the two models above. However, as we are interested in the question whether subjects are switching processes, we introduce a temporal dependency on the process variables. Specifically, we use a hidden Markov structure, in which the process that subject p is using on item i is predicted from the process that this subject used on the previous item. Formally:

$$P(C_{pi} = 1) = P(C_{p1} = 1) \times \prod_{j=2}^i P(C_{pj} = 1 \mid C_{p(j-1)}) \quad (3)$$