Evidence for multiple routes in learning to read

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Abstract

We describe a multiple-route model of reading development in which coarse-grained orthographic processing plays a key role in optimizing access to semantics via whole-word orthographic representations. This forms part of the direct orthographic route that gradually replaces phonological recoding during the initial phases of reading acquisition. The model predicts distinct developmental trajectories for pseudo-homophone and transposed-letter effects – two benchmark phenomena associated with phonological recoding and coarse-grained orthographic processing, respectively. Pseudo-homophone effects should decrease over the first years of reading acquisition, whereas transposed-letter effects should initially increase. These predictions were tested in a lexical decision task with 334 children in grades 1–5, and 29 skilled adult readers. In line with the predictions, we found that the pseudo-homophone effect diminished as reading level increased, whereas the transposed-letter effect first increased and then diminished.

1. Introduction

The average child embarking on the process of learning to read a language written with an alphabetical script comes equipped with two important pieces of prior knowledge: the letters of the alphabet (typically mastered in kindergarten), and expertise in spoken language comprehension and production entailing knowledge of the sounds of words (a phonological word-form lexicon) and their associations with meaning. It is generally agreed that children learning to read must first master the rules of sublexical spelling-to-sound translation, which is initially the most efficient means of getting from print to meaning (Share, 1995). However, it is also generally agreed that the child will eventually develop whole-word orthographic representations and their associations with semantics, which is thought to constitute another pathway for accessing meaning from print in skilled readers. These two mechanisms form the basis of a generic dual-route model of skilled reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Diependale, Ziegler, & Grainger, 2010; Grainger & Ferrand, 1994; Grainger & Holcomb, 2009; Grainger & Ziegler, 2011; Harm & Seidenberg, 1999, 2004; Perry, Ziegler, & Zorzi, 2007, 2010; Seidenberg & McClelland, 1989), and the basis of several influential accounts of the process of learning to read (Ehri, 1992; Frith, 1985; Seymour, 1997; Share, 1995; Ziegler & Goswami, 2005). What is less generally agreed upon, on the other hand, is the nature of the processing involved in accessing such whole-word orthographic representations, and how the beginning reader might develop such representations. Indeed, there is very little research, either empirical or theoretical, investigating the development of orthographic representations during reading acquisition (for reviews, see Castles & Nation, 2006; Metsala & Ehri, 1998, and for two recent theoretical investigations see Dufau et al., 2010; Glotin et al., 2010).

The starting point of the present research is a description of the type of representations involved in processing of the two routes of a generic dual-route model of reading. We first describe the general theoretical framework in terms of a multiple-route model of silent word reading,
before examining the specific mechanisms that might be involved in learning the different types of representation involved in each processing route. We use the developmental framework proposed by Share (Share, 1995, 1999, 2004) in order the bridge the gap between our account of skilled reading and the processes involved in learning to read. The result is a developmental multiple-route model of how children learn to silently read words. We then derive precise experimental predictions from this framework, in terms of developmental patterns for two benchmark phenomena associated with skilled silent word reading: transposed-letter effects and pseudo-homophone effects.

1.1. A multiple-route model of skilled reading

Fig. 1 describes a multiple-route model of printed word recognition that is basically an extension of the bi-modal interactive-activation model (BIAM) first proposed by Grainger and Ferrand (1994) and recently implemented by Diependale et al. (2010). Like the BIAM, our multiple-route model of word recognition has many similarities with dual-route models of reading aloud (Coltheart et al., 2001), and particularly the CDP+ model (Perry et al., 2007, 2010). The model proposed in Fig. 1 provides a more explicit description of the processing involved in getting from print to meaning via orthographic representations alone, and draws a key distinction between location-specific and location-invariant (stimulus-centered) orthographic codes (the code that defines a set of letter identities and their positions). Another key postulate underlying this theory is that fundamentally different types of orthographic coding are involved in processing in the two routes. This forms the basis of a dual-route theory of orthographic processing that provides a further distinction between the two processing routes of the generic dual-route approach, going beyond the standard distinction in terms of whether or not phonology is involved (Grainger & Dufau, 2011; Grainger & Ziegler, 2011). It is the integration of the dual-route approach to orthographic processing within a generic dual-route model of word recognition that gives rise to our multiple-route model.

According to the model depicted in Fig. 1, the indirect route from print to meaning via phonology, involves fine-grained orthographic processing. That is, the system needs to know precisely the ordering of the different letter identities in the stimulus word (Goswami & Ziegler, 2006). This is particularly important for extracting contiguous letter combinations that form multi-letter grapheme representations, such as the “ch” and “ai” in the word “chair”. It is also thought to be the mechanism responsible for extracting other types of frequently co-occurring letter combinations, such as affixes. Because of the need to process fine-grained orthographic structure, this route is thought to be more demanding in terms of focused spatial attention (Facoetti et al., 2008; Perry et al., 2007, 2010). Pseudo-homophone effects seen with skilled readers represent one key empirical signature of this kind of fine-grained orthographic processing. Pseudo-homophones are nonwords that can be pronounced like a real word, such as the letter string “brane” pronounced as the word “brain”. These stimuli are harder to reject as nonwords in a lexical decision task (e.g., Goswami, Ziegler, Dalton, & Schneider, 2001; Ziegler, Jacobs, & Klueppel, 2001), generate more semantic categorization errors (e.g., Van Orden, 1987), and are more effective primes compared with carefully matched orthographic controls (e.g., Ferrand & Grainger, 1992, 1993, 1994; Frost, Ahissar, Gotesman, & Tayeb, 2003; Lukatela & Turvey, 1994; Perfetti & Bell, 1991; Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000; see Rastle & Brysbaert, 2006, for review). Note that these pseudo-homophone effects observed with skilled adult readers are thought to reflect fast automatic computation of sound from print upon presentation of a pronounceable string of letters (Braun, Hutzler, Ziegler, Dambacher, & Jacobs, 2009).

In the multiple-route model shown in Fig. 1, the fastest route from orthography to semantics involves coarse-grained orthographic processing. The main hypothesis here is that the skilled reader has learned to optimize the mapping of letter representations onto semantics using the best quality information in the stimulus (the most visible letters) and selecting subsets of letters that best help identify the stimulus as a unique orthographic word form. Given these constraints, it is hypothesized that such letter combinations often involve non-contiguous elements in the string (Dandurand, Grainger, & Dufau, 2010; Dandurand, Grainger, Duñabeitia, & Granier, 2011). This possibility is illustrated in Fig. 1, where it is proposed that both contiguous and non-contiguous bigrams (so-called “open-bigrams”, Grainger & van Heuven, 2003) are involved in processing along the coarse-grained pathway (see Whitney, 2001, for an alternative theory of orthographic processing involving open-bigram representations). For the present purposes, there are two key properties of the coarse-grained orthographic code. The first of these key properties is the word-centered nature of the coordinate system used for letter position coding.
That is, letter identities are associated with a given position in the word, independently of eye fixation location. The second of the key properties is the flexible nature of the letter position coding system. It is this flexibility that allows the coding scheme described on the left side of Fig. 1, and a number of alternative schemes (Davis, 2010; Gomez, Ratcliff, & Perea, 2008; Whitney, 2001) to account for the two principal empirical signatures of coarse-grained orthographic processing: transposed-letter effects and relative-position priming effects.

In the following section, we examine how these different processes, hypothesized to be involved in skilled reading, might be established during reading acquisition.

1.2. A multiple-route theory of learning to read words

The main task of the beginning reader is to associate letter identities with sounds in order to make contact with the whole-word phonological representations of known words (phonological recoding). Initially, this will involve a serial letter-by-letter reading strategy, since the mechanism for parallel letter identification is not yet established. By shifts of the eyes and shifts of attention, the beginning reader identifies the different letters of the word one at a time, and learns what sounds they correspond to. This mechanism simply capitalizes on the two key sources of information that the beginning reader has available—knowledge of the alphabet and spoken vocabulary.

Inspired by the self-teaching hypothesis of Share (1995), we propose that it is during this relatively slow and painstaking process of phonological recoding that exposure to printed words enables the setting-up of a specialized system for parallel orthographic processing. According to Share, each successful decoding that is achieved via the laborious serial procedure provides the beginning reader with an opportunity to set up connections between the printed word and the decoded meaning that only involve orthographic representations. Within the present theoretical framework, this specifically involves the development of parallel, independent letter processing. It is the development of parallel letter processing, thought to initially involve some form of location-specific letter code, that then leads to the development of two types of location-invariant sublexical representations: (a) coarse-grained representations for fast access to semantics from orthography and (b) fine-grained representations involving a modification of the process used to translate print-to-sound (grapheme representations) and the development of morpho-orthographic representations (affixes).

This developmental progression is illustrated in Fig. 2.

Parallel independent letter processing is hypothesized to involve a bank of location-specific letter detectors. Thus, when fixating the letter “b” in the word “table”, at this level of coding, the system “knows” simultaneously that there is a “b” on fixation, an “a” just to the left, and a “t” even further left, etc. Understanding how such a system is learnt is currently the object of ongoing research, but is not the primary focus of the present study. Instead we focus on the location-invariant orthographic codes that are derived from this location-specific map of letter identities (see Fig. 2). The system for coding for location-invariant orthographic information must adapt to the constraints imposed by the development of parallel letter processing. For the coarse-grained processing route that provides direct access to semantics via orthographic information alone, this adaptation is hypothesized to involve the development of letter combination detectors that optimize the mapping of a subset of the word’s letters onto a unique word identity. For this purpose, the system is hypothesized to select letter combinations that maximize the visibility of their constituent letters and maximize the amount of information they carry with respect to word identity (Dandurand et al., 2011; Grainger & Dufau, 2011; Grainger & Ziegler, 2011).

The development of parallel independent letter processing also leads to adaptation in the fine-grained orthographic processing involved in the phonological route of our multiple-route model. As noted above, this process of phonological recoding is thought to initially involve a serial letter-by-letter reading strategy, where order information is provided by the sequence of encoding events. The development of parallel letter identification is therefore hypothesized to cause a shift from a strictly sequential letter encoding (that outputs an ordered set of phonemes) to a more parallel mapping of letters onto higher level orthographic representations such as graphemes and affixes, that retains the same level of precision as the strictly sequential mechanism (see Alario, De Cara, & Ziegler, 2007). Whether or not the mapping of graphemes onto phonemes also becomes more parallel is another issue still open to debate.1 Here it is hypothesized that a precise word-centered letter-position coding scheme enables the chunking of frequently co-occur-

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1 Although, in the limit, parallel processing cannot be distinguished from very fast sequential processing, we use the term parallel processing to refer to the simultaneous uptake of information from different retinal locations within a single eye fixation, as is generally considered to be the case for visual object identification. We would argue that visuo-orthographic processing mimics visual object identification in this respect, and that it is only when orthographic representations start to play a role. We also draw a distinction between the slow and effortful serial processing involved in phonological recoding, compared with the faster and more automatic spelling-to-sound translation that develops with exposure to print.
ring contiguous letter combinations, such as multi-letter graphemes and affixes, independently of eye fixation location in the word. The development of a parallel version of this fine-grained orthographic coding is particularly important for the extraction of suffixes or rhymes, for which the positions of the component letters are defined with respect to word endings (e.g., Treiman, Mullenix, Bijeljac-Babic, & Richmond-Welty, 1995). Furthermore, we follow Hutzler, Ziegler, Perry, Wimmer, and Zorzi’s (2004) proposal that the associations established between sublexical orthographic and phonological representations (such as graphemes and phonemes) are initially acquired via supervised learning. However, this supervision can be both externally driven (via a teacher) and internally driven, by using the output of the letter-by-letter strategy to modify the mapping of the parallel orthographic code onto phonology.

Finally, Fig. 2 defines the time course of these different developmental processes. Here once again we follow the logic of Share’s (1995) self-teaching hypothesis, such that development of the direct orthographic route will lag behind development of phonological recoding. A part from the initial acquisition of a small sight vocabulary (involving the most frequently occurring words), we agree with Share and others that phonological recoding is the essential first step in reading acquisition (e.g., Ehri, 1992). As argued above, via a combination of passive exposure (implicit learning, e.g., Dufau et al., 2010) and supervision driven by the output of phonological recoding, a system for parallel letter processing is set up. Parallel letter processing then enables direct orthographic access to semantics via coarse-grained orthographic representations, plus the development of fine-grained orthographic representations involved in optimizing the automatic extraction of phonological and morphological information from print.

1.3. The present study

In the present study, five groups of children (grades 1–5 of primary education) and a group of adult readers were asked to classify letter strings as being real words or nonwords (lexical decision). While the lexical decision task is widely used with adult readers (e.g., Dufau, Grainger, & Ziegler, in press; Dufau et al., 2011), it is less commonly used in research with children. Here, the critical manipulation was on the nonword stimuli, which were intermixed with a set of words matched in length in letters to the nonword stimuli, and expected to be known by the end of 1st grade (estimated from the Manulex database – Lété, Sprenger-Charolles, & Colé, 2004). The nonwords included pseudo-homophones (e.g., trane) and their orthographic controls (e.g., trand), and transposed-letter nonwords (e.g., talbe) and their orthographic controls (e.g., tarpe). If pseudo-homophones are misclassified as real words (false positive responses) more often than non-homophonic controls, it can be inferred that participants’ responses were based on whole-word phonological representations that were activated via sublexical spelling-to-sound correspondences.\(^2\) If transposed-letter nonwords are misclassified as real words more often than double-substitution control nonwords, it can be inferred that participants’ responses were based on whole-word orthographic representations that were activated via a coarse-grained orthographic code that is less sensitive to letter order.

The developmental predictions to be tested in the present study are straightforward. Given the hypothesized existence of multiple processing routes for word identification and the hypothesized developmental time-course of these routes (Fig. 2), we expect to see strong pseudo-homophone effects in first graders that diminish with increasing age. This developmental pattern should reflect a decrease in reliance on a phonological recoding strategy. Even if more automatic phonological processing gradually takes over in the course of development, its influence is thought to be relatively minor compared with the influence of phonological recoding. This leads us to predict a rather rapid drop in the size of pseudo-homophone effects in the first years of reading acquisition, during which the process of phonological recoding is gradually abandoned. This should be followed by a relative stabilization in the size of the effects as more automatic phonological processes kick-in and compensate for the diminished role of phonological recoding.

As concerns the transposed-letter nonwords, on the other hand, we predict that transposed-letter effects should initially increase in size following the development of coarse-grained orthographic coding. Thus, in an early developmental time window (grades 1–2), there should be an opposing trend for the two marker effects. Pseudo-homophone effects should decrease while transposed-letter effects should increase. To further clarify the reasoning here, it is important to note that phonological recoding requires precise information about letter positions in order to accurately align letters in complex graphemes and graphemes in words. Therefore, beginning readers who rely mainly on phonological recoding for word identification should show small transposed-letter effects and large pseudo-homophone effects. As phonological recoding becomes replaced or supplemented by more parallel orthographic processing, including coarse-grained coding, we should see a trade-off between reduced pseudo-homophone effects and increased transposed-letter effects. After grade 2, whole-word orthographic representations are thought to gain in stability and precision and, from there on, both effects should decrease in size as participants can reject both types of nonwords (pseudo-homophones and transposed-letter nonwords) on the basis of a mismatch with whole-word orthographic representations. Even if whole-word orthographic representations continue to be activated by coarse-grained orthography, their connectivity with fine-grained orthography enables nonwords to be more accurately rejected on the basis of this information. Statistically speaking, we predict two-way interactions between the effects of grade and pseudo-homophone status and between grade and transposed-letter status. Most important is that we predict a triple interaction between grade and pseudo-homophone and transposed letter effects, reflecting the different developmental trajectories of these two effects.

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\(^2\) Note that such phonological influences could be due to either the phonological recoding route shown in Fig. 2, or due to access to sublexical phonology via fine-grained orthographic representations.
Note that the prediction of an initial increase in the size of transposed-letter effects is a key prediction of the multiple-route model, since most accounts of reading acquisition would predict a gradual decrease in the size of transposed-letter effects with reading experience, via an increase in the precision with which orthographic knowledge is represented. Under one specific hypothesis, the lexical tuning hypothesis (Castles, Davis, Cavaulet, & Forster, 2007), orthographic representations would initially be broadly tuned, with only approximate knowledge of letter identities and positions, thus producing maximal effects of letter transpositions. With an increase in vocabulary size, orthographic representations become more and more finely tuned in order to permit accurate discrimination between words. This fine-tuning of orthographic representations should lead to a decrease in letter transposition effects as reading acquisition develops, as argued by Castles, Davis, and Leecher (2007). Alternatively, according to some accounts of orthographic processing (Norris, Kinoshita, & van Casteren, 2010), transposed-letter effects reflect the noisy operation of general-purpose position-coding mechanisms, and therefore should not be influenced by reading development.

In sum, according to the multiple-route account of reading acquisition, we should see a rapid reduction in the size of pseudo-homophone effects over the first years of reading acquisition, accompanied by an increase in the size of transposed-letter effects. Although a reduction in the size of pseudo-homophone effects is expected on the basis of general accounts of reading acquisition according to which phonological recoding is gradually replaced by direct orthographic access (e.g., Ehri, 1992; Share, 1995), the claim that the reduction of the pseudo-homophone effect should be accompanied by an increase in the size of transposed-letter effects is a strong prediction of our specific approach.

2. Method

2.1. Participants

Three hundred and thirty-four children were pre-tested in June, at the end of their school year: 70 were 1st graders, 68 were 2nd graders, 56 were 3rd graders, 60 were 4th graders, and 50 were 5th graders. Participants retained in grade 1, 52 in grade 2, 37 in grade 3, 33 in grade 4, and 28 in grade 5. An additional group of 29 2nd-year psychology students at the University of Lyon were tested. They were between 19 and 23 years of age (mean age = 21 years 10 months). All were native speakers of French.

2.2. Materials

The stimuli were constructed using Manulex (Lété et al., 2004), a computerized lexical database which provides frequency-based lists of non-lemmatized (orthographic forms) and lemmatized words compiled from the 1.9 million words found in the main reading books used in French primary schools. Frequency of occurrence is given for four levels: 1st grade, 2nd grade, 3rd–5th grades, and all grades combined. To maximize the likelihood that the base-words of our pseudo-homophone and transposed-letter nonwords would be known by all the children we tested, we selected words that were high-frequency at all grade levels according to Manulex.

2.2.1. Pseudo-homophone stimuli

A set of 36 items was constructed from base-words of 4 to 6 letters (mean word frequency per million = 270, range 42–777). There were 18 pseudo-homophones that were constructed in such a way that their pronunciation, but not their spelling, was identical to the base-word (e.g., base-word: vent [wind], pronounced /v@/; pseudo-homophone: vant pronounced /v@/). Orthographic changes only involved one phoneme of the base-word, and the substitution involved replacing the grapheme in the base-word with a grapheme that is more frequently associated with the given phoneme according to sound-spelling consistency measures for French. Eighteen control nonwords were constructed to match the pseudo-homophones. These had the same level of orthographic overlap with the base-word as the corresponding pseudo-homophone, but were phonologically different from the base-word (e.g., base-word: vent [wind]; pseudo-homophone: vant; control nonword: vunt). The control nonwords and pseudo-homophones did not differ significantly in orthographic neighborhood (N) size (respectively 2.8 and 4.1 orthographic neighbors on average, F(1,34) = 1.55, p = 0.22).

2.2.2. Transposed-letter nonwords

A set of 24 items was constructed from base-words of 5 and 6 letters (mean word frequency per million = 110, range 53–164). These comprised 12 transposed-letter nonwords and their respective controls. The transposed-letter nonwords were constructed by swapping two adjacent letters (only consonants were involved in the transposition) in the real word, either the third and the fourth letter (for nine items) or the fourth and the fifth letter (three items) (e.g., base-word: table [table]; transposed-letter nonword: talbe). These 12 items were matched to controls that were constructed by substituting the transposed consonants by two other consonants (e.g., base-word: table [table]; transposed-letter nonword: talbe; control nonword: tarfe). The control nonwords and transposed-letter nonwords did not differ significantly in orthographic neighborhood size (1.3 orthographic neighbors on average for each type of nonword, F(1,22) = 0.02, p = 0.89). See Appendix for the complete set of stimuli.

3 The Alouette reading test is the most commonly used standardized reading test in France. It compares favorably with other French reading tests in terms of sensitivity, specificity, and efficiency (see Bertrand, Fluss, Billard, & Ziegler, 2010). The test involves having children read a meaningless text for 3 min in order to measure reading speed and accuracy (number of words read correctly). The reading score is typically converted into reading age.
2.3. Procedure and apparatus

Participants were seated in front of a 17" color monitor connected to a Pentium III laptop computer running DMDX software (Forster & Forster, 2003), at a viewing distance of approximately 60 cm. The stimuli were displayed in lowercase in 24-point Courier font with a 640 × 480 resolution. Participants were tested individually in a single 20-min session. Each trial consisted of the following sequence of events. Participants were first instructed to look at a fixation point ("*" intention centered on the fixation point. The target remained on the screen until participants responded by selecting the word-response (right shift key) or the nonword-response (left shift key on the keyboard). Participants were instructed to respond as quickly and as accurately as possible. Speed was emphasized in order to encourage spontaneous responses. Targets were presented in a different random order to each participant. There was one block of 24 practice trials followed by five blocks of 24 experimental trials, with a short break in between blocks.

Children were tested in groups of four by two experimenters in the same room. The lexical decision task was explained by an experimenter who gave the children examples of words and nonwords written on paper, and asked them to respond together and orally if the letter string was a word or a nonword. The experimenter let the children express their opinion before providing the correct response. Examples were given until the experimenter believed that children had correctly understood the lexical decision task. During the practice trials, experimenters were watchful about the position of children in front of the screen, and their correct use of the keyboard to give their response.

3. Results

As in most developmental studies on reading acquisition (e.g., Goswami et al., 2001), we focused on accuracy as the main critical dependent variable because the high percentage of errors in grades 1 and 2 in some conditions (>50%) makes the use of reaction time (RT) data less reliable. For reasons of completeness, we nevertheless report and analyze RT data with the exception of grade 1, for which error rates were above 75% in some conditions.

RTs were inverse transformed (1/RT) before analysis in order to normalize the RT distributions and reduce effects of outliers (Ratcliff, 1993). The RT data were analyzed using linear mixed effects models (Baayen, Davidson, & Bates, 2008), and the error data were analyzed using logistic mixed effects models (Jaeger, 2008).

3.1. Overall analysis

3.1.1. Error data

Percent errors to the pseudo-homophones, transposed letter nonwords and their respective controls are shown in Table 1.

The individual responses for each item (correct/error) were entered into a Generalized Linear Mixed Effect analysis for binary distributions (GLIMMIX procedure of SAS version 9.1) treating participants and items as random factors. Grade (1–5 and adults), Type of Manipulation (pseudo-homophone vs. letter transposition) and Condition (experimental vs. control) were entered as fixed factors. There were main effects of Grade (F(5,13593) = 50.96, p < .0001), Type of Manipulation (F(1,13593) = 189.08, p < .0001), and Condition (F(1,13593) = 319.94, p < .0001). Most importantly, the predicted triple interaction between the effects of Grade, Type of Manipulation and Condition was significant (F(5,13593) = 8.52, p < .0001). The triple interaction is illustrated in Fig. 3, which plots the distinct developmental trajectories of pseudo-homophone and transposed-letter effects. In follow-up analyses, to be presented in the following Sections 3.2 and 3.3, this triple interaction is broken down by examining pseudo-homophone and transposed-letter effects separately.

3.1.2. RT data

RTs to the pseudo-homophones, transposed-letter nonwords and their respective controls are shown in Table 2. A Linear Mixed Effect analysis (MIXED procedure of SAS version 9.1) was performed on the inverse RT data after excluding the data from the 1st graders (see above). Participants and items were treated as random factors. Grade (2nd–5th grade, adults), Type of Manipulation (pseudo-homophone vs. letter transposition) and Condition (experimental vs. control) were treated as fixed factors. There were main effects of Grade (F(4,173) = 113.98, p < .0001), Type of Manipulation (F(1,8533) = 45.42, p < .0001) and Condition (F(1,8531) = 273.08, p < .0001). There

<table>
<thead>
<tr>
<th>Condition</th>
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<td></td>
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<td>20.87</td>
<td>16.07</td>
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<td></td>
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<td>0.5</td>
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Table 1
Mean percentage of error for pseudo-homophones (PsH), transposed-letter nonwords (TL) and their respective controls across grades (standard errors in parentheses). The difference between PsH and controls reflects the coarse-grained orthography effect. This difference is also reported in terms of standardized effect sizes (η²).
were significant interactions between Grade and Condition \((F(4,8531) = 3.40, \ p = .0088)\) and Grade and Type of Manipulation \((F(4,8533) = 6.88, \ p < .001)\). The interaction between Condition and Type of Manipulation just failed to reach significance \((F(1,8531) = 3.36, \ p = .067)\). The triple interaction was not significant \((p = .18)\).

### 3.2. Pseudo-homophone effect

To analyze the pseudo-homophone effect by itself, the individual responses (correct/incorrect) were entered into a Generalized Linear Mixed Effect analysis for binary distributions (GLIMMIX procedure in SAS version 9.1) with participants and items as random factors and Grade and Homophone Status as fixed factors. There was a main effect of Grade \((F(5,8068) = 62.30, \ p < .0001)\) and a main effect of Homophone status \((F(1,8068) = 379.46, \ p < .0001)\). Significantly more errors were made to pseudo-homophones than to control nonwords (44.14% and 17.98%, \*\*\* \(p < .0001)\). Error rate decreased with age and significantly more errors were made to transposed-letter nonwords than to the corresponding controls (18.67% and 9.06%, \*\*\* \(p < .0001)\). Importantly, there was a significant interaction between the effects of Grade and Letter Transposition \((F(5,5295) = 4.09, \ p = .001)\).

### 3.4. Regression analyses

To further investigate the developmental trajectories for both the pseudo-homophone and the transposed-letter effect, we performed regression analyses for the complete set of 334 children that were tested in this study. The net pseudo-homophone effect (i.e., pseudo-homophone minus control) and the net transposed-letter effect (transposed-letter nonword minus control) on errors served as dependent variables while the reading age of each child (as measured by the Alouette reading test) served as independent variable. We tested nonlinearity by adding a quadratic term to the regression. The analysis revealed a linear relation between reading age and the size of the pseudo-homophone effect \((R^2 = .13, \ \beta = -4.52, t(302) = -6.72, \ p < .0001)\). The quadratic relation was not significant \((p = .22)\). Concerning the effects of transposed-letters, the linear relation between reading age and effect size was not significant \((p = .94)\) but the quadratic relation was \((R^2 = .02, \ \beta = -6.3, t(301) = -2.45, \ p = .015)\). The corresponding scatter plots and regression lines are shown in Fig. 4.

In order to provide a more detailed picture of the critical initial phase of reading development, a followed-up regression analysis was performed on a group of children with a reading age below 9 years \((N = 203)\). Visual inspection of the scatter plots shown in Fig. 4 suggests a qualitative shift in the pattern of pseudo-homophone and transposed-letter effects at around this point. These follow-up analyses revealed a significant linear decrease in the size of pseudo-homophone effects with increasing reading level \((R^2 = .04, \ \beta = -5.89, t(201) = -2.88, \ p < .005)\), and a significant

### 3.3. Transposed-letter effect

To analyze the transposed-letter effect by itself, we performed the same mixed effect analysis as above with participants and items as random factors, and Grade and Letter Transposition as fixed factors. There was a main effect of Grade \((F(5,5295) = 19.95, \ p < .0001)\) and a main effect of Letter Transposition \((F(1,5295) = 82.56, \ p < .0001)\). Error rate decreased with age and significantly more errors were made to transposed-letter nonwords than to the corresponding controls (18.67% and 9.06%, \*\*\* \(p < .0001)\). Importantly, there was a significant interaction between the effects of Grade and Letter Transposition \((F(5,5295) = 4.09, \ p = .001)\).
linear increase in the size of transposed-letter effects ($R^2 = .03, \beta = 3.94, t(201) = 2.30, p < .05$).

4. Discussion

Children in grades 1–5 of primary education in France, plus a group of University students, were tested in a lexical decision task in which the key manipulation concerned the nature of the nonword stimuli. We compared performance to nonwords that were homophonic with real words (pseudo-homophones, e.g., trane) with non-homophonic control nonwords that were carefully matched in terms of their orthographic overlap with the same word as the pseudo-homophone (e.g., trand). We also compared performance to nonwords formed by transposing two inner letters of a real word (e.g., talbe) with performance to nonwords formed by substituting two letters of the same word with different letters (e.g., tarpe). These two manipulations were designed to test the predictions of a multiple-route model of learning to read according to which: (i) word reading in beginning readers is principally achieved via phonological recoding and (ii) as reading skills develop, this initial predominance of phonological recoding is gradually replaced by an increasing role for direct orthographic access (coarse-grained orthography) accompanied by fine-grained orthographic processing that enables fast automatic computation of sound from print.

Within this theoretical framework, pseudo-homophone effects seen in the first years of reading acquisition were taken as a signature of phonological recoding, thought to be the principal means by which beginning readers map letters onto meaning (Share, 1995). Effects of transposed-letter nonwords were taken as a signature of coarse-grained orthographic processing that is used in the parallel mapping
of letters onto whole-word orthographic representations and from there onto meaning (see Fig. 2). We therefore expected to see very strong effects of pseudo-homophones in 1st graders that rapidly diminish as reading expertise increases, whereas transposed-letter effects were expected to initially increase in size as reading expertise increases. Fig. 3 shows the evolution of pseudo-homophone and transposed-letter effects as a function of grade. We can clearly see in Fig. 3 that pseudo-homophone effects rapidly diminished in size with increasing age. This was confirmed statistically by a significant interaction between Grade and Homophone Status. Furthermore, a regression analysis of the size of the pseudo-homophone effect as a function of reading age revealed a significant linear decrease in the size of the effect as reading age increased (Fig. 4).

On the other hand, we expected to see an initial growth in the size of transposed-letter effects that would eventually stabilize with increasing age. The summary of our results shown in Fig. 3 indeed shows a small increase in size of transposed-letter effects from grade 1 to grade 2, with the effect then remaining relatively stable up to 4th grade and finally decreasing in size. This was confirmed statistically by a significant interaction between Grade and Transposition. A regression analysis of transposed-letter effects and reading age also revealed a significant quadratic relation between these two variables, as shown in the bottom panel of Fig. 4. Furthermore, a regression analysis excluding the results of children with the highest reading age revealed a significant linear increase in transposed-letter effects as reading level increased. This contrasted strikingly with the strong decrease in pseudo-homophone effects that accompanied an increase in reading-level in the same group of children. Therefore, both the group analysis using grade level and the regression analysis using an individual measure of reading age revealed distinct developmental trajectories for the pseudo-homophone and transposed-letter effects. These distinct developmental trajectories were confirmed statistically by the significant triple interaction between Grade, Type of Manipulation (pseudo-homophone vs. letter transposition), and Condition (experimental vs. control).

The size of the pseudo-homophone effect in first graders and its rapid decrease with increasing age is taken as evidence for the initial predominance of a phonological recoding strategy that gradually diminishes as direct orthographic access to meaning is reinforced. One previous study using a longitudinal design revealed a similar pattern of pseudo-homophone effects in silent reading as a function of grade level (Sprenger-Charolles, Siegel, Béchencé, & Serniclaes, 2003). In the Sprenger-Charolles et al. study, errors to pseudo-homophones were compared to the errors made to matched orthographic control nonwords in a semantic categorization task (e.g., is this an animal?). Children were tested at the middle and end of grade 1, and at the end of grades 2–4. The error rates to the pseudo-homophones found in that study correspond remarkably well to those found in the present study using lexical decision rather than semantic categorization. However, more errors were made to the visual control stimuli compared with our study, leading to overall smaller effects of homophone status, with a maximum of 23% at the end of grade 2, and declining from then on. This is possibly due to the semantic categorization task (with relatively narrow semantic categories) providing top-down support that led children to accept stimuli that they otherwise would not have recognized as a word they knew. In any case, the developmental pattern of pseudo-homophone effects was very similar to the one found in the present study.

These results therefore provide key support for the general approach to reading development championed by Share (1995) and others (e.g., Ehri, 1992). They also provide support for the generic dual-route architecture for visual word recognition shared by models in both the DRC (Coltheart et al., 2001; Perry et al., 2007, 2010) and the PDP tradition (Seidenberg & McClelland, 1989; Plaut, McClelland, Seidenberg, & Patterson, 1996; Harm & Seidenberg, 2004). There are two pathways from orthography to meaning in this generic architecture – a direct pathway, and a pathway that is mediated by phonology. In support of this division of labor within the reading system, our results show distinct developmental trajectories for two marker effects associated with processing along one or the other pathway. What is fundamentally new in our approach, is the hypothesis that the mapping of sublexical orthography onto phonology on the one hand, and onto meaning on the other, involves different orthographic codes in the first place. This hypothesis emerged from a consideration of how some form of location-invariant sublexical orthographic representation could be derived from a lower-level location-specific orthographic code, and how the solution to this problem might be constrained by the specific nature of the computations to be performed (Grainger & Ziegler, 2011). Contrary to this approach, all prior models within the PDP and DRC traditions implement a single type of word-centered sublexical orthographic code. This unique orthographic code will have the level of precision necessary to accurately perform sublexical spelling-to-sound translation, and therefore will be unable to capture the kind of coarse-grained orthographic processing revealed by transposed-letter effects (see Grainger, 2008, for a summary of the arguments).

Our multiple read-out model shares many features with other accounts of reading acquisition, and is indeed inspired by the self-teaching hypothesis of Share (1995) and related theoretical work. It did, however, lead to one prediction that does not naturally follow from alternative accounts of reading development. This is the predicted increase in transposed-letter effects in the initial phase of learning to read. In line with the self-teaching hypothesis, we agree that phonological recoding is gradually replaced by some form of direct orthographic access. What is novel in our approach is that direct orthographic access is thought to involve a relatively coarse-grained orthographic code, and it is the development of this coarse-grained code that leads to the observed increased sensitivity to letter transpositions. An alternative account of orthographic development, the lexical tuning hypothesis (Castles, Davis, & Lechter, 2007; Castles et al., 2007), predicted, on the contrary, that orthographic representations become more and more fine-tuned during reading acquisition. That is, more and more precise information is available about letter identities and letter positions in order to accurately iden-
tify words within an increasingly dense neighborhood of orthographically similar words. This hypothesis predicted that transposed-letter effects should show the same pattern as pseudo-homophone effects, that is, a decrease in size as reading experience increases.

In the multiple-route model, direct orthographic access not only requires the development of a system that enables parallel independent letter processing, but it also involves the development of coarse-grained orthographic coding, where priority is given to informative subsets of letter identities while minimizing the importance of precise letter order information (Dandurand et al., 2011). This mechanism provides just enough information to enable accurate word identification, while minimizing processing, and retaining enough flexibility to be robust to noisy input. It is this specification of direct orthographic access that led us to predict that transposed-letter effects, contrary to pseudo-homophone effects, should initially increase in size in the earliest stages of reading acquisition. This is because transposed-letter effects should be less evident prior to the establishment of direct orthographic access, since phonological recoding requires precise letter position coding. The results of the present study revealed such an initial increase in the size of transposed-letter effects in children in grades 1–2.

The fact that transposed-letter effects were already near their maximum in 2nd graders is in line with prior research examining such effects using the masked priming paradigm and the lexical decision task (Acha & Perea, 2008; Castles, Davis, Cavalot, et al., 2007; Castles, Davis, & Lechter, 2007). In line with our findings, Castles, Davis, Cavalot, et al. (2007) and Castles, Davis, and Lechter (2007) found that transposed-letter priming effects were larger in 3rd graders (the youngest children tested) than in a group of adult participants. A similar pattern was found by Acha and Perea (2008), who found maximal effects of transposed-letter primes in 3rd graders (again the youngest children tested) that diminished in size in 6th graders and university students. These results all suggest that the process of direct orthographic access is rapidly established once reading acquisition is initiated. This is line with the evidence that orthographic learning via Share’s (2004) self-teaching mechanism can take place rather quickly, after only a limited number of exposures to the novel orthographic forms (Bowey & Muller, 2005; Reitsma, 1983).

This is also in line with the evidence that parallel letter processing is already in place by the end of grade 1, at least for the best readers. For example, studies measuring eye movement patterns in beginning readers show that there is a sharp increase in the length of progressive saccades, accompanied by a sharp drop in fixation durations from 1st to 2nd graders (McConkie et al., 1991). Furthermore, first graders already show the inverted U-shaped pattern of word identification accuracy as a function of within-word fixation position that is characteristic of parallel letter processing (Aghababian & Nazir, 2000; Ducrot, Lété, Sprenger-Charolles, Pynte, & Billard, 2003). That is, word identification accuracy in conditions of limited exposure duration is best when eye fixation is near the centre of the word, and drops as fixation location moves from the centre to the beginning or the end of the word, with an advantage for leftward positions (in languages read from left-to-right).

On the other hand, Aghababian and Nazir (2000) did find a large effect of word length on word identification accuracy in first graders, that gradually diminished as reading experience increased. This general pattern has been replicated in other paradigms used to measure silent reading (Acha & Perea, 2008; Bijeljac-Babic, Millogo, Farioli, & Grainger, 2004), and could be a reflection of the diminishing role of phonological recoding in silent reading as a function of reading expertise, much like the pseudo-homophone effects found in the present study. Within our multiple route model of learning to read (see Fig. 2), phonological recoding involves sequential letter-by-letter processing, and this predominantly serial process gradually gives way to more parallel processing, both in terms of the mapping of orthography onto semantics and in terms of mapping orthography onto phonology during silent reading. Although length effects can result from parallel processing (notably via the influence of correlated factors), they are generally taken as a clear-cut signature of serial processing (for discussion, see Perry et al., 2007). The fact that word length effects do persevere until quite late during reading acquisition could be an indication that phonological recoding continues to be used as a necessary strategy for dealing with new words, and therefore conjointly influencing word recognition along with the processing performed by the other routes of our multiple route model.

Another key feature of our approach is that phonological recoding, as implemented in the very initial phase of reading acquisition, is gradually replaced by an alternative mechanism for automatic translation of orthographic information into a sublexical phonological code. This implies that although phonological influences do diminish with increasing reading experience, they never completely disappear, as seen in the results of the adult participants in the present study. Indeed, in 5th grade children the size of the pseudo-homophone effect is still greater than the size of the transposed-letter effect, again attesting to the key role played by phonological information throughout the process of reading acquisition. According to our model, however, the nature of such phonological influences changes during the course of reading acquisition. One clear prediction of our approach is that automatic phonological influences on silent word reading, such as those revealed by masked phonological priming for example, should not be visible in the earliest phases of reading acquisition. This is because such automatic, phonological influences depend on the setting-up of parallel letter processing plus the mechanisms that enable the transformation of this type of orthographic code into a sublexical phonological code. In line with this prediction, prior research has shown that phonological priming effects are stronger in sixth graders compared with second graders when the prime duration is sufficiently limited, hence revealing more automatic processes (Booth, Perfetti, & MacWhinney, 1999).

Finally, one other feature of our theoretical framework is that it provides a means of distinguishing between two types of morphological influence on visual word recognition: morpho-orthographic and morpho-
The segmentation of morphologically complex words (e.g., “farmer”) and pseudo-complex words (e.g., “corner”) into their component morphemes (e.g., “farm” + “er”), even when these elements do not function as morphemes in the word (e.g., “corn” + “er”). Evidence for such morpho-orthographic segmentation has also been found with morphologically complex non-word stimuli (e.g., “rapidify”; Longtin & Meunier, 2005), and is therefore thought to arise prior to contact with whole-word representations. Morpho-orthographic segmentation requires fine-grained orthographic information, that is knowing exactly which letters are next to which, in order to extract co-occurring contiguous letter sequences such as affixes. Morpho-semantic processing, on the other hand, is hypothesized to be driven by the connectivity established between members of the same morphological family, that share both form and meaning, and is therefore thought to arise after the processing of whole-word form representations (Giraudo & Grainger, 2000, 2001). Within our multiple route model, morpho-semantic processing can therefore occur via coarse-grained orthographic processing and does not depend on a fine-grained orthographic code (Grainger & Ziegler, 2011). Therefore, given that morpho-orthographic effects necessarily involve fine-grained orthographic processing, while morpho-semantic effects do not, the developmental time-course of these two effects will provide an indication of the relative speed of development of the coarse-grained and fine-grained orthographic processing routes in our model. With the growing number of recent studies examining the role of morphological factors in reading acquisition (e.g., Casalis, Dusautoir, Colé, & Ducrot, 2009; Colé, Bouton, Leuwers, & Casalis, 2012; Roman, Kirby, Parrila, Wade-Woolley, & Deacon, 2009), answers to such key questions should be available soon.

5. Conclusions

In the present work we have described a multiple-route model of learning to read words that specifies the different types of orthographic and phonological processes involved in the shift from novice to skilled word reading. Our theorizing builds on the pioneering work of Share (1995), whereby phonological recoding provides reading. Our theorizing builds on the pioneering work of Grainger (1995). Aspects of the visual processes underlying word recognition. Journal of Experimental Child Psychology, 76, 123–150.

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Appendix A

<table>
<thead>
<tr>
<th>Base-words</th>
<th>Pseudo-homophone</th>
<th>Orthographic control</th>
<th>Number of letters</th>
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References


