



Developmental dyslexia and the dual route model of reading: Simulating individual differences and subtypes [☆]

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Abstract

Developmental dyslexia was investigated within a well-understood and fully specified computational model of reading aloud: the dual route cascaded model (DRC [Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J.C. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, 108, 204–256.]). Four tasks were designed to assess each representational level of the DRC: letter level, orthographic lexicon, phonological lexicon, and phoneme system. The data showed no single cause of dyslexia, but rather a complex pattern of phonological, phonemic, and letter processing deficits. Importantly, most dyslexics had deficits in more than one domain. Subtyping analyses also suggested that both the phonological and surface dyslexics almost always had more than a single underlying deficit. To simulate the reading performance for each individual with the DRC, we added

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noise to the model at a level proportional to the underlying deficit(s) of each individual. The simulations not only accounted fairly well for individual reading patterns but also captured the different dyslexia profiles discussed in the literature (i.e., surface, phonological, mixed, and mild dyslexia). Thus, taking into account the multiplicity of underlying deficits on an individual basis provides a parsimonious and accurate description of developmental dyslexia. The present work highlights the necessity and merits of investigating dyslexia at the level of each individual rather than as a unitary disorder.

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1. Introduction

Reading is a highly complex task that relies on the integration of visual, orthographic, phonological, and semantic information. The complexity of this task is clearly illustrated in recent computational models of reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Harm & Seidenberg, 1999; Perry, Ziegler, & Zorzi, 2007; Plaut, McClelland, Seidenberg, & Patterson, 1996; Zorzi, Houghton, & Butterworth, 1998). For example, in the dual route model of reading aloud, the *DRC* (Coltheart et al., 2001), the reading process is fully specified as a series of interacting stages going from letter feature detection to phonological output processes. Reading aloud is achieved via two major routes: the lexical orthographic route and the non-lexical phonological route (see Fig. 1). The lexical route is necessary for the correct pronunciation of irregular words, while the nonlexical route is necessary for the pronunciation of novel words and nonwords. Accurate attentional, visual and low-level orthographic processing are necessary for normal reading via either route. The dual route model has been tested in numerous studies (Coltheart & Rastle, 1994; Rastle & Coltheart, 1999; Ziegler, Perry, & Coltheart, 2000; Ziegler, Perry, & Coltheart, 2003).

Reading impairments (dyslexia) within the dual-route framework can stem from deficits in either lexical or nonlexical processes, or a combination of the two. The idea of two representationally independent routes has been supported by the famous double dissociation between acquired *phonological* or acquired *surface* dyslexia (Coltheart, 1985). Phonological dyslexia is a condition in which after brain damage a previously skilled reader has a selective deficit in reading nonwords aloud (e.g., Funnell, 1983). Surface dyslexia is a condition in which after brain damage a previously skilled reader has a selective deficit in reading irregular words aloud (e.g., see MT, Behrmann & Bub, 1992; or KT, McCarthy & Warrington, 1986).

In contrast to acquired dyslexia, which results from a neural insult to a fully developed system, *developmental dyslexia* is a disorder that prevents the developing reading system from becoming efficient and automatized. Children with developmental dyslexia suffer from severe reading problems despite normal intelligence and teaching, and in the absence of any obvious sensory deficit (Snowling, 2000). While research on skilled reading has increasingly focused on the complex and dynamic

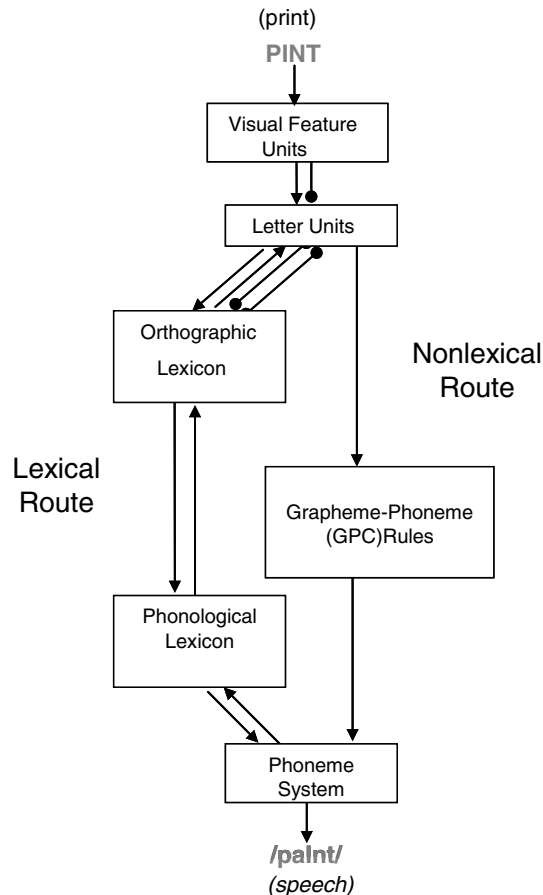


Fig. 1. Architecture of the DRC model (Coltheart et al. 2001). For an implementation in French see Ziegler et al. (2003).

interaction between various processes involved in reading (Van Orden, Jansen op de Haar, & Bosman, 1997), research in dyslexia has often strived to find a single unique deficit responsible for developmental dyslexia, for example, a *cerebellar* deficit (Nicolson, Fawcett, & Dean, 2001), a *rapid temporal processing* deficit (Tallal & Piercy, 1973), a *magnocellular* deficit (Stein & Walsh, 1997) or a *phonological* deficit (Snowling, 2001). There are in fact comparatively few studies that have investigated the relative importance of different deficits using the same population (for notable exceptions, see Ramus et al., 2003; White et al., 2006).

In the present research, we investigated developmental dyslexia in the context of the dual route model of reading (Coltheart et al., 2001). Rather than trying to isolate a single deficit, our aim was to jointly investigate all component processes of reading, as specified and implemented within the DRC model. We were interested in finding

out which stages of the DRC model contribute to explaining developmental dyslexia, and how the different explanations compare to one another. For example, we know that some children with dyslexia have difficulties using the lexical procedure (Castles & Coltheart, 1993; Valdois, Bosse, & Tainturier, 2004). However, it is not always clear whether this deficit is due to impaired letter identification or impaired access to the orthographic lexicon. Similarly, most dyslexic children have phonological deficits (e.g., de Jong & van der Leij, 2003; Manis et al., 1997; Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004; Swan & Goswami, 1997; White et al., 2006). However, it is not always clear whether these deficits only affect the nonlexical route (grapheme-to-phoneme conversion) or also the lexical route (access to the phonological lexicon).

To investigate potential deficits at each representational level of the model, we designed tests that allowed us to assess the functioning of each level. Importantly, these tests did not rely on irregular word or nonword reading, because, as we have argued above, word and nonword reading always involve more than one processing level (e.g., nonword reading requires not only phonological processes but also letter perception). If we know which levels are deficient for each participant, this information can ultimately be used to simulate dyslexia for each individual.

To investigate position-specific letter processing and the functioning of the orthographic lexicon, we used a letter search task, in which participants had to identify whether a pre-specified target letter was present in an unpronounceable consonant string (e.g., FXVRN) or a word (Ziegler & Jacobs, 1995; Ziegler, Van Orden, & Jacobs, 1997). Looking at letter search performance in unpronounceable consonants allows us to test the efficiency of letter processing without any lexical activation. To investigate the functioning of the orthographic lexicon, we used the *word superiority effect*. The word superiority effect refers to better identification of a target letter when it is embedded in real words than when it is embedded in nonwords (Reicher, 1969). In classic word recognition models, the word superiority effect is modeled by assuming either feedback from the orthographic lexicon (McClelland & Rumelhart, 1981) or the joint integration of letter-level and word-level orthographic information (Grainger & Jacobs, 1994). In both cases, the existence of a word superiority effect necessitates relatively efficient access to the orthographic lexicon. Indeed, previous work has shown that dyslexic children with severe phonological problems can show a normal word superiority effect (Grainger, Bouttevin, Truc, Bastien, & Ziegler, 2003), which suggests that orthographic access is possible even when phonological processing is impaired (Coltheart & Coltheart, 1997).

To test access to the phonological lexicon, we used a computer-controlled picture naming task. In the picture naming task used here, participants were asked to produce the names of five objects that were repeatedly displayed on the computer screen. This task requires rapid access to phonological representations (Glaser, 1992; Swan & Goswami, 1997; Wolf & Bowers, 1999) while obviously not requiring orthographic processes or grapheme-to-phoneme conversion. We used repetition of the same five objects because previous research has shown that children with dyslexia show strong deficits when a small number of objects are used repeatedly (Brizzolara et al., 2006; Denckla & Rudel, 1974; Di Filippo et al., 2005; Manis, Seidenberg, & Doi, 1999;

McCrorry, Mechelli, Frith, & Price, 2005; Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000).

Finally, to test the efficiency of the nonlexical route, which, according to DRC, is based on grapheme–phoneme-conversion (GPC), we used a task in which participants had to analyze the phonological similarity of phonemes either at the beginning or the end of spoken words. This task measures the capacity to detect and manipulate phonemes while not requiring orthographic or visual-attentional processes. Although phoneme matching does not directly measure the GPC procedure, the claim is that meta-linguistic awareness of individual phonemes is necessary to create grapheme–phoneme mappings (Hulme, Caravolas, Malkova, & Brigstocke, 2005). Despite our efforts to design tasks that tap only one component, it is fair to say that it is probably impossible to design tasks that “cleanly” measure a single component. Obviously, each task will require more than a single process (e.g., object naming also requires visual encoding and articulatory output processes). However, letter search in nonword strings, word superiority effects, rapid naming of single objects, and phoneme matching are sufficiently tied to a single component of the DRC model to make model-based explorations of dyslexia possible.

In summary, the goal of the present study was to provide a relatively complete model-based description of developmental dyslexia which should lead to a better understanding of the deficits underlying this condition. Our main predictions were as follows: if the core deficit in developmental dyslexia were phonological, as suggested by many studies (e.g., Bradley & Bryant, 1983; Ramus et al., 2003; Scarborough, 1998; Ziegler, Pech-Georgel, George, Alario, & Lorenzi, 2005), we should find deficits in both rapid access to the phonological lexicon and in phoneme matching. If the core deficits were related to letter string processing (Bosse, Tainturier, & Valdois, 2007; Hawelka & Wimmer, 2005; Hawelka, Huber, & Wimmer, 2006; Stein & Walsh, 1997; Valdois et al., 2004), we should find deficits in letter perception in nonword strings. Finally, if there were considerable variability across subjects (Seymour, 1994), we should find different combinations of deficits involving the various processing levels (visual, orthographic, and phonological).

Previous research has identified two prominent subtypes of dyslexics who have relatively selective deficits when reading irregular words and nonwords (Castles & Coltheart, 1993; Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996; Sprenger-Charolles, Cole, Lacert, & Serniclaes, 2000, but see Griffiths & Snowling, 2002). In particular, surface dyslexics are poor at irregular word but relatively normal at nonword reading. In contrast, phonological dyslexics are poor at nonword but relatively normal at irregular word reading. It was of interest to us to investigate whether the above identified subtypes could be given a coherent conceptual interpretation based on the ancillary component tasks (for a similar approach, see Griffiths & Snowling, 2002). According to dual route hypotheses, surface dyslexics should show larger deficits on the lexical route (access to the orthographic and phonological lexicons), whereas phonological dyslexics should show larger deficits on the nonlexical route.

With the individual deficit data and the reading data in hand, our goal was to simulate reading impairment with the DRC using a participant-based modeling

approach (Dell, Schwartz, Martin, Saffran, & Gagnon, 1997). That is, we attempted to simulate the performance of each individual by adding noise to those component processes that were impaired in a given individual. Such a participant-based modeling approach is novel to the field of developmental dyslexia.

2. Methods

2.1. Participants

Twenty-four dyslexic children (9 girls, 15 boys) were recruited from the neuropsychiatric care unit of the University hospital “La Timone” in Marseille, France. They were on average 9;10 years old (range: 8;1–12;1). They were native speakers of French and came from middle-class suburban areas of Marseille. They were included in the study if their reading age was at least 18 months below the age norm on a standardized reading test (Alouette, Lefavrais, 1965). They were excluded from the study if their nonverbal IQ was below 85 on the *WISC-III* (Wechsler, 1996), if they were in the pathological range on the inattention/hyperactivity scale of the *Child Behavior Checklist (CBCL, Achenbach & Rescorla, 2001)*, if they had any obvious neurological or sensory deficits, or if they were 3 SDs below the norm on at least two subtests of a spoken language test (*L2MA, Chevrie-Muller, Simon, Fournier, & Brochet, 1997*).

Twenty-four normally developing children (12 boys, 12 girls) were matched for chronological age with the dyslexic children. They were on average 9;10 years old (range: 8;0–12;2). None of them had a history of written or spoken language impairment. They were native speakers of French and came from the same middle-class suburban area as the dyslexics. The study was conducted with the understanding and consent of the participants and their parents.

2.2. Tasks

2.2.1. Reading

Reading speed and accuracy were assessed by having participants read aloud 20 nonwords, 10 regular words, and 10 irregular words. Regular and irregular words were matched in terms of length and word frequency ($F < 1$) according to the LEXIQUE database (New, Pallier, Ferrand, & Matos, 2001). No frequency manipulation was performed because the regularity effect in French is present and of similar size for both low and high frequency words (Content, 1991; Ziegler et al., 2003). Nonwords were created by changing either the onset, the vowel or the coda of an existing word that was matched in terms of frequency and length to the regular and irregular words.

The items were presented at the centre of the computer screen. The experiment was controlled by the experimental software DMDX (Forster & Forster, 2003). Participants' responses were recorded with a voice key and saved as separate wave files. These files were used for error coding and latency measures. Latency was measured

from the appearance of the stimulus on the screen until the participant started to utter the response.

2.2.2. Letter search

The task was to search for a target letter embedded in a letter string. Following an initial fixation point, a target letter (e.g., “A”) appeared on the computer screen for 500 ms (milliseconds) followed by the stimulus (word or unpronounceable letter string), which stayed on the screen until the participant pressed one of the two response buttons to indicate whether the target letter was present or not in the stimulus. The stimuli were 20 five-letter words and 20 five-letter nonwords (i.e., unpronounceable letter strings). Identity and position of the target letter was matched across words and nonwords (e.g., “R” in “boire” versus “ghyrc”). To avoid visual matching strategies, target letters were presented in upper case and letter strings were presented in lower case. The dependent variables were errors and latency.

2.2.3. Picture naming

Two sets of five line drawings of familiar objects were selected (monkey, cup, skirt, lamp, and vase for the first set; ring, fly, cage, bowl, and shovel for the second one) from a French database for picture naming (Alario & Ferrand, 1999). All pictures names had a consonant–vowel–consonant (CVC) structure. There was no phonological overlap between them. For the first set of stimuli, mean name agreement was 98%. Mean familiarity was 3.2 on a 5-points scale (see Alario & Ferrand, 1999). For the second set of stimuli, mean name agreement was 97% and mean familiarity was 3.4.

The objects were displayed in the centre of the computer screen one per trial. The participant’s task was to name the object as quickly as possible. The two lists of five objects were repeated in pseudo-random order 10 times each (i.e., a total of 50 naming responses per list). During training, participants were first presented with a sheet that contained the five objects in an unspeeded naming task. This initial training allowed us to make sure that the participants were familiar with the objects and that they provided the correct name. After that, participants were trained twice in the speeded computer-based version of the task on a subset of 10 items. Following training, participants did the picture naming task twice, once using the items of list 1 and once using the items of list 2 (counterbalanced across participants). During the test, participants’ responses were recorded with a voice key. Each response was saved as a sound file. The sound files were used for off-line error coding and for the measurement of reaction times. Latency and errors were used as the dependent variables.

2.2.4. Phoneme matching

Participants were asked to assess the phonological similarity of spoken words either for the initial or the final phoneme. On each trial, three spoken CVC words were presented. Two of them shared either the initial or the final phoneme. The participants’ task was to indicate which item did not share the initial or the final phoneme. To facilitate the task, phoneme position was blocked (first position block

versus final position block). The order of blocks was counterbalanced across participants. The dependent variable was error rate.

2.3. Procedure

Dyslexic children were tested in the neuropsychiatric care unit of the La Timone hospital. Normal readers were tested in several primary schools of Marseille. All participants were tested individually on a laptop computer in a quiet room. A session lasted for an hour and 50 min, with a short break between each task. The order of tasks was counterbalanced across participants.

3. Results

The results are organized into three parts. First, for each task, we present the performance of dyslexics and controls. Then, we investigate whether there are subtypes of dyslexics in terms of surface and phonological dyslexia. Finally, we simulate reading performance of each participant with the DRC by implementing noise in those parts of the model for which a given individual showed impaired performance on the DRC component tasks.

3.1. Reading performance

Reading performance of regular, irregular, and nonwords is presented in Table 1. The individual data of all dyslexics appear in Appendix A. Word reading performance was assessed in a 2×2 analysis of variance (ANOVA) with Regularity (regular versus irregular words) and (dyslexics versus controls) as factors. The ANOVA showed main effects of Group (accuracy: $F(1,46) = 16.80$, $p < .0001$; RTs: $F(1,46) = 16.76$, $p < .0001$) and Regularity (accuracy: $F(1,46) = 35.84$, $p < .0001$; RTs: $F(1,45) = 35.97$, $p < .0001$). The interaction between Group and

Table 1
Reading performance (accuracy and latency) of dyslexics and controls

	Controls	Dyslexics	Δ	t -value
Accuracy (% correct)				
Regular	99.2 (2.8)	97.1 (5.5)	2.1	1.65
Irregular	92.5 (7.9)	68.8 (28.0)	23.7	3.99***
Nonwords	96.3 (5.8)	78.3 (17.5)	18.0	4.75***
Latency (ms)				
Regular	700 (144)	876 (235)	176	3.12**
Irregular	812 (159)	1124 (335)	312	4.11***
Nonwords	938 (188)	1186 (333)	248	3.17**

Notes. ** $p < .01$; *** $p < .001$; Δ = mean difference.
Standard deviations in brackets.

Regularity was significant (accuracy: $F(1, 46) = 13.73, p < .001$; RTs $F(1, 45) = 6.31, p < .05$). The significant interaction reflects the fact that dyslexic children showed a much stronger deficit on irregular words (Δ 24% and 312 ms) than on reading regular words (Δ 2% and 175 ms). While the interaction on the accuracy data could have been caused by a ceiling effect, this is not a problem for the latency data. Yet, even the latency exhibited a significant interaction. The nonword reading deficit was examined using a between-groups *t*-test. The difference between dyslexics and controls was highly significant (see Table 1).

3.2. DRC component tasks

The performance of dyslexics and controls on the different DRC component tasks is presented in Table 2. The deficit on each task was assessed using between-groups two tailed *t*-tests. In the letter search task in nonwords, a deficit was obtained on error rates ($t(1, 46) = 2.58, p = .013$) but not on latencies ($t(1, 46) = 1.53, p = .13$). Similarly, in the letter search task in words, a significant deficit was obtained for error rates ($t(1, 46) = 2.51, p = .013$) but not for latencies ($t(1, 46) = 1.69, p = .10$).

With respect to the efficiency of orthographic access, both dyslexics and controls showed a clear word superiority effect (better performance when target letters were embedded in words than in nonwords). The size of the dyslexics' word superiority effect was not different from that of the controls. The word superiority effect was assessed in an ANOVA with word superiority (words versus nonwords) and group (dyslexics versus controls) as factors. The ANOVA showed a significant word supe-

Table 2
Performance of the two groups of participants in the DRC component tasks

	Dyslexics	Controls	<i>z</i> -scores	<i>t</i> -value
Letter search (nonwords)				
% errors	22.29 (17.5)	13.1 (9.2)	.99	2.58**
RT	1507 (394)	1361 (250)	.58	1.53
Letter search (words)				
% errors	19.38 (14.7)	11.1 (10.5)	.79	2.51**
RT	1391 (466)	1210 (239)	.75	1.69
Word superiority [†]				
% correct benefit	2.9 (12.2)	2.1 (8.2)	.09	.41
RT benefit	116 (269)	151 (106)	.33	.58
Picture naming				
% errors	14.8 (8.8)	5.3 (3.1)	3.06	4.81***
RT	839 (145)	726 (107)	1.05	2.95**
Phoneme matching				
Initial (% errors)	27.1 (17.7)	8.1 (7.3)	2.60	4.84***
Final (% errors)	21.8 (12.9)	3.5 (4.9)	3.73	6.52***

Notes. ** $p < .01$, *** $p < .001$.

[†]Word superiority = word/nonword difference.

Standard deviations in brackets. Deficits of dyslexics are expressed in *z*-scores.

riority effect with RTs ($F(1,46) = 20.60, p < .0001$), and a marginally significant effect on error rate ($F(1,46) = 3.25, p = .078$). Most importantly, there was no significant interaction between word superiority and group (all F s < 1 , RT: $p = .56$; errors: $p = .67$) suggesting that the size of the word superiority effect was not significantly different between the dyslexics and controls. In the picture naming task, dyslexics took significantly longer to name the objects than did the controls ($t(1, 46) = 4.81, p < .0001$); they also committed more errors than the controls ($t(1, 46) = 2.95, p = .005$). Finally, phoneme matching was significantly poorer in dyslexics than controls, both at initial and final phoneme positions ($t(1, 46) = 4.84, p < .0001$ and $t(1, 46) = 6.52, p < .0001$, respectively).

Overall, dyslexic children in our study exhibited clear deficits on three predictor tasks that directly relate to processing levels in DRC. Deficits in letter search suggest problems in position-specific letter processing. Deficits in picture naming suggest impaired access to the phonological lexicon and deficits in phoneme matching suggests impairments in DRC's phoneme system. Thus, the data suggest that dyslexics have deficits both in the lexical and sublexical route as well as at a processing levels that are common to both routes (e.g., letter processing). Surprisingly, we did not find deficits in orthographic access or feedback from the orthographic lexicon (see below for a discussion of this finding).

Whilst the averaged data suggest that the dyslexics show multiple deficits as a group, it is logically possible that each individual had only a single deficit. In this case, the pattern of multiple deficits would only appear as a consequence of the averaging process. We therefore considered the individual data, and we expressed the deficits of each individual on these three tasks in terms of z -scores that reflect the difference between dyslexics and controls. z -scores were computed for all dyslexics with respect to the control mean and standard deviation. These data are presented in [Appendix A](#) (see z -score Deficits). If we take as a deficit criterion 1.65 standard deviations below the mean of the controls (i.e., a z of -1.65 which corresponds to 5% of the distribution, we can see that out of 24 dyslexics, 5 have a triple deficit, 9 have a double deficit, 6 have a single deficit, and 4 have no deficit. Interestingly, the size of the deficits varies dramatically. For example, the deficits expressed in z -scores vary between $-.22$ and -8.77 in the phoneme task, between $-.46$ and -4.73 in object naming, and between $-.07$ and -3.12 in letter search. These data suggest that, for the majority of dyslexics, reading impairment cannot be attributed to a single deficit.

3.3. Subtypes of dyslexia

Another way to search for systematic differences between individuals is to look for distinct profiles of reading impairment in terms of surface versus phonological subtypes (Castles & Coltheart, 1993; Griffiths & Snowling, 2002; Manis et al., 1996; Sprenger-Charolles et al., 2000; Stanovich, Siegel, & Gottardo, 1997). In a first step, we investigated whether we would find a reasonable number of surface and phonological dyslexics in our own data. In a second step, we investigated whether the surface and phonological dyslexics could be distinguished in terms of their underlying deficits.

In the first step, subtypes were defined using Castles and Coltheart's (1993) regression procedure, where pseudoword performance is plotted against irregular word performance (and vice versa), and the 90% confidence intervals around the regression line are determined from the control group. A child is considered a phonological dyslexic if they are below the 90% confidence interval when pseudowords are plotted against irregular words but within the 90% confidence interval when irregular words are plotted against pseudowords. Surface dyslexics are defined conversely. Note that the classification was based on accuracy data only. Latency data were not used for the classification because many dyslexics had error rates well above 50%. Due to the small number of items, such high error rates make the RT means somewhat unreliable (too few data points per cell) for the purpose of subtyping.

According to the regression procedure, 29% of the sample were surface dyslexics (7 out of 24) and 19% were phonological dyslexics (4 out of 24). The mean age of the surface dyslexics was 9;6 years (range 8;11–10;8) and that of the phonological dyslexics was 9;2 (range 8;5–10;11). As a comparison with English, using the same procedure, Castles and Coltheart (1993) found a 30% rate of surface dyslexia and a 54% rate of phonological dyslexia. Similar figures were obtained for surface dyslexia in studies by Manis et al. (1996) and Stanovich et al. (1997) who reported 33% and 22% of surface dyslexics, respectively. However, both studies found a somewhat lower rate of phonological dyslexia than Castles and Coltheart (29% in Manis et al. and 25% in Stanovich et al.). Note that there has been a considerable amount of discussion about whether chronological age controls provide the best baseline for these analyses (for an excellent review, see Stanovich et al., 1997). Although we share many of the concerns and criticisms, we were not really interested in subtypes per se but rather in using the most conventional analyses as one tool to systematically look at individual differences in our population.

In the second step, we investigated whether the above identified subtypes could be given a coherent conceptual interpretation based on the ancillary tasks, we analyzed the data independently for each subtype group. These analyses are presented in Table 3. To assess the extent to which performance on a given task is impaired, the deficits of the dyslexics were expressed in *z*-score differences with respect to the controls. Differences between surface and phonological dyslexics were assessed using *t*-tests.

As can be seen in Table 3, the strongest deficits of the surface dyslexics were found in the picture naming and in the phoneme matching tasks. Somewhat weaker deficits were found in letter search in words and unpronounceable consonant strings. The size of the word superiority on RTs was within the normal range even if its size was somewhat smaller than that of controls ($z = -0.7$). As concerns the phonological dyslexics, the strongest deficits were obtained in picture naming and phoneme matching, and weaker deficits were obtained for letter search in words and unpronounceable consonant strings. The size of the word superiority effect was again normal (positive *z*-scores indicate the absence of a deficit). Two domains could be identified, in which surface dyslexics significantly differed from phonological dyslexics. First, surface dyslexics exhibited stronger deficits in picture naming than did the phonological dyslexics. This finding suggests that surface dyslexics have a greater impairment in accessing the phonological lexicon. Second, surface dyslexics made

Table 3
Performance of the surface and phonological dyslexics on the reading and DRC component tasks

	Surface dyslexics	z-score	Phono dyslexics	z-score	Surface versus phono <i>t</i> -value
Reading accuracy (% correct)					
Regular	97.1	-0.7	95.0	-1.5	.48
Irregular	41.4	-6.4 ⁺⁺	82.5	-1.3	3.3 ^{**}
Nonwords	79.3	-2.9 ⁺	62.5	-5.9 ⁺⁺	1.8 [*]
Letter search (nonwords)					
% errors	28.3	-1.7 ⁺	26.2	-1.4	.22
RT	1424	-0.3	1723	-1.4	1.6
Letter search (words)					
% errors	27.9	-1.6	15.0	-0.4	1.9 [*]
RT	1349	-0.6	1542	-1.4	.66
Word superiority					
% correct benefit	1.4	-0.1	11.3	1.1	.95
RT benefit	74	-0.7	181	0.3	.51
Picture naming					
% errors	19.0	-4.5 ⁺⁺	12.3	-2.3 ⁺	2.1 [*]
RT	903	-1.7	788	-0.6	1.2
Phoneme matching (% errors)					
	32.1	-4.9 ⁺⁺	25.0	-3.6 ⁺⁺	.77

Notes. ⁺z-scores < -1.65; ⁺⁺z-scores < -3.0; **p* < .05; ***p* < .01.

z-scores express the difference between the dyslexics and controls on a given task.

significantly more errors than phonological dyslexics in letter search in words. In fact, surface dyslexics showed almost identical performance for letter search in words and nonwords. Such a reduced word superiority effect is suggestive of an impaired access to the orthographic lexicon. Note, however, that the present differences have to be taken with caution because of the small sample size within each subtype.

4. Discussions

The results showed that dyslexics as a group exhibited deficits in almost all of DRC's representational levels. The strongest deficits were obtained for phonological processes. The phonological deficit concerned both lexical and sublexical processes. The lexical deficit was identified by poor picture naming. It is commonly agreed that picture naming taps access to lexical phonology (Caramazza, 1997; Levelt, Roelofs, & Meyer, 1999). The sublexical phonological deficit was identified by poor phoneme matching. We have argued earlier that good phoneme representations are necessary to learn reliable grapheme-to-phoneme mappings (Hutzler, Ziegler, Perry, Wimmer, & Zorzi, 2004). The dyslexics also showed a clear letter processing deficit in words and nonwords. This latter finding is consistent with recent studies suggesting that deficits in the parallel processing of letters might play an important role in dyslexia (Bosse et al., 2007; Hawelka & Wimmer, 2005; Hawelka et al., 2006; Stein & Walsh,

1997; Valdois et al., 2004). The analysis of the individual data also showed that most participants exhibited multiple deficits and that these deficits varied considerably in size across subjects.

The analysis of the individual data in terms of selective reading deficits showed that about 30% of the participants could be classified as surface dyslexics, whereas 20% could be classified as phonological dyslexics. Surface dyslexia is often interpreted as a nonphonological deficit in the lexical route (e.g., access problems to the orthographic lexicon). However, in our study, the surface dyslexics had clear phonological deficits. First, surface dyslexics exhibited deficits in phoneme awareness, and this deficit was not significantly different from that of phonological dyslexics. This finding is different from previous studies, which typically reported poorer phonological awareness skills for phonological dyslexics than for surface dyslexics (Manis et al., 1996; Stanovich et al., 1997; but see Sprenger-Charolles et al., 2000, for a similar finding in French). We will come back to this discrepancy in Section 6.2. Second, surface dyslexics exhibited deficits in picture naming, and this deficit was significantly larger than that of the phonological dyslexics. Finally, the letter search deficit in words was larger in surface than in phonological dyslexics, which is suggestive of a small impairment in accessing the orthographic lexicon.

In summary, the performance of the surface and phonological dyslexics on the ancillary reading independent tests did not allow us to find a convincing conceptual interpretation of the subtypes in terms of *single* dissociated deficits. Rather than having a single deficit on either the lexical or nonlexical route, surface and phonological dyslexics seem to have multiple deficits in both the lexical and sublexical route. Thus, at first sight, the classification of dyslexic children into subtypes yields a relatively poor description of the dyslexic population (see also Griffiths & Snowling, 2002). Therefore, in the following section, instead of trying to simulate surface or phonological dyslexia by producing a lesion in either the lexical or nonlexical route (see for example Coltheart et al., 2001), we will use the various deficits in the ancillary tasks to predict reading performance for each individual participant. One challenging test is to see whether the individual simulations will allow us to reproduce the reading patterns of surface and phonological dyslexics without explicitly trying to simulate these subtypes.

5. Simulations with the DRC model

The goal of the present modeling work was to simulate normal and impaired reading with the French version of the DRC model (Ziegler et al. 2003). Note that this implementation is identical to the English model (Coltheart et al., 2001) apart from the fact that the nonlexical route “runs” faster in French than in English, which is due to the greater consistency of the French orthography (for a justification, see Ziegler et al., 2003).

The novelty of the present modeling approach was to use the individual deficits on the DRC component tasks as “input” to the model. That is, instead of using a uniform impairment for all dyslexics, we used the *z*-score deficits of each individual on the component tasks to decide whether an underlying process was impaired, and, if so, how much noise should be added to the system in order to simulate this impair-

ment. Impaired letter processing was estimated from the results obtained in the letter search task in nonwords. Accuracy and latency were combined to obtain a single z -score to take potential speed–accuracy trade-offs into account. This was done by averaging the accuracy and latency z -scores. Impaired access to the phonological lexicon was estimated from deficits in picture naming (again accuracy and latency were combined). Finally, deficient functioning of the phoneme system was estimated from deficits in the phoneme matching task. The z -score deficits on these three tasks are presented in [Appendix A](#).

As an illustration of this modeling approach, take the first subject from [Appendix A](#). This dyslexic child was poor at irregular word reading (20% correct) and fairly normal at nonword reading (90% correct). The z -score deficits of this child on the three main component tasks reveal that this participant had no letter processing deficit ($z = 0$) but a marked deficit in accessing the phonological lexicon ($z = -2.3$) and a strong deficit in phoneme processing ($z = -5.9$). In the simulation of this participant, we therefore added noise to two of the DRC processes: the phonological lexicon and the phoneme system (see [Fig. 1](#)). The amount of noise added was simply a linear function of the size of his/her deficits (see below).

Noise was calculated and added to every unit of the model (e.g., each lexical entry, each letter in each letter position, etc.) as follows: First, a random number was sampled from a Gaussian distribution with a mean of zero and a standard deviation of 1. Next, the number was multiplied by the parameter associated with each representational level calculated from the z -scores. Finally, the number was added to the net input of the unit (see Eqs. 3 and 6 of [Coltheart et al., 2001](#), pages 215–216). This process was repeated for each unit at each processing cycle of the model.

Data fitting was fairly simple. For each task, we found the participant with the strongest impairment. For example, suppose the strongest deficit in the phoneme task was $z = -8.0$. We then determined a noise level at the corresponding representational level that would lead to a significant drop in performance (about 50% in the present simulations). For example, a noise level of .004 in the phoneme system results in approximately 50% reading errors. This allowed us to establish an association between a z -score and a noise level. That is, a z -score of -8.0 would correspond to a noise level of .004, a z -score of -4.0 would correspond to a noise level of .002, and a z -score of -2.0 would correspond to a noise level of .001, and so on. In other words, the amount of noise at a given level was a linear function of a dyslexic's z -score at that level. This procedure was repeated for each of the three representational levels (letter level, phonological lexicon, phoneme system). The exact noise values for each level and each dyslexic are presented in the last three columns of [Appendix A](#). Positive z -scores (no deficit) were set to a noise level of zero.

5.1. Overall simulation results

Impaired reading of the dyslexic group was simulated for each participant adding noise to maximally three levels (letter processing, phonological lexicon, phoneme system) according to the noise function described earlier. The data of the control group were simulated by submitting the lists of regular/irregular words and non-

words to the original French DRC operating with the original parameter set (i.e., the *normal* model). Accuracy (% correct) and latency (number of cycles needed to produce a correct pronunciation) are given in Fig. 2.

Visual inspection of Fig. 2 showed a striking fit between the human data and the simulations both for accuracy and latency. To assess the results quantitatively, we computed the same ANOVAs that were used to analyze the human data, that is a 2×2 ANOVA with Regularity (regular versus irregular words) and Group (impaired versus normal) as factors (see Section 3.1). As in the human data, the ANOVA exhibited main effects of Group (accuracy: $F(1,18) = 27.02$, $p < .0001$; RTs: $F(1,17) = 255.94$, $p < .0001$) and Regularity (accuracy: $F(1,18) = 23.58$, $p < .0001$; RTs: $F(1,17) = 188.88$, $p < .0001$). Moreover, the interaction between Group and Regularity was significant (accuracy: $F(1,18) = 26.82$, $p < .0001$; RTs: $F(1,17) = 23.24$, $p < .0001$). The pseudoword reading deficit was significant both

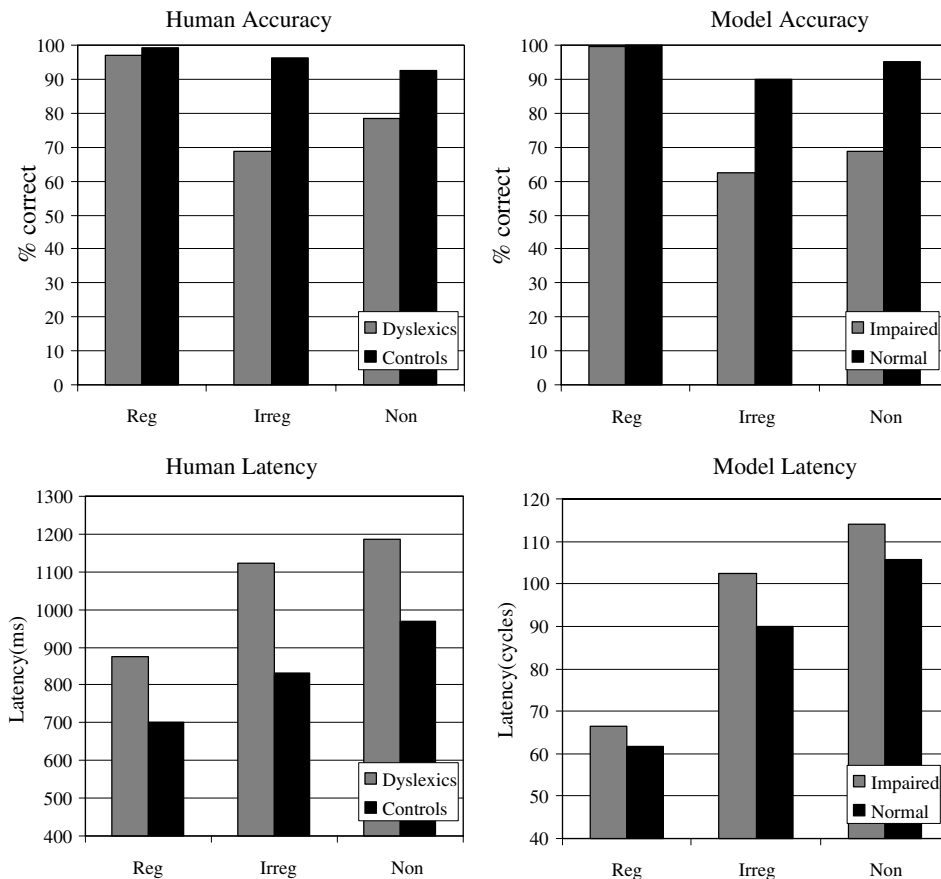


Fig. 2. Simulations of normal and impaired reading accuracy and reading speed with the French version of the DRC model. Impaired reading was simulated by using the individual deficits to determine the noise level of each of DRC's component processes.

for accuracy ($F(1, 20) = 114.09, p < .0001$) and RTs ($F(1, 19) = 64.84, p < .0001$). In summary, the present analysis showed that all main effects and interactions that were significant in the human data were also significant in the simulation data.

5.2. How good are the model fits?

The novelty of the present approach was to simulate impaired performance on the basis of the individual deficits in the ancillary tasks. Two questions seem crucial at this point: (1) how good are the individual fits and (2) could alternative noise manipulations that are not based on the individual deficits produce similar results?

With regard to the quality of the individual fits, we performed a linear regression between the accuracy rate of the 24 dyslexics on regular words, irregular words, and nonwords (72 data points) and the predictions of the model for these 24 dyslexics (72 data points). The model accounted for 48% of the variance ($F(1, 71) = 62.93, p < .0001$). As a comparison, using z -score deficits on letter search, picture naming, and phoneme matching as predictor variables, the three predictor variables together only accounted for 15% of the variance.

With regard to the issue of whether alternative noise manipulations would produce similar results, we ran 24 new simulations (one for each dyslexic) but instead of adding noise as a function of each dyslexic's deficit, we added noise randomly to the three levels that were degraded in our previous simulations (letter level, phoneme level, and phonological lexicon). For each dyslexic and each level, the noise level was picked randomly within the range of noise levels used in the previous simulations. The main idea of these new simulations was to have a baseline against which to compare the benefit of explicitly taking into account the individual deficits in the DRC component tasks. The results of these simulations are presented in Fig. 3.

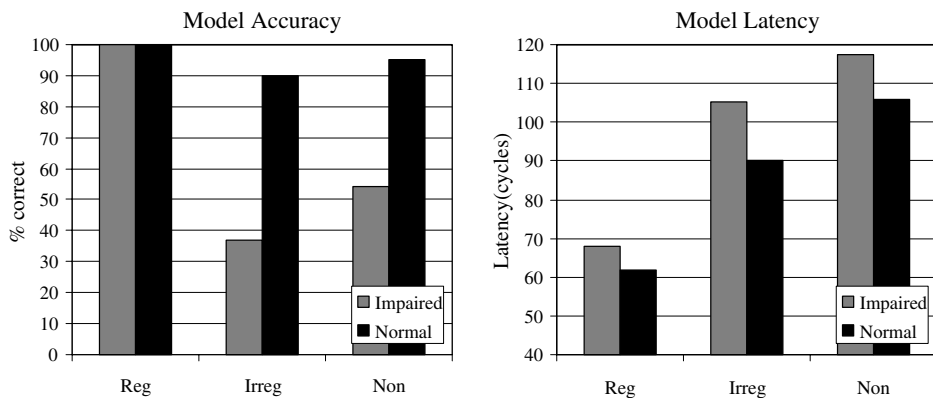


Fig. 3. DRC simulations of reading accuracy and latency with random noise added to the letter level, the phonological lexicon and the phoneme system.

As can be seen in Fig. 3, the random noise simulations reproduced the correct overall pattern. However, when the predictions of the random noise model were regressed onto the dyslexics' reading performance on regular, irregular, and nonwords, the random noise model only accounted for 8.5% of the variance ($F(1, 71) = 6.5, p < .05$), whereas the deficit-based model accounted for 48% of the variance. Thus, clearly, the strength of the individual-deficit approach must be seen in its ability to predict the reading performance of individual participants (see also section on subtypes).

5.3. Simulating different profiles of dyslexic readers

To investigate whether the simulations would capture individual profiles in Appendix A, we classified the individual data based on the accuracy data into five groups: surface, phonological, mixed, mild, and compensated dyslexics. The surface and phonological dyslexics were those who had been previously identified by the regression procedure (see Section 3.3).¹ The mixed group was composed of seven dyslexics who had a marked reading deficit but whose irregular and nonword reading were less than one standard deviation apart. The mild dyslexia group was composed of eight dyslexics whose reading scores on both irregular and nonword reading was equal or greater than 80%. Note that the mild dyslexics were still significantly different from controls with respect to nonword reading accuracy ($p < .05$) and speed of irregular word and nonword reading ($ps < .05$). Finally, three dyslexics were classified as compensated. This classification was done ad hoc based on the discrepancy between the model and the human data. That is, for these three subjects, the model predicted massive nonword reading deficits (around 30%) based on their performance in the ancillary tasks. However, their nonword reading performance was close to ceiling ($\geq 90\%$). These are very interesting cases for two reasons. First, they show that the model can be completely wrong, which suggests that the model is not overfitted. Second, the discrepancy of the simulations and the actual performance suggests that nonword reading could possibly be improved without actually improving the underlying component processes (e.g., phoneme matching). The human data and the simulation data of the first four groups are presented in Fig. 4.

As can be seen in Fig. 4, the model captures the dissociation between surface and phonological dyslexia surprisingly well. For the surface dyslexics, the model only reads 20% of the irregular words correctly even though it reads 80% of the nonwords correctly. For the phonological dyslexics, the model reads only 50% of the nonwords correctly even though it reads 70% of the irregular words correctly. This double dissociation is very close to the human data. As concerns the mixed dyslexics, the model does an excellent job because it predicts an almost identical impairment (about 40% errors) on both irregular and nonword reading. Finally, the model also produces a good fit of the mild dyslexics because irregular and nonword reading is above 80% correct. Note again that none of these patterns were explicitly fitted. They directly resulted

¹ To obtain a clearer dissociation, we only accepted those surface and phonological dyslexics whose irregular and nonword reading were at least one standard deviation apart (4 surface dyslexics and 2 phonological dyslexics).

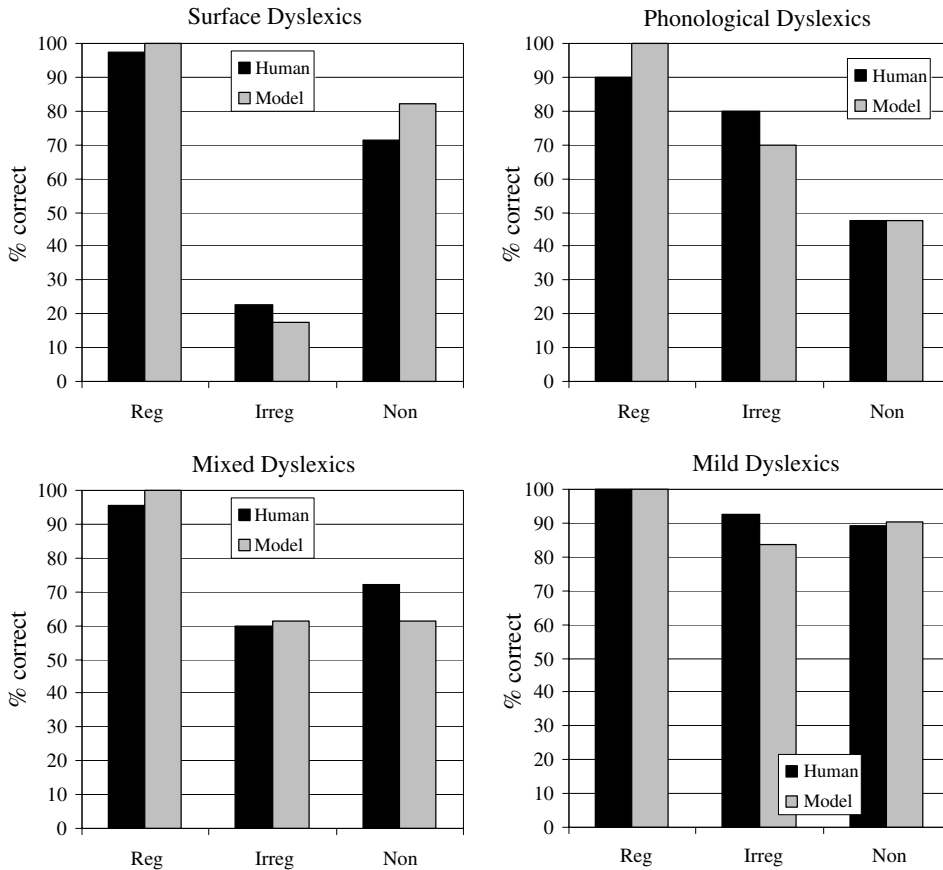


Fig. 4. Simulations of different profiles of dyslexic readers.

from the individual simulations. Note that adding the “compensated dyslexics” to their respective subtype group would only affect the fits of the “mild dyslexics” because all of the compensated dyslexics were originally in the “mild subtype” group. If we were to add these cases, the model would overestimate the deficits of the “mild dyslexics” by about 10% on irregular words and 18% on nonwords. These results show that continuous noise manipulations can reproduce common categorically defined groups in developmental dyslexia research (i.e., surface, phonological, and mixed dyslexia).

6. General discussion

The goal of this research was tripartite. First, we wanted to investigate which of the core representations and processes in the DRC (i.e., letter perception, orthographic lexicon, phonological lexicon, phoneme system) were compromised in developmental dyslexia. Second, we attempted to see whether surface and phonological

dyslexia could be given a clear conceptual interpretation on the basis of these core deficits. Finally, we wanted to know whether information about the presence and size of the underlying deficits would allow us to simulate individual reading impairments with the DRC model.

6.1. *Which processes are compromised?*

The present research identified three core deficits: (1) deficient access to the phonological lexicon as measured by picture naming; (2) deficient use of phoneme information necessary for normal functioning of the phoneme system and for setting up the GPC procedure; and (3) impaired letter processing. These deficits were quite general. If we take the *z*-score differences in [Appendix A](#), all dyslexics had a negative *z*-score in phoneme matching, 20 out of 24 dyslexics had a negative *z*-score in picture naming, and 14 out of 24 had a negative *z*-score in letter search. Thus, our results are consistent with a rich body of literature suggesting that phonological deficits are the main cause of developmental dyslexia (for reviews see [Snowling, 2001](#); [Ziegler & Goswami, 2005](#)). Note that these deficits affect processing via both the lexical and the nonlexical route, which might explain why we found deficits in both irregular word and nonword reading.

In addition to phonological deficits, the data revealed letter identification deficits for some of the subjects. The deficits were present when letters were embedded in words and when they were embedded in unpronounceable consonant strings, which suggests a fairly general deficit in letter perception and letter string processing. Such deficits have been found in a number of recent studies ([Bosse et al., 2007](#); [Hawelka & Wimmer, 2005](#); [Hawelka et al., 2006](#)). To what extent the letter perception problem could be caused by a more general visuo-spatial attentional deficit needs further investigation ([Facoetti et al., 2006](#)).

Surprisingly, no deficits were found in our marker effect for orthographic access, the existence of a word superiority effect. This finding suggests relatively normal functioning of the orthographic lexicon. This conclusion was not based on a null effect but on a positive effect, namely the finding that dyslexics showed a normal word superiority effect. [Grainger et al. \(2003\)](#) also reported normal word superiority effects in children with developmental dyslexia using the original two-alternative forced choice task used by [Reicher \(1969\)](#). The presence of a word superiority effect seems to indicate that access to the orthographic lexicon must be relatively spared even if access to the orthographic lexicon might be somewhat delayed or noisy due to the letter processing deficit. Such a conclusion is also consistent with the fact that the size of the word frequency and regularity effects appears relatively normal in children with dyslexia ([Landerl, Wimmer, & Frith, 1997](#); [Metsala, Stanovich, & Brown, 1998](#)). Moreover, it seems that sensitivity to orthographic cues might be enhanced in those dyslexics for whom a normal, phonology-based word recognition processing is not achieved ([Lavidor, Johnston, & Snowling, 2006](#); [Siegel, Share, & Geva, 1995](#)).

6.2. *Surface dyslexia: True issues and false trails*

In the context of the dual-route framework, it is assumed that the surface dyslexic profile is due to a nonphonological deficit in the lexical route ([Castles & Coltheart,](#)

1993). According to this view, deficits in irregular word reading are thought to result from deficits in accessing the orthographic lexicon. Our results clearly draw a different picture of surface dyslexia than the one commonly suggested in the literature. Although our surface dyslexics showed small impairments in orthographic access (letter search deficit in words, which resulted in reduced word superiority effects compared to phonological dyslexics), the main deficits of our surface dyslexics were phonological in nature (picture naming and phoneme matching).

The severe picture naming deficit of our surface dyslexics gives an interesting explanation for how irregular word reading can be impaired in the absence of a strong deficit to the orthographic lexicon. That is, in order to read irregular words via the lexical route, readers do not only need the ability to access their orthographic lexicon but also their phonological lexicon. If access to the phonological lexicon is impaired, as suggested in our picture naming data, a dyslexic reader would show a deficit on irregular word reading (for a similar suggestion, see Zorzi et al., 1998). Indeed, the picture naming deficit was significantly larger in surface dyslexics compared to phonological dyslexics, which underscores the possibility that irregular word reading deficits might be due to poor phonological lexical representations. Furthermore, on the total sample of 48 participants, picture naming was the best predictor of irregular word reading ($r = .701, p < .0001$, and $r = .634, p = .003$ for RTs and accuracy, respectively). This correlation was higher than that of letter identification (RTs: $r = .28, p = .026$; accuracy: $r = .33, p = .01$), word superiority (RTs: $r = .06, p = .34$; accuracy: $r = .028, p = .42$), or phoneme matching (RTs: $r = .56, p < .0001$; accuracy: $r = .61, p < .0001$).

Most studies in the literature found that surface dyslexics had weaker phonological deficits than phonological dyslexics (Manis et al., 1997; Stanovich et al., 1997), whereas our study and a previous French study by Sprenger-Charolles and colleagues (2000) suggested that phonological deficits were as strong in surface dyslexics as in phonological dyslexics. How can we explain this discrepancy? The most likely explanation is in terms of cross-language differences in the ease of reading irregular versus nonwords. It is well established that nonword reading is particularly difficult in English because of the inconsistency of grapheme–phoneme relations (for a review see Ziegler & Goswami, 2005). Thus, the bottleneck for the beginning or dyslexic reader of English might be situated at the level of grapheme–phoneme decoding. In contrast, French orthography is much more consistent than English orthography at least in the direction from spelling to sound (Ziegler, Jacobs, & Stone, 1996). Thus, it is much easier to teach and train grapheme–phoneme decoding in French than it is in English. Indeed, it is often the case that the phonological decoding deficits of French dyslexics disappear in the course of reading remediation, whereas deficits in irregular word and text reading remain. Therefore, we believe that once grapheme–phoneme decoding has been extensively trained, the bottleneck for the beginning or dyslexic reader of French is no longer at the level of phonological decoding (at least not accuracy). As a result, when subtyping is solely based on irregular versus nonword reading, one gets the impression that there are more surface dyslexics in French than there are in English (Genard et al., 1998; Sprenger-Charolles et al., 2000). Note, however, that the French surface dyslexics still show phono-

logical deficits in favor of the idea that surface and phonological dyslexia lie on a phonological deficit continuum (Griffiths & Snowling, 2002; Harm & Seidenberg, 1999; Manis et al., 1996; Snowling, 2001).

6.3. *Simulating individual differences and reading profiles*

One of the strengths of computational models is their capacity to simulate impaired reading (e.g., Harm, McCandliss, & Seidenberg, 2003; Harm & Seidenberg, 1999; Plaut et al., 1996). In earlier simulations, impaired reading was simulated by adding noise until the performance of the model dropped to that of a patient (Harm & Seidenberg, 1999). The originality of the present simulations lies in the fact that several tasks were used to estimate *for each person* which of the DRC's core processes were deficient. This information was then used to add noise proportionally to the size of the individual deficit. This procedure clearly reduces the degrees of freedom in simulating reading impairments.

We ran a total of 24 simulations, one for each dyslexic. The results averaged across the 24 subjects showed a striking match between the human data and the model both for accuracy and latency. The model correctly predicted massive deficits for irregular word and nonword reading in French dyslexics. As in the human data, the strongest deficits were obtained for irregular words. For regular words, the model correctly predicted no deficits for accuracy but robust deficits for reading speed. The model did a very good job in predicting individual accuracy data. Indeed, the deficit-based simulations accounted for 48% of the individual variance in reading, whereas a random noise model only accounted for 8.5% of the individual variance. The fits for the latency data were not as good as those for the accuracy data (the model explained around 15% of the variance) probably because latency measures were often based on very few data points (because of the high error rates and the relatively few items per category).

One of the most striking results was that the model produced simulations of a number of individual subjects that showed quite extreme patterns of both surface and phonological dyslexia despite the fact that the performance on the ancillary tasks showed no clear dissociations for surface and phonological dyslexia. The ability of the model to produce a double dissociation in such a way clearly illustrates the added value of having an implemented model.

To try to understand why the model was able to produce dissociated reading patterns, we looked at the associated deficits of the four dyslexics with the poorest nonword reading performance (subjects number 2, 5, 6, and 13) and the four dyslexics with poorest irregular word reading (1, 2, 3, and 13). The individual data of these subjects (see [Appendix A](#)) seemed to suggest that the poorest nonword readers all had letter perception deficits, whereas the poorest irregular word readers all had phonological deficits in picture naming and phoneme processing. The DRC model seemed very sensitive to the effects of these variables because adding noise to the phonological levels strongly affected irregular word reading, whereas adding noise to the letter level strongly affected nonword reading.

The finding that noise in the phoneme system produced irregular word reading deficits is somewhat counter-intuitive and appears inconsistent with previous dyslexia simulations. In particular, Harm and Seidenberg (1999) used a version of the triangle model to show that the more severe the impairment to the phonological network, the greater the nonword reading deficit. Only the most severe phonological impairments also affected irregular word reading. However, keep in mind that these are different models. The bottleneck of the triangle model is nonword reading partially because the model is never trained on nonwords. In contrast, nonword reading is much less of a problem for DRC because it contains a powerful set of grapheme–phoneme rules, which allows the model to read any nonword. Note that we did not add noise to the rules per se. This would have clearly resulted in deteriorated nonword reading. Instead, the fact that noise in the phoneme system affected irregular word reading is due to the high interactivity of the DRC. Because there is strong feedback between the phoneme system and the phonological lexicon,² a high level of noise in the phoneme system will strongly inhibit the rise of activation of word candidates in the phonological lexicon. As a consequence, the model will make regularization errors because activation from the phonological lexicon is too weak to override the assembled pronunciation.

The finding that noise to the letter level affected nonword reading is clearly consistent with recent evidence from spatial attention tasks, which suggests that the phonological dyslexics (not the surface dyslexics) suffer from spatial attention problems which have their most disturbing effect on nonword reading (Facoetti et al., 2006). Indeed, some studies suggest that focused visuo-spatial attention is more important for nonword reading than for word reading. For instance, Sieroff and Posner (1988) used spatial cueing to manipulate focused visual attention during reading. Participants made more errors in reporting the letters from the unattended side of nonwords compared to words. Moreover, patients with hemispatial neglect make more errors on the contralesional side of nonwords compared to words (Sieroff, Pollatsek, & Posner, 1988). Note that recent developments of the dual route model of reading include an attentional window that operates on the input to the nonlexical route (Perry et al., 2007). Such a model clearly predicts that deficits in focused visual attention would affect nonword more than irregular word reading.

Apart from surface and phonological dyslexia, the model also captured the reading patterns of mixed dyslexics who showed similar impairments on irregular word and nonword reading. Finally, the model accurately predicted the close-to-ceiling performance of mild dyslexics who were above 80% on either irregular word or nonword reading. Note again that none of these patterns were explicitly fitted. The excellent fits simply resulted from the individual simulations, in which noise was a linear function of the deficits obtained in the ancillary tasks.

Can the model predict all individual reading patterns? Clearly not. As can be seen in Appendix A, we identified three dyslexics, referred to as “compensated” dyslexics, for

² Such feedback is indeed necessary to simulate phonological influences on reading, such as the pseudohomophone effect (see Ziegler, Jacobs, & Klueppel, 2001).

whom the model produced incorrect simulations. In all three cases, the model predicted strong nonword reading deficits, whereas the dyslexics showed almost perfect performance in nonword reading. If we look at the associated deficits, it is quite clear why the model came to a wrong prediction. Two of the three dyslexics had strong letter perception deficits ($z < -2.5$), all of them had phoneme deficits ($z < -1.9$), and two of them had additional deficits in picture naming ($z < -2.6$). Given these strong associated deficits, the model had to predict very poor nonword and irregular word reading. How can we explain the discrepancy between the human data and the model? One suggestion would be that this group might be composed of older dyslexics. However, this was not the case because the mean average age of this group was comparable to the other groups (9;6 years, range 8;8–10;7). A second possibility would be that some of the dyslexics had been enrolled in reading training programs before participating in our study. Thus, it might be possible that these training programs directly improved nonword reading without actually producing any changes of the underlying phonological deficits (Harm et al., 2003). This is even more plausible if we take into consideration that nonword reading accuracy can be trained quite quickly in a regular orthography (Thaler, Ebner, Wimmer, & Landerl, 2004).

7. Conclusions

The present research highlights two facets of developmental dyslexia. On the one hand, there is a considerable amount of heterogeneity across developmental dyslexics because most of them exhibit a variety of deficits across different domains (letter processing, phoneme processing, phonological lexicon). The combination of deficits and their relative size seem to predict reading failure and success. Others before us have underscored the probabilistic and multifactorial nature of dyslexia (e.g., Pennington, 2006), which is hardly surprising given the complexity of the reading task. On the other hand, there is a reasonable amount of stability across subjects in the sense that almost all dyslexics show phonological deficits, a finding that is consistent with the phonological deficit theory of developmental dyslexia (for review see Snowling, 2001).

In response to the heterogeneity of developmental dyslexia, we propose a new modeling approach which consists of simulating individual differences in reading different kinds of words on the basis of underlying deficits in core components of the reading system. Although the DRC model was used in the present study as a theoretical framework, the present approach is not tied to a particular model. Instead, this approach could be used with other frameworks and models (e.g., Harm and Seidenberg, 1999; Hutzler et al., 2004; Perry et al., 2007; Plaut et al., 1996). What is needed, however, is a detailed description of the deficits involved in developmental dyslexia, a clear theory of how these deficits map onto the components of the model, and a fully implemented model which allows one to simulate individual reading latency and accuracy. The merits of such an approach are obvious. First, it reduces the arbitrariness of deficit simulations by permitting only those deficits that have a clear behavioral basis. Second, it promotes a closer connection between the model and the human data.

Appendix A

Type	Reading accuracy (% correct)						Reading latency						z-score deficits						Noise parameter ($x \times 10^{-3}$)							
	Dyslexics			Model			Dyslexics (ms)			Model (cycles)			Dyslexics			Model			Dyslexics			Model				
	REG	IR	NON	REG	IR	NON	REG	IR	NON	REG	IR	NON	REG	IR	NON	REG	IR	NON	REG	IR	NON	REG	IR	NON	REG	IR
1	Surface♣	100	20	90	100	100	1355	1360	1384	72	115	118	0.00	-2.32	-5.91	0	9	3								
2	Surface♣	100	20	55	100	20	1233	985	1459	70	96	120	-2.83	-4.14	-3.85	57	17	2								
3	Ssurface♣	90	20	70	100	30	864	880	1174	69	106	113	0.44	-1.40	-4.39	0	6	2								
4	Surface♣	100	30	70	100	10	1020	995	1255	80	134	125	-0.81	-3.07	-8.77	16	12	5								
5	Phono♣	80	80	40	100	80	735	823	1191	64	97	112	-1.81	-0.66	-0.97	36	3	1								
6	Phono♣	100	80	55	100	43	849	1473	1048	68	102	120	-3.12	-2.74	-3.85	62	11	2								
7	Mixed♣	100	60	75	100	70	71	796	1857	1252	71	108	115	-0.78	-3.79	-4.96	16	15	3							
8	Mixed♣	100	70	75	100	70	805	1331	1086	65	105	121	-1.81	-3.82	-4.01	36	15	2								
9	Mixed♣	90	70	95	100	80	732	844	994	65	100	110	-0.07	-2.53	-1.35	1	10	1								
10	Mixed♣	100	60	75	100	43	803	1225	1023	64	101	112	-1.12	-2.22	-3.06	22	9	2								
11	Mixed♣	90	70	75	100	40	822	1446	970	69	97	120	-0.66	-4.42	-6.30	13	18	3								
12	Mixed♣	100	80	75	100	50	1105	1529	1439	68	110	116	-1.06	-1.96	-4.77	21	8	3								
13	Mixed♣	90	10	35	100	60	1441	-	1699	66	106	114	-1.80	-4.73	-5.00	36	19	3								
14	Mild	100	80	90	100	80	875	943	1475	61	94	107	-0.11	-1.53	-0.22	2	6	0								
15	Mild♣	100	90	80	100	80	894	964	934	65	103	109	0.24	-0.95	-1.55	0	4	1								
16	Mild	100	90	90	100	90	537	612	698	65	102	109	0.99	0.98	-1.93	0	0	1								
17	Mild	100	90	90	100	90	764	1034	848	62	90	106	1.48	0.33	-0.78	0	0	0								
18	Mild	100	90	95	100	70	669	1002	968	64	105	114	-1.10	-1.98	-1.93	22	8	1								
19	Mild	100	100	90	100	80	715	1216	1339	65	104	111	0.17	0.44	-1.73	0	0	1								
20	Mild	100	100	90	100	90	550	662	661	65	103	109	0.27	-0.46	-1.55	0	2	1								
21	Mild	100	100	90	100	90	826	1102	1529	61	89	106	0.97	-1.70	-0.40	0	7	0								
22	Comp	90	80	90	100	40	812	961	1101	67	109	130	-2.51	0.98	-6.10	50	0	3								
23	Comp	100	90	95	100	70	1175	1805	2111	63	90	92	-0.98	-4.09	-2.50	20	16	1								
24	Comp♣	100	70	100	100	80	636	793	827	69	97	131	-2.99	-2.60	-1.93	60	10	1								

Notes. ♣, surface dyslexic according to regression method; ♠, phonological dyslexic according to regression method; comp, compensated dyslexic; REG, regular; IR, irregular; NON, nonword; Phon, phoneme; P-Lex, phonological lexicon.

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