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Do Dual-Route Models Accurately Predict Reading and Spelling Performance in Individuals with Acquired Alexia and Agraphia?

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Abstract

Coltheart and colleagues (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Castles, Bates, & Coltheart, 2006) have demonstrated that an equation derived from dual-route theory accurately predicts reading performance in young normal readers and in children with reading impairment due to developmental dyslexia or stroke. In this paper we present evidence that the dual-route equation and a related multiple regression model also accurately predict both reading and spelling performance in adult neurological patients with acquired alexia and agraphia. These findings provide empirical support for dual-route theories of written language processing.

Keywords

dual-route theory; reading; spelling; alexia; agraphia

INTRODUCTION

Dual-route models are scientific hypotheses about the cognitive architecture of the information-processing system used for reading and spelling (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Jackson & Coltheart, 2001; Houghton & Zorzi, 2003). According to these models, written language processing is accomplished by two distinct but interactive procedures that are referred to as the *lexical* and *non-lexical routes* (Figure 1).¹ Reading and spelling by the lexical route relies on the activation of word-specific orthographic and phonological memory representations. Although spoken and written words also automatically activate the

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¹Whether reading and spelling rely on shared or independent cognitive systems is a controversial issue in neuropsychology. Fig. 1 depicts a shared-components dual-route model in which a common orthographic lexicon is used for reading and spelling familiar words and a single non-lexical module mediates both grapheme-phoneme (GP) and phoneme-grapheme (PG) conversion. By contrast, independent-components dual-route models (e.g., Patterson & Shewell, 1987) postulate distinct orthographic input and output lexicons for reading and spelling, as well as separate non-lexical procedures for GP and PG conversion. Although there is no consensus in the literature on this issue, the brunt of the neuropsychological evidence seems to favor the shared-components dual-route model (for a review, see Tainturier & Rapp, 2001). The shared-components view is also supported by data from individuals with developmental dyslexia/dysgraphia (e.g., Curtin, Manis, & Seidenberg, 2001) and by behavioral (e.g., Burt & Tate, 2002; Holmes & Babauta, 2005), genetic (Bates et al., 2007), and functional neuroimaging studies (e.g., Cohen et al., 2002; Beeson et al., 2003) of reading and spelling in normal individuals.

corresponding conceptual representations in the semantic system, access to word meanings is not considered critical for accurate oral reading or spelling to dictation. The lexical route can process all familiar words, regardless of whether they are regular or irregular in terms of their letter-sound relationships, but it fails with unfamiliar words or non-words because these items do not have lexical representations. In contrast to the whole-word retrieval process employed by the lexical route, the non-lexical route utilizes a subword-level procedure based on sound-spelling correspondence rules. The non-lexical route can succeed with non-words (e.g., *plunt*) and also with regular words that strictly obey English phoneme-grapheme conversion rules (e.g., *must*), but it cannot produce a correct response to irregular words that violate these rules (e.g., *choir*). Attempts to read or spell irregular words by the non-lexical route result in regularization errors (e.g., *have* read to rhyme with *save*, or *tomb* spelled as *toom*). It should be noted that although dual-route models contain functional components that are unique to either the lexical route (e.g., orthographic lexicon) or the non-lexical route (e.g., phoneme-grapheme conversion module), the two procedures are not considered to be completely independent. For instance, the two routes share processing components at the phoneme and letter levels (Fig. 1). Furthermore, it is assumed that all written and spoken input is processed obligatorily by both routes in parallel, with cooperative or competitive interactions taking place at the phoneme (reading) or letter (spelling) output stage (Coltheart et al., 2001; Houghton & Zorzi, 2003). However, dual-route theory maintains that only the lexical route can deliver a correct response to irregular words, whereas the integrity of the non-lexical route is essential for accurate reading/spelling of non-words.

Dual-route models have provided a powerful theoretical framework for interpreting the written language performance of individuals with acquired alexia/agraphia. In particular, by specifying the functional architecture of the written language processing system it becomes possible to use the impaired and preserved reading/spelling abilities of neurological patients to identify the damaged or dysfunctional cognitive module. For instance, damage to the lexical route gives rise to surface dyslexia/dysgraphia, characterized by a disproportionate difficulty in reading/spelling irregular words (Patterson, Marshall, & Coltheart, 1985; Beauvois & Dérouesné, 1981; Roeltgen & Heilman, 1984; Rapcsak & Beeson, 2004). Reading/spelling of regular words and non-words is relatively spared, however, as these items can be processed successfully by the intact non-lexical route. By contrast, damage to the non-lexical route results in phonological dyslexia/dysgraphia, characterized by poor reading/spelling of non-words (Beauvois & Dérouesné, 1979; Coltheart, 1996; Shallice, 1981; Roeltgen, Sevush, & Heilman, 1983; Henry, Beeson, Stark, & Rapcsak, 2007). Reading/spelling of familiar regular and irregular words is relatively unimpaired because, for these items, patients can rely on the preserved lexical route.

In addition to explaining different subtypes of acquired alexia/agraphia by reference to a cognitive model of normal written language processing, dual-route theory can also be used to generate *quantitative* predictions about reading/spelling performance. For instance, Coltheart and colleagues (Coltheart et al., 2001; Castles, Bates, & Coltheart, 2006; Coltheart, 2006a) have suggested that one can predict regular word reading accuracy by knowing how well individuals perform on lists of irregular words and non-words. Recall that according to dual-route models irregular words can only be read correctly by a lexical strategy, whereas non-words can only be read correctly by a non-lexical strategy. Therefore, the proportion of irregular words, or $p(\text{IRREG})$, and the proportion of non-words, or $p(\text{NWD})$, that a person can accurately read provide relatively pure estimates of the competency of the lexical and non-lexical routes. Because dual-route theory posits that either route can process regular words, reading accuracy for these items, or $p(\text{REG})$, should be predictable from $p(\text{IRREG})$ and $p(\text{NWD})$ by the following formula:

$$p(\text{REG}) = p(\text{IRREG}) + [1 - p(\text{IRREG})] \times p(\text{NWD})$$

To illustrate the logic behind the equation, let us assume that a patient obtains reading scores of 60% correct for irregular words and 40% correct for non-words. Because irregular word scores estimate the competency of the lexical route, we can predict that this individual should be able to read 60% of regular words by a lexical strategy. Reading accuracy for the remaining 40% of regular words will be determined by the functional capacity of the non-lexical route, as reflected by non-word reading scores. This means that our patient should be able to read an additional 16% of regular words by a non-lexical strategy (i.e., 40% of the remaining 40% regular word items). Therefore, the dual-route equation predicts that by relying on the combined residual capacity of the lexical and non-lexical routes this person should obtain a reading score of 76% (i.e., 60% + 16%) correct on a list of regular words.

Coltheart and colleagues (Coltheart et al., 2001; Castles et al., 2006) have applied the prediction equation to 9 sets of reading data obtained from 3 different subject populations: young normal readers ($n=2136$), children with developmental dyslexia ($n=93$), and children with brain damage due to stroke ($n=17$). These investigators documented a high correlation between predicted and observed regular word reading scores in all three groups (range: $+0.825$ to $+0.980$) and concluded that the findings provided strong support for dual-route models of reading.

The purpose of our study was to determine whether the dual-route equation does an equally good job with reading data obtained from adult neurological patients with acquired alexia and to explore whether the formula can be used to predict spelling performance in these individuals. We also examined whether a multiple regression model based on dual-route theory successfully predicts the reading and spelling performance of our patients.

METHODS

Participants

The data reported here were collected from 33 neurological patients who were administered a comprehensive reading/spelling battery as part of an ongoing investigation of the cognitive mechanisms and neural substrates of written language processing (e.g., Rapcsak & Beeson, 2004; Henry et al., 2007). All subjects gave informed consent prior to participation and the study was approved by the IRB of the University of Arizona. All participants were native English speakers and none had a history of developmental dyslexia/dysgraphia. Mean age was 65.3 years (range: 40–86) and participants had an average of 14.7 years of formal education (range: 10–20). All patients were neurologically stable at the time of testing and were evaluated in the subacute or chronic stages of their illness (several months or years post onset). CT or MRI lesion information was available for all participants. Twenty-five patients had evidence of left-hemisphere ischemic or hemorrhagic stroke involving the distributions of the middle or posterior cerebral arteries. Another eight patients developed progressive language impairment (7 fluent and 1 non-fluent) in the context of focal cortical atrophy and were given the diagnosis of primary progressive aphasia (PPA) (Mesulam, 2001). The clinical syndrome of PPA can be associated with a variety of neurodegenerative conditions including Pick's disease, frontotemporal atrophy with ubiquitin positive inclusions, dementia lacking distinctive histopathology, corticobasal degeneration, and Alzheimer's disease (Mesulam, 2001; Grossman & Ash, 2004; Davis et al., 2005; Knibb, Xuereb, Patterson, & Hodges, 2006). Definitive diagnosis of the responsible disease entity requires neuropathological examination of the brain.

Consistent with the wide distribution of lesion sites, our patient group was heterogeneous with respect to alexia/agraphia subtype and included individuals with phonological dyslexia/dysgraphia, surface dyslexia/dysgraphia, letter-by-letter reading, as well as individuals with mixed patterns of written language impairment. There was also considerable variation in terms of the severity of the reading/spelling deficit.

Assessment of Reading and Spelling

For the analyses reported here, we used single word oral reading and spelling to dictation scores for 40 regular words, 40 irregular words, and 20 non-words from our original test battery. Regular words contained common or high-probability phoneme-grapheme mappings (e.g., grill), whereas irregular words contained at least one uncommon or low-probability mapping (e.g., gauge). Therefore, regular words could be read/spelled correctly either by a lexical strategy or by a non-lexical strategy based on knowledge of frequently occurring English sound-spelling correspondences. By contrast, accurate reading/spelling of irregular words could only be accomplished by a lexical procedure. Regular and irregular words were closely matched on a number of lexical-semantic variables, including word frequency, imageability, length, bigram frequency, and orthographic neighborhood size (for a summary of descriptive lexical statistics see Table 1). One-way ANOVAs indicated that regular and irregular words did not significantly differ on any of the relevant variables ($F < 1$ and $p > .60$ for all comparisons). The classification of items into regular vs. irregular categories was further confirmed by submitting all monosyllabic words (85% of all test stimuli) to the online N-Watch database (<http://www.maccs.mq.edu.au/~cdavis/N-Watch>) (Davis, 2005) that generates pronunciations for input letter strings based on the grapheme-phoneme conversion (GPC) rules specified in the Dual Route Cascaded (DRC) model of reading (Coltheart et al., 2001). The 20 non-word items used in our battery were derived from real words by changing some of the letters while maintaining phonological plausibility (e.g., nace). Non-word stimuli were matched with real words for length (mean = 4.95). The reading and spelling portions of the battery were administered during separate testing sessions. One patient was unable to complete the reading portion of the battery due to severe anarthria, so for this subject only spelling scores were used.

RESULTS

Observed accuracy for reading/spelling regular words plotted against predicted accuracy from the dual-route equation (Coltheart et al., 2001; Castles et al., 2006) is shown in Figure 2. It is apparent that the equation performs remarkably well in predicting written language performance in neurological patients with alexia/agraphia. In particular, simple regression analyses indicated that the dual-route equation explains 88.8% of the variance in regular word reading scores ($F_{1,30} = 237.518$; $p < .0001$) and 92.1% of the variance in regular word spelling scores ($F_{1,31} = 359.027$; $p < .0001$). These figures are comparable to the ones reported by Castles et al. (2006) in groups of children with reading impairment due to developmental dyslexia or stroke (range: 67.8% to 96%).

To confirm these findings and learn more about the contribution of the lexical and non-lexical routes to written language processing, we conducted multiple regression analyses using irregular word and non-word reading/spelling scores as predictors of regular word reading/spelling performance. Both independent variables were entered simultaneously and each variable was evaluated in terms of what it added to the prediction that was different from the other variable in the model. The results of these analyses are summarized in Table 2. Consistent with findings obtained using the dual-route equation, the combination of lexical and non-lexical predictor variables explained 83.8% of the variance in regular word reading scores and 85.5% of the variance in regular word spelling scores. In addition, individual t-tests confirmed that irregular word and non-word scores each made significant unique contributions to explaining variance in regular word reading/spelling accuracy (Table 2). These findings are consistent with the assertion of dual-route theory that the lexical and non-lexical routes both contribute to reading/spelling performance in an interactive fashion (Hillis & Caramazza, 1991; Coltheart et al., 2001; Rapp, Epstein, & Tainturier, 2002; Houghton & Zorzi, 2003). However, a comparison of β weights and sr^2 values indicated that irregular word scores were more powerful predictors of regular word reading/spelling accuracy and accounted for a larger proportion of

unique variance than did non-word scores (Table 2). These results suggest that reading/spelling responses to familiar regular words in our patients were dominated by the output of the lexical route.

DISCUSSION

Support for dual-route theories of written language processing comes from a variety of sources, including observations in normal readers/spellers, neuropsychological data from individuals with developmental or acquired alexia/agraphia, computational modeling, functional neuroimaging, and genetic research (for reviews, see Coltheart et al., 2001; Jackson & Coltheart, 2001; Jobard, Crivello, & Tzourio-Mazoyer, 2003; Houghton & Zorzi, 2003; Coltheart, 2006b; Castles, Bates, Coltheart, Luciano, & Martin, 2006; Bates et al., 2007). In this paper we presented evidence that the dual-route equation introduced by Coltheart and colleagues (Coltheart et al., 2001; Castles et al., 2006) and a related multiple regression model accurately predict reading/spelling performance in adult neurological patients with acquired alexia/agraphia. Specifically, we found that irregular word and non-word reading/spelling scores, which provide direct estimates of the functional capacity of the lexical and non-lexical routes, explain most of the variance in regular word reading/spelling ability. Our results complement data obtained by Castles et al. (2006) in young normal readers and in children with reading impairment due to developmental dyslexia or stroke and demonstrate further the utility of this approach in predicting spelling performance. Taken together, these findings are consistent with the notion that a basic dual-route cognitive architecture supports both reading and spelling. In this context, it is important to point out that the prediction equation and related multiple regression model are expected to work equally well with the shared-components dual-route model shown in Fig. 1 and with independent-components dual-route models that postulate distinct orthographic input and output lexicons as well as separate non-lexical procedures for grapheme-phoneme and phoneme-grapheme conversion (e.g. Patterson & Shewell, 1987). Furthermore, because prediction accuracy is expected to be similar regardless of whether patients demonstrate complementary (associations) or divergent (dissociations) reading and spelling profiles, the methodological approach adopted in this paper cannot be used to adjudicate between rival dual-route models of written language processing.

As noted earlier, our subject group was heterogeneous in terms of disease etiology, lesion location, alexia/agraphia subtype, and the overall severity of the reading/spelling impairment. Consequently, our sample can be considered representative of the spectrum of written language disorders encountered in neurological patients with left-hemisphere damage. The considerable diversity in clinical presentation also suggests that the brain damage in this group of patients affected a number of different functional components of the dual-route cognitive model depicted in Fig. 1. Our results demonstrate that, despite significant variation in the neuropsychological mechanisms underlying the reading/spelling impairment, dual-route theory makes accurate predictions about written language performance in individuals with alexia/agraphia. Nevertheless, we believe that it will be important to establish in future studies whether or not prediction accuracy varies as a function of disease etiology, lesion location, or alexia/agraphia subtype (i.e., whether there are differences in predictive power depending on the nature of the brain injury or based on which processing route or functional component is affected by the lesion). This endeavor, however, will require the study of a much larger sample of left-hemisphere damaged patients with carefully documented written language profiles and precise neuroanatomical information about lesion location.

In addition to testing the predictive accuracy of dual-route models, the methodological approach employed in this paper has potential for clarifying the relative contributions of the lexical and non-lexical routes to reading/spelling performance in patients with alexia/agraphia and can provide information about the extent to which the balance between the two routes has

been altered as a result of brain damage. The dual-route equation and related multiple regression model may also be of value in understanding and monitoring treatment response in individual patients or groups of patients with acquired disorders or reading/spelling and could be used to test the efficacy of different therapeutic approaches aimed at strengthening the lexical or non-lexical routes or promote the interactive use of the two processing routes (Beeson, White, & Rapcsak, 2007).

Finally, it is important to ask whether connectionist models that do not postulate distinct lexical and non-lexical procedures for reading/spelling words vs. non-words (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996; Harm & Seidenberg, 1999) could make similarly accurate predictions about written language performance in individuals with developmental or acquired alexia/agraphia. As pointed out by Castles et al. (2006), only actual simulations with such computational models can provide a definitive answer to this question. This would require either interfering with the learning of the model or “lesioning” different components of the fully trained network and then determining whether the model’s performance on irregular words and non-words accurately predicts its performance with regular words. Castles et al. (2006) expressed skepticism about the success of this enterprise, citing that the processing of regular words, irregular words, and non-words in connectionist models with a single implemented phonological pathway for orthographic-to-phonological translations is too interdependent to allow for the type of straightforward predictions that follow naturally from dual-route theory. Prediction accuracy may be higher for connectionist models that incorporate an additional fully implemented semantic pathway (e.g., Harm & Seidenberg, 2004). However, these “division of labor” connectionist models are also conceptually more similar to dual-route models in that they postulate separate pathways for processing irregular words and non-words (Coltheart, 2005).

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References

- Baayen, RH.; Piepenbrock, R.; van Rijn, H. The CELEX Lexical Database. Philadelphia, PA: Linguistic Data Consortium, University of Pennsylvania; 1995.
- Bates TC, Castles A, Luciano M, Wright MJ, Coltheart M, Martin NG. Genetic and environmental bases of reading & spelling: a unified genetic dual route model. *Reading and Writing* 2007;20:147–171.
- Beauvois MF, Dérouesné J. Phonological alexia: three dissociations. *Journal of Neurology, Neurosurgery and Psychiatry* 1979;42:1115–1124.
- Beauvois MF, Dérouesné J. Lexical or orthographic agraphia. *Brain* 1981;104:21–49. [PubMed: 7470843]
- Beeson PM, Rapcsak SZ, Plante E, Chargualaf J, Chung A, Johnson SC, Trouard T. The neural substrates of writing: A functional magnetic resonance imaging study. *Aphasiology* 2003;17:647–665.
- Beeson, PM.; White, B.; Rapcsak, SZ. Toward a better understanding of response to agraphia treatment. Paper presented at the 35th Annual Meeting of the International Neuropsychological Society; Portland, OR. 2007; 2007.
- Burt JS, Tate H. Does a reading lexicon provide orthographic representations for spelling? *Journal of Memory and Language* 2002;46:518–543.
- Castles A, Bates TC, Coltheart M. John Marshall and the developmental dyslexias. *Aphasiology* 2006;20:871–892.
- Castles A, Bates T, Coltheart M, Luciano M, Martin NG. Cognitive modeling and the behavior genetics of reading. *Journal of Research in Reading* 2006;29:92–103.

- Cohen L, Lehericy S, Chochon F, Lemer C, Rivaud S, Dehaene S. Language-specific tuning of visual cortex? Functional properties of the Visual Word Form Area. *Brain* 2002;125:1054–1069. [PubMed: 11960895]
- Coltheart M. The MRC Psycholinguistic Database. *Quarterly Journal of Experimental Psychology* 1981;33A:487–505.
- Coltheart M. Phonological dyslexia: past and future issues. *Cognitive Neuropsychology* 1996;13:749–762.
- Coltheart, M. Modeling reading: the dual-route approach. In: Snowling, MJ.; Hulme, C., editors. *The Science of Reading: A Handbook*. Malden, MA: Blackwell Publishing; 2005. p. 6-23.
- Coltheart M. The genetics of learning to read. *Journal of Research in Reading* 2006a;29:124–132.
- Coltheart M. Acquired dyslexias and the computational modeling of reading. *Cognitive Neuropsychology* 2006b;23:96–109.
- Coltheart M, Rastle K, Perry C, Langdon R, Ziegler J. DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review* 2001;108:204–256. [PubMed: 11212628]
- Cortese MJ, Fugett A. Imageability ratings for 3,000 monosyllabic words. *Behavior Research Methods, Instruments, & Computers* 2004;36:384–387.
- Curtin S, Manis FR, Seidenberg MS. Parallels between the reading and spelling deficits of two subgroups of developmental dyslexics. *Reading and Writing* 2001;14:515–547.
- Davis CJ. N-Watch: a program for deriving neighborhood size and other psycholinguistic statistics. *Behavior Research Methods, Instruments, & Computers* 2005;37:65–70.
- Davis RR, Hodges JR, Kril JJ, Patterson K, Halliday GM, Xuereb JH. The pathological basis of semantic dementia. *Brain* 2005;128:1984–1995. [PubMed: 16000337]
- Grossman M, Ash S. Primary progressive aphasia: a review. *Neurocase* 2004;10:3–18. [PubMed: 15849155]
- Harm MW, Seidenberg MS. Phonology, reading acquisition, and dyslexia: insights from connectionist models. *Psychological Review* 1999;106:491–528. [PubMed: 10467896]
- Harm MW, Seidenberg MS. Computing the meanings of words in reading: cooperative division of labor between visual and phonological processes. *Psychological Review* 2004;111:662–720. [PubMed: 15250780]
- Henry ML, Beeson PM, Stark AJ, Rapcsak SZ. The role of left perisylvian cortical regions in spelling. *Brain and Language* 2007;100:44–52. [PubMed: 16890279]
- Hillis AE, Caramazza A. Mechanisms for accessing lexical representations for output: evidence from a category-specific semantic deficit. *Brain and Language* 1991;40:106–144. [PubMed: 2009445]
- Holmes VM, Babauta ML. Single or dual representations for reading and spelling? *Reading and Writing* 2005;18:257–280.
- Houghton G, Zorzi M. Normal and impaired spelling in a connectionist dual-route architecture. *Cognitive Neuropsychology* 2003;20:115–162.
- Jackson, NE.; Coltheart, M. *Routes to Reading Success and Failure: Toward an Integrated Cognitive Psychology of Atypical Reading*. New York, NY: Psychology Press; 2001.
- Jobard G, Crivello F, Tzourio-Mazoyer. Evaluation of the dual route theory of reading: a metaanalysis of 35 neuroimaging studies. *NeuroImage* 2003;20:693–712. [PubMed: 14568445]
- Knibb JA, Xuereb JH, Patterson K, Hodges JR. Clinical and pathological characterization of progressive aphasia. *Annals of Neurology* 2006;59:156–165. [PubMed: 16374817]
- Mesulam MM. Primary progressive aphasia. *Annals of Neurology* 2001;49:425–432. [PubMed: 11310619]
- Patterson, K.; Shewell, C. Speak and spell: dissociations and word-class effects. In: Coltheart, M.; Sartori, G.; Job, R., editors. *The Cognitive Neuropsychology of Language*. London: Lawrence Erlbaum; 1987. p. 273-294.
- Patterson, KE.; Marshall, JC.; Coltheart, M. *Surface Dyslexia. Neuropsychological and Cognitive Studies of Phonological Reading*. London: Lawrence Erlbaum; 1985.
- Plaut DC, McClelland JL, Seidenberg MS, Patterson K. Understanding normal and impaired word reading: computational principles in quasi-regular domains. *Psychological Review* 1996;103:56–115. [PubMed: 8650300]

- Rapcsak SZ, Beeson PM. The role of left posterior inferior temporal cortex in spelling. *Neurology* 2004;62:2221–2229. [PubMed: 15210886]
- Rapp B, Epstein C, Tainturier MJ. The integration of information across lexical and sublexical processes in spelling. *Cognitive Neuropsychology* 2002;19:1–29.
- Roeltgen DP, Heilman KM. Lexical agraphia: further support for the two-system hypothesis of linguistic agraphia. *Brain* 1984;107:811–827. [PubMed: 6206909]
- Roeltgen DP, Sevush S, Heilman KM. Phonological agraphia: writing by the lexical-semantic route. *Neurology* 1983;33:755–765. [PubMed: 6682519]
- Shallice T. Phonological agraphia and the lexical route in writing. *Brain* 1981;104:413–429. [PubMed: 7272708]
- Tainturier, M-J.; Rapp, B. The spelling process. In: Rapp, B., editor. *The Handbook of Cognitive Neuropsychology: What Deficits Reveal about the Human Mind*. Philadelphia: Psychology Press; 2001. p. 263-289.

Figure 1. Dual-route cognitive model of reading and spelling. PG = phoneme-grapheme, GP = grapheme-phoneme conversion.

Figure 2.
Predicted vs. observed accuracy for reading and spelling regular words.

Table 1

Descriptive lexical statistics for regular and irregular words

Test Items	Frequency	Imageability	Length	Bigram Frequency	Ortho-N
Regular	97.97	4.76	4.95	2.89	4.28
Irregular	98.68	4.83	4.95	2.86	3.88

Word frequency values are from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1995). Imageability ratings represent averaged values from the MRC Psycholinguistic Database (Coltheart, 1981) and the Cortese & Fughett (2004) list. Ratings were available for 77/80 items (96%). Bigram frequency = mean log bigram frequency and Ortho-N = orthographic neighborhood size from the N-Watch database (Davis, 2005).

Results of multiple regression analyses using irregular word and non-word reading/spelling scores as predictors of regular word reading/spelling accuracy.

Task	R	R ²	F	df1	df2	p	Predictors	β	t	p	sr ²
Reading	.915	.838	75.020	2	29	<.0001	Irregular	.774	9.995	<.0001	.558
							Non-word	.326	4.204	.0002	.099
Spelling	.925	.855	88.576	2	30	<.0001	Irregular	.642	8.123	<.0001	.318
							Non-word	.427	5.408	<.0001	.141

sr² = square of the semipartial correlation indicating the proportion of unique variance explained by each independent variable in the model. Summed unique variance for reading = .657, shared variance = .181, summed unique variance for spelling = .459, shared variance = .396.