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Regularity Effects and the Phonological Deficit Model of Reading Disabilities: A Meta-Analytic Review

Jamie L. Metsala
University of Maryland College Park

Keith E. Stanovich
University of Toronto

Gordon D. A. Brown
University of Warwick

This article presents a meta-analysis of spelling-to-sound regularity effects in individuals with reading disabilities and reading-level comparison groups. The phonological-deficit model of reading disabilities, coupled with the classic dual-route model of word recognition, has led to two predictions: (a) a specific deficit in the pseudoword reading of those with reading disabilities and (b) an absent or reduced regularity effect for those with reading disabilities relative to reading-level controls. Previous reviews confirm the first prediction. The present meta-analysis tested the second prediction. There was a clear effect of word regularity for individuals with reading disabilities, the magnitude of which did not differ from the word regularity effect for reading-level controls. The authors explore how the contradictory support for these 2 predictions is inconsistent with classic dual-route models of word reading and how connectionist models are consistent with the empirical findings on reading disability.

There has recently been a great deal of research aimed at developing more fundamental explanations of reading disability in terms of neuropsychological processes, computer models, and neurophysiology. For example, some investigators are attempting to model the performance patterns of poor readers with connectionist computer models (e.g., Brown, 1997; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg, 1993). Other investigators have attempted to characterize the functional neurophysiology of individuals with reading disabilities and to localize the information-processing deficits of these readers in certain parts of the brain (e.g., Galaburda, 1994; Hynd, Clinton, & Hiemenz, in press; Shaywitz, 1996). Still others have attempted to analyze the genetics of reading disability and to estimate the heritability of information-processing operations that are particularly deficient in children with reading disabilities (e.g., Olson, in press; Olson, Forsberg, & Wise, 1994).

All of these reductive efforts are, however, completely dependent on an accurate characterization of the phenotypic performance pattern of children with reading disabilities. That is, if these research programs are to succeed, there must first be knowledge of what is unique about the information-processing characteristics of such children. For example, Pennington (1986) noted that "powerful genetic techniques are becoming increasingly available for the study of inherited, complex behavior disorders, including learning disabilities. Yet the utility of these techniques is directly affected by how we define the behavioral phenotype in question" (p. 69). In the area of reading disability, researchers have recently made considerable progress in specifying the unique phenotypic processing profile (see Fletcher et al., 1994; Stanovich & Siegel, 1994), so much so that it is now reasonable to carry out investigations underlying the cognitive levels of analysis (e.g., neurological, and genetic).

Much of what is known about that unique information-processing profile at the phenotypic level is embodied in the phonological deficit model of reading disability. According to this model, the primary locus of difficulty for children with reading disabilities is word recognition (Liberman & Shankweiler, 1985; Share, 1995; Snowling, 1991, 1995; Snowling & Hulme, 1994; Stanovich, 1988; Stanovich & Siegel, 1994). Word recognition is thought to be impeded because of problems in segmental language representation at the phonological level (Elbro, 1996; Fowler, 1991; Goswami & Bryant, 1990; Liberman & Shankweiler, 1985; McBride-Chang, 1995a, 1995b, 1996; Metsala, 1997a, 1997b; Olson, 1994; Stanovich, 1986, 1991). These segmental language problems are proposed to underlie the difficulties

Jamie L. Metsala, Department of Human Development, University of Maryland College Park; Keith E. Stanovich, Department of Human Development, University of Toronto, Toronto, Ontario, Canada; Gordon D. A. Brown, Department of Psychology, University of Warwick, Warwick, England.

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Correspondence concerning this article should be addressed to Jamie L. Metsala, Department of Human Development, 3304 Benjamin Building, University of Maryland, College Park, Maryland 20742-1131. Electronic mail may be sent to jm251@umail.umd.edu.

of children with reading disabilities in making explicit reports about sound segments at the phoneme level, their difficulties in repeating pseudowords, their abnormal categorical perception of certain phonemes, and their speech production difficulties (e.g., Bowey, Cain, & Ryan, 1992; Bradley & Bryant, 1978; Bruck & Treiman, 1990; Kamhi & Catts, 1989; Liberman, Meskill, Chatillon, & Schupack, 1985; Olson, Wise, Connors, Rack, & Fulker, 1989; Siegel & Ryan, 1988; Snowling, 1991; Stanovich, 1986, 1992; Taylor, Lean, & Schwartz, 1989; Wolf, 1991). It is still not clear that all of these phonologically related deficits reflect a single underlying processing problem, although a growing number of investigators are working to resolve this issue (see Bowey & Hansen, 1994; McBride-Chang, 1995a, 1996; McBride-Chang & Manis, 1996; Metsala & Walley, in press; Pennington, Van Orden, Smith, Green, & Haith, 1990; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; Wagner, Torgesen, & Rashotte, 1994; Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993; Wagner et al., 1997).

The phonological deficit model has enriched understanding of some of the core cognitive processes in individuals with reading disabilities; however, there are still empirical puzzles—even at the level of the basic processing of words themselves—that have not been completely explained by the model. Thus, the full phenotypic processing pattern that needs explanation by reductive theorists working at more fundamental levels of analysis remains incompletely specified. In simple terms, with regard to certain information-processing patterns, one cannot say which neuropsychological, physiological, genetic, or computational model explains the data because the data pattern itself is in dispute. In the present study, we attempted to clarify one important performance pattern that has been the subject of some dispute by conducting a meta-analysis to discern trends in the literature.

It has been suggested that inefficient use of the spelling-to-sound code by people with reading disabilities is the immediate consequence of the phonological-core deficit. That is, it is widely believed that deficits in segmental language representations and awareness manifest themselves in difficulties establishing an efficient spelling-to-sound translation routine that makes use of sublexical spelling–sound correspondences. However, theories of spelling-to-sound coding (called cipher reading by Gough, Juel, & Griffith, 1992) have been an area of great contention in the reading research field (e.g., Besner, Twilley, McCann, & Seergobin, 1990; Coltheart, Curtis, Atkins, & Haller, 1993; Humphreys & Evett, 1985; Seidenberg & McClelland, 1989), and some basic data patterns have only recently become firmly established. For example, for a considerable time it was unclear whether individuals with reading disabilities displayed pseudoword reading deficits relative to reading-level controls. Recently, Rack, Snowling and Olson (1992) presented a qualitative review of the experimental studies that have examined this question, and Ijzendoorn and Bus (1994) subsequently conducted a quantitative meta-analysis. Both sets of reviewers concluded that children with reading difficulties do show a pseudoword reading deficit, even in comparisons with reading-level controls.

The finding of a pseudoword reading deficit in a reading-level match has most often been interpreted within the context of dual-route models of spelling-to-sound coding during reading (e.g., Coltheart, 1978). This class of model posits two alternate recognition pathways to the lexicon: a direct visual access route that does not involve phonological mediation (i.e., the "lexical," "orthographic," or "addressed" route) and an indirect route through phonological processing that involves stored spelling–sound correspondences (the "sublexical," "phonological," or "assembled" route). The size (or grain) of the spelling–sound correspondences that make up the phonological route differs from model to model. Versions of dual-route models also differ in assumptions about the various speeds of the two recognition paths involved and how conflicting information is resolved. Discussions of the many variants of this type of model are contained in many excellent reviews (e.g., Carr & Pollatsek, 1985; Coltheart et al., 1993; Henderson, 1982, 1985; Humphreys & Evett, 1985; Patterson & Coltheart, 1987; Rayner & Pollatsek, 1989).

The pseudoword naming deficit has been interpreted by dual-route theorists to indicate that the sublexical route is relatively more impaired than the lexical route in individuals with reading disabilities. A pseudoword (e.g., *blint*), by definition, does not have a corresponding lexical entry, and thus it can be pronounced only through the use of sublexical spelling–sound correspondences. This interpretation was consistent with findings indicating that individuals with reading disabilities were relatively less impaired in orthographic coding abilities that stressed lexical-level processing or direct visual access (Frith & Snowling, 1983; Holligan & Johnston, 1988; Levinthal & Hornung, 1992; Olson, Kliegel, Davidson, & Foltz, 1985; Olson et al., 1989; Pennington et al., 1986; Rack, 1985; Siegel, Share, & Geva, 1995; Snowling, 1980; Stanovich & Siegel, 1994).

Although there is considerable consistency regarding the relative deficits in phonological and orthographic coding displayed by individuals with reading disabilities on certain tasks, one unresolved issue concerns relative differences between reading groups in their processing of words of varying degrees of spelling-to-sound regularity. Regular words are those whose pronunciations reflect common spelling–sound correspondences (e.g., *made* or *rope*); irregular or exception words are those whose pronunciations reflect atypical correspondences (e.g., *sword, pint, have,* or *aisle*). The issue of how best to define regularity is complex and contentious (Brown, 1987; Henderson, 1982, 1985; Humphreys & Evett, 1985; Kay & Bishop, 1987; Patterson, Marshall, & Coltheart, 1985; Rosson, 1985; Venezky & Massaro, 1987). Disagreement about how to classify words in terms of spelling-to-sound regularity is widespread because the degree of regularity assigned depends greatly on the size of the coding unit used to define spelling–sound correspondences (Kay & Bishop, 1987). Simply put, many more words are regular when large-unit mappings are used (Henderson, 1982; Mason, 1977; Ryder & Pearson, 1980; Venezky, 1970; see especially Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995). For this reason, many investigators reserve the term *regularity* to refer to spelling-to-sound predictability based on small-unit, or grapheme–phoneme, correspondences (see Berndt, Reggia, & Mitchum, 1987) and use the term *consistency* to refer to spelling-to-sound predictability based on large-unit correspondences involving word bodies (e.g., *-ock*, *-ess*, or *-ame*). Most of the studies analyzed here used exception words that were both irregular and inconsistent.

The regularity effect in reading has been defined as the observation of superior performance in recognition of regular versus exception words. The regularity variable attained prominence in the experimental psychology of reading largely because of the early influence of the dual-route models (e.g., Coltheart, 1978) mentioned previously. In short, the presence or absence of the spelling-to-sound regularity effect has been used as a marker for the efficient functioning of the phonological route. The regularity effect in reading has been considered to arise because sublexical spelling–sound correspondences can be used to correctly pronounce regular words but not irregular words. The simultaneous activation of both routes for regular words will lead to consistent output, whereas this is not the case for irregular items. Therefore, regular words will have an advantage. However, if the phonological route is less available as a result of impairment, all words will be read by the lexical route, and therefore the expected advantage for regular words should be eliminated or reduced.

Nondisabled children and adults do have more difficulty processing words with exceptional pronunciations. In adults, word naming latency is generally slower for words with irregular or inconsistent pronunciations, especially words of lower frequency (e.g., Seidenberg, Waters, Barnes, & Tanenhaus, 1984; Szeszulski & Manis, 1987; Taraban & McClelland, 1987; Waters & Seidenberg, 1985). In children, regularity effects have been observed in error rates, single-word reading times, or both (e.g., Laxon, Masterson, & Coltheart, 1991; Laxon, Masterson, & Moran, 1994; Waters, Bruck, & Seidenberg, 1985). Thus, there is ample evidence that effects of spelling-to-sound regularity can be reliably observed in both children and adults.

Given the indications of relative differences between individuals with reading disabilities and nondisabled readers on the phonological and orthographic processing tasks discussed earlier, it has seemed to many investigators that the spelling-to-sound regularity effect should provide a converging pattern. Indeed, several theorists (Barron, 1981; Castles & Coltheart, 1993; Manis, Szeszulski, Holt, & Graves, 1990; Olson et al., 1985; Treiman & Hirsh-Pasek, 1985) have suggested that the regularity effect should be an indicator of the differential functioning of phonological and orthographic coding skills, which have been observed to differ between normal readers and those with reading disabilities. Many investigators have argued that this follows from the classic dual-route model of word recognition coupled with the phonological-deficit model of reading disabilities (Barron, 1986; Carr & Pollatsek, 1985; Coltheart, 1978; Humphreys & Evett, 1985):

> The regularity effect provides an index of subjects' use of spelling-to-sound correspondences to pronounce familiar words. If dyslexic children are less able to apply their knowledge of these correspondences, they should show smaller regularity effects than normal readers. (Manis et al., 1990, pp. 229–230)

> The regular words are presumed to be processed by both the phonological and orthographic paths, while the exception words are confined to the orthographic path. In this model, disabled readers should show a smaller regular word advantage because their phonological coding is uniquely deficient. (Olson et al., 1985, p. 18)

> If the less skilled readers are slower in activating phonological information than the skilled readers, then phonological information would be less likely to influence word recognition. As a result, they should be less likely than skilled readers to be faster on regular than exception words. (Barron, 1981, p. 305)

Despite such predictions of a reduced regularity effect for individuals with reading disabilities versus normal readers, the empirical literature on the nature of the regularity effect in groups with reading disabilities is puzzling. Although some studies have found the expected interaction between participant group and spelling-to-sound regularity (Barron, 1981; Beech & Awaida, 1992; Frith & Snowling, 1983; Snowling, Stackhouse, & Rack, 1986), an even larger number of studies using reading-level controls have not (Baddeley, Logie, & Ellis, 1988; Beech & Harding, 1984; Ben-Dror, Pollatsek, & Scarpati, 1991; Bruck, 1990; Holligan & Johnston, 1988; Olson et al., 1985; Stanovich, Nathan, & Zolman, 1988; Treiman & Hirsh-Pasek, 1985). Research on the differential display of the regularity effect has not been adequately synthesized and, thus, appears to have produced inconsistent findings.

As discussed by Schmidt (1996), an emphasis on comparing individual studies can often obscure consistent trends running through the literature when it is broadly interpreted. A focus on significance testing in the context of single studies often makes the literature seem more inconsistent than it really is (Schmidt, 1996). To examine whether a focus on the inconsistencies among individual studies has obscured underlying trends in the literature, we conducted a meta-analysis designed to test the prediction of the dual-route version of the phonological-deficit model: that regularity effects should be attenuated for individuals with reading disabilities relative to reading-level controls. Regardless of the outcome of our test of this hypothesis, the results of our meta-analysis should serve to further specify the characteristics of the phenotypic performance pattern of children with reading disabilities.

We addressed three main research questions. First, do individuals with reading disabilities demonstrate a regularity effect? Second, is the magnitude of the regularity effect the same for this population and the reading-level-matched, normally achieving population? Third, which variables other than reading group account for significant variance among regularity effect sizes?

Method

Database

The criteria applied for study selection were as follows. First, the study had to be published and had to involve a reading-level-match design. Second, the study was required to report means and standard deviations for accuracy on reading performance on regular and irregular words by reading group (or to report whether the regularity effect was significant for each reading group). Following the recent meta-analysis of the pseudoword reading deficit (Ijzendoorn & Bus, 1994), we suggest that, because null results follow from the phonological-deficit account (i.e., no regularity effect in individuals with reading disabilities), such outcomes would be as likely to be published as statistically significant findings. We therefore suggest that there is unlikely to be a publishing bias for our particular research question (see Rosenthal, 1991).

The studies included in two recent syntheses on the pseudoword reading deficit were examined (Ijzendoorn & Bus, 1994; Rack et al., 1992), and those that met the preceding criteria were included in this meta-analysis. In addition, major educational and psychological research indexes were searched, and appropriate studies were included. This resulted in a total of 17 studies (see Table 1).

In two of these studies, results were reported separately for different age groups (Siegel & Ryan, 1988; Szeszulski & Manis, 1987). Because age was a factor of potential interest, we treated these age group results as separate studies; that is, we included in the analyses effect sizes for each of the younger and older reading disability and normally achieving groups for these two studies. Therefore, we calculated an effect size, indicating the magnitude of the regularity effect, for each reading disability and normally achieving sample, yielding a total of 38 effect sizes.

Four studies analyzed performance on regular and irregular word reading for high-frequency and low-frequency words separately (as shown in Table 1). For these studies, we calculated effect sizes based on performance for low-frequency words (three of these four studies showed the same pattern of regularity effects for the high and low word-frequency conditions). We reasoned that because the relationship between word frequency and effect size was of potential interest, it would not have been appropriate to collapse across frequency. We did examine frequency as a potential predictor of the effect size, as reported in the Results section.

In the study by Olson et al. (1985), there were two estimates of the regularity effect reported for the same participants. A second test of the regularity effect was carried out in their study because both reading groups failed to show a regularity effect for the first set of stimuli. The authors suggested that this may have been due to a ceiling effect in the participants' reading performance; therefore, they examined the regularity effect for stimuli that were more difficult for their participants. We calculated effect sizes based on Olson et al.'s second test of the regularity effect. Because detailed descriptions of word stimuli were not available for these results, this study was not included in analyses examining predictor variables other than reading group.

For five studies, means and standard deviations were not available, but the authors reported whether or not the regularity effect was significant for each reading group (Table 1 identifies these five studies). We followed Ijzendoorn and Bus (1994; see also Cooper & Hedges, 1994) in using a conservative estimate for these five studies (i.e., $p = .05$ for significant effects and $p = .5$ for nonsignificant effects), and we derived a t value from this estimated significance level and the group size for each reading group (see meta-analytic procedures described subsequently). The main Q-test analyses for testing homogeneity of effect sizes and the significance of reading group were calculated with and without these five studies included (Rosenthal, 1995). The pattern of significant effect sizes was identical with and without these studies included, and we therefore report the inclusive analyses.

Predictor Variables

We were also interested in examining the relationship between additional predictor variables and regularity effects. Therefore, in addition to the information needed to calculate effect sizes, we recorded the following information reported in each study.

Age. For each reading disability and normally achieving group, the mean age (in months) of the participants was recorded.

Year. For each study, the year of publication was recorded.

Average number of syllables and letters. In most of the studies, word lists were included or were available on request from the authors. For each study, we calculated the mean number of syllables, as well as the mean number of letters for the total set of word stimuli.

Word frequency. For each study, we calculated the mean frequency for each of the regular and irregular word stimuli. These frequencies were recorded for each word from the Kucera and Francis (1967) word frequency base. In the case of 2 studies (Baddeley et al., 1988; Frith & Snowling, 1983), the word stimuli and the mean Kucera and Francis (1967) frequencies were not available. We therefore substituted the mean frequency for each of the regular and irregular word lists reported in 10 of the other studies (this number excluded those 4 studies from which our selection of stimuli was restricted to low-frequency words). Analyses examining regular and irregular word frequencies as predictors of effect size were calculated both with and without these 2 studies (Rosenthal, 1995). The significant results for both sets of analyses were identical; thus, we present only the results for analyses that included these 2 studies.

Meta-Analytic Procedure

The effect size statistic used was the standardized mean difference d. For each reading disability and normally achieving group in each study, d_i was calculated by subtracting the mean accuracy score for irregular words (M2) from the mean accuracy score for regular words (M1) and dividing by the pooled standard deviation (S pooled) of these two word conditions (Rosenthal, 1994; Shadish & Haddock, 1994; see also Hedges & Olkin, 1985). This formula is $d_i = \text{M1} - \text{M2/S pooled}$.

For five studies, we estimated p and found the corresponding t value for the given sample size. The formula given by Rosenthal (1994) was then used to calculate d_i: $d_i = 2t/(2n)^{1/2}$.

The conditional variance (v_i) associated with each effect size was also calculated (Shadish & Haddock, 1994). The formula for our within-group effect size calculations reduced to $v_i = 2n/n^2 + d^2/(4n)$. To combine effect sizes, we calculated all associated weights (w_i) for each d_i: $w_i = 1/v_i$.

We used w_i to calculate combined effect sizes, and we also used these weights in our examinations of predictor variables. Such weighting procedures for combining effect sizes are based on the assumption that larger sample sizes will be associated with smaller variance and therefore are more precise estimates of population effect sizes (e.g., Shadish & Haddock, 1994; Schafer, in press). Thus, in the analyses in which effect sizes were combined, studies with smaller conditional variances were accorded more weight.

Results

Combined Effect Sizes

The combined studies included a total of 1,116 participants (536 with reading disabilities and 580 normally achieving readers). Table 1 displays descriptive characteristics for each study, including, when available, number of participants by reading group, mean age, mean and standard deviation for reading accuracy, reading level, IQ test used, IQ mean or cutoff score, and conclusion concerning the regularity effect. Table 2 displays the effect size and conditional variance for each study.

We first calculated the weighted mean effect size by reading group and then collapsed across reading groups. The question we addressed was whether the effect size for each reading population was significantly different from zero.

The mean weighted effect size (d) for groups with reading disabilities was 0.58, and the standard error of estimate for the combined effect sizes was 0.06. The 95% confidence interval for the estimated effect size was 0.46–0.70. Given that the confidence interval does not contain zero, one can conclude that there is a significant regularity effect for the population of individuals with reading disabilities. The mean unweighted effect size was 0.64 for this population.

The mean weighted effect size for the normally achieving, reading-level-matched population was 0.68; the standard error of estimate for the combined effect sizes was 0.06, and the 95% confidence interval was 0.56–0.80. The mean unweighted effect size for the normally achieving population was 0.85.

The analogous measures for the combined population of all readers were as follows: mean weighted d, 0.63; standard error of estimate, 0.04; and 95% confidence interval, 0.64–0.71. The unweighted mean effect size across reading groups was 0.74, and the median was 0.60. The range of effect scores was −0.02 to 2.29 (see Table 2). In summary, both individuals with reading disabilities and normally achieving readers showed clear regularity effects.

Relatedness of Reading Group and Regularity Effect

In examining whether variance in effect sizes was related to reading group, we first tested the null hypothesis that the 38 populations involved a common effect size estimate. For this test, the Q statistic was calculated; Q has an approximate chi-square distribution, and, for this test of homogeneity, the degrees of freedom are equal to the number of effect sizes minus 1. We rejected the null hypothesis in our data, $Q(37) = 120.99$, $p < .005$, and concluded that there was significant variance among effect size estimates, thus warranting further investigation of variables that may be systematically related to the magnitude of regularity effects.

The main prediction this meta-analysis was designed to address was whether the magnitude of regularity effect is smaller for individuals with reading disabilities than it is for normally achieving readers. We therefore examined whether effect size was related to reading group (those with reading disabilities vs. normal achievers). The Q statistic, testing the null hypothesis that effect size was unrelated to reading group across the study populations, was not significant, $Q(1) = 1.43$, $p > .10$. Therefore, we could not reject the null hypothesis, and we concluded that the tests of regularity in each of the two reading groups were estimating the same effect size. Contrary to the version of the phonological-deficit model based on a dual-route conceptualization, the literature does not support evidence of a smaller magnitude of regularity effect size for individuals with reading disabilities versus normally achieving readers.

We next examined the combined effect sizes for only those studies that reported findings differing from a significant regularity effect of equal magnitude for the reading disability and normally achieving groups. Eight pairs of effect sizes fell into this category (see Table 1, last column). We did this to address whether these individual studies that were inconsistent with the preceding overall conclusion would nonetheless cumulatively show the same pattern of effect sizes.

The combined weighted effect size across these eight data points for groups with reading disabilities was 0.44, and the 95% confidence interval was 0.26–0.62. The combined weighted effect size for eight matched normally achieving samples was 0.67, and the 95% confidence interval was 0.49–0.85.

We further examined whether effect size was related to reading group across this limited number of studies. The Q statistic was not significant, $Q(1) = 3.84$, $p > .05$. Thus, even for these studies that individually reported a different pattern of findings, there was a significant regularity effect for the population of individuals with reading disabilities, and the magnitude of the regularity effect size was not predicted by reading group. This finding is similar to results from the Ijzendoorn and Bus (1994) meta-analysis on the pseudoword deficits of individuals with reading disabilities. That is, in that synthesis, even individual studies that did not report a significant pseudoword reading deficit for participants with reading disabilities relative to reading-level-matched participants did show this pattern when the results were combined across the same studies.

Relationship Between the Regularity Effect and Predictor Variables

We examined each of the predictor variables in turn in an attempt to explain the variance among the estimated effect sizes. The Q test uses a regression-based logic (Shadish & Haddock, 1994); all Q tests reported assessed the significance of the relationship between one predictor variable and weighted effect sizes (thus, $df = 1$; see Schafer, in press) and, unless otherwise stated, were significant at the $p < .05$ level. Overall, we found that, for each predictor variable reported, there remained a significant amount of variance among effect sizes. Therefore, no individual predictor accounted for all of the variance among effect sizes.

Age did not predict variability in effect sizes ($Q < 1.00$, $p > .10$). The year the study was published did predict effect sizes ($Q = 34.35$), with larger effect sizes associated with more recently published studies. Studies more recently published may have improved in general methodology and may have been more likely to control for confounding variables, including differences between word frequencies and word length across regularity conditions.

The stimulus characteristics of mean number of syllables and mean number of letters were also examined in separate analyses. Mean number of letters was not significantly related to effect sizes ($Q < 1.00$, $p > .10$). Mean number of syllables did predict statistically significant variance in effect sizes ($Q = 12.21$; $R = .32$ and $R^2 = .10$ in weighted Q test).

The frequency of regular words and the frequency of

Table 1
Summary of Studies in Meta-Analysis

Study	*n*	Mean age (months)	Reading level	IQ	Accuracy regular words	Accuracy irregular words	Study conclusion[a]
			Schonell (AE)	Percentile	% error out of 12	% error out of 12	
Baddeley et al. (1988)[b]							1
RD	15	143.0	9:1	73 WISC-R	22.2	45.6	
NA	16	103.0	9:1	76.3 Raven	24.0	37.5	
			WRMT-R	WAIS-R	% error out of 39	% error out of 39	
Ben-Dror et al. (1991)[c]							1
RD	18	272.0	<40th percentile	106 (7.6)	12.6 (6.1)	26.4 (11.1)	
NA	20	140.4			7.5 (5.5)	20.7 (10.4)	
			WRAT-R[e] (GE)		No. errors out of 10	No. errors out of 10	
Bruck (1988)[d]							1
RD	14–17	128.4	3.6	99.8			
High frequency					2.4 (1.9)	3.4 (2.5)	
Low frequency					2.8 (1.5)	5.7 (1.5)	
NA	17	91.2	4.5				
High frequency					1.1 (1.5)	2.0 (1.8)	
Low frequency					1.2 (1.6)	4.9 (1.6)	
			WRAT-R (GE)	PPVT-R	No. errors out of 15	No. errors out of 15	
Bruck & Treiman (1990)[b,c,d]							1
RD	20	252.0	10E[h]	97.0			
High frequency					.65	1.7	
Low frequency					1.2	4.1	
NA	15	132.0	11B[h]	112.0			
High frequency					.27	1.1	
Low frequency					.27	5.8	
			BAS (AE)	WISC-R (>90)	% correct out of 15	% correct out of 15	
Holligan & Johnston (1988)[d]							1
RD	20	102.0 (4.7)	7.0 (.31)	103.7 (9.3)			
High frequency					67.6 (17.8)	56.7 (20.1)	
Low frequency					51.3 (18.3)	29.3 (13.6)	
NA	20	85.9 (2.4)	7.2 (.20)	107.7 (14.9)			
High frequency					67.7 (14.4)	57.7 (16.4)	
Low frequency					51.3 (18.7)	32.2 (9.2)	
			WRMT (GE)	WISC-R	% correct out of 10	% correct out of 10	
Manis et al. (1990)[d]							1
RD	52	141.0 (16.4)	3.9 (0.9)	108.2 (10.8)			
High frequency					96.0 (6.0)	88.7 (10.9)	
Low frequency					82.7 (19.0)	71.3 (19.2)	
NA	35.0	98.5 (8.9)	4.0 (0.8)	107.3 (8.5)			
High frequency					97.1 (4.6)	91.7 (10.1)	
Low frequency					82.6 (17.8)	75.4 (19.0)	
			PIAT decoding	WISC-R	% correct out of 20	% correct out of 20	
Olson et al. (1985)[b]							1
RD	23	96–132 (approximately)		>90.0	77.0	45.0	
NA	26	168–204 (approximately)		>90.0	77.0	40.0	

Table 1 (*continued*)

Study	*n*	Mean age (months)	Reading level	IQ	Accuracy regular words	Accuracy irregular words	Study conclusion[a]
			Metropolitan[g] (GE)	PPVT-R percentile	No. error out of 8	No. error out of 8	
Stanovich et al. (1988)[f]							1
RD	19	104.9 (4.8)	4.37 (1.5)	76.7	1.58 (1.1)	2.05 (1.4)	
NA	20	158.7 (7.6)	4.35 (0.8)	73.3	1.3 (0.92)	2.2 (1.1)	
			Gilmore (GE)	WISC-R	% correct out of 24	% correct out of 24	
Szeszulski & Manis (1987)[b]							
Younger participants							2
RD	37	124.2 (21.4)	2.4 (0.7)	98.9 (10.1)	66.6	50.3	
NA	14	85.6 (7.8)	2.7 (0.6)	106.0 (8.6)	81.0	57.1	
Older participants							1
RD	15	158.5 (17.0)	4.7 (0.7)	101.1 (8.4)	95.3	84.4	
NA	20	106.7 (11.2)	4.9 (0.8)	106.5 (10.9)	97.1	80.6	
			BAS (AE)	Raven percentile	No. correct out of 68	No. correct out of 68	
Beech & Awaida (1992)							2
RD	38	114.4 (2.9)	7.8 (.48)	66.2 (19.2)	43.2 (12.7)	34.2 (34.2)	
NA	40	94.9 (5.4)	8.0 (.45)	62.9 (21.0)	47.9 (10.1)	36.8 (36.3)	
			WRAT-R (SS)	WISC-R (V)	No. correct out of 38	No. correct out of 38	
Murphy & Pollatsek (1994)							2
RD	65	138.1 (11.2)	77.1 (8.79)	105.1 (10.2)	28.3 (7.1)	20.0 (6.8)	
NA	65	91.9 (9.3)	110.4 (8.4)		30.7 (6.5)	19.8 (6.6)	
			DST (GE)	PPVT-R	No. correct out of 25	No. correct out of 25	
DiBenedetto et al. (1983)							3
RD	20	122.5 (14.4)	3.6 (1.0)	111.3	18.8 (3.9)	15.9 (4.1)	
NA	20	96.2 (8.0)	3.7 (1.1)	112.6	21.0 (2.6)	17.4 (2.8)	
			BAS (AE)	WISC-R	No. correct out of 12	No. correct out of 12	
Frith & Snowling (1983)							3
RD	8	120.0–144.0	8:4–10:9	100.0–133.0	10.0 (2.0)	9.6 (2.7)	
NA	10	108.0–120.0	8:6–10:2		11.4 (.8)	9.3 (1.8)	
			WRAT-R		No. correct out of 36	No. correct out of 36	
Siegel & Ryan (1988)[f]							
Younger participants							3
RD	12	120.0	<25th percentile		10.33 (7.6)	10.50 (6.5)	
NA	27	90.0	>30th percentile		9.07 (7.2)	7.11 (5.6)	
Older participants							2
RD	44	168.0	<25th percentile		29.8 (4.1)	27.8 (4.0)	
NA	117	138.0	>30th percentile		30.4 (3.9)	28.2 (3.6)	
			BAS (AE)	WISC	% correct out of 14	% correct out of 14	
Johnston et al. (1990)[d]							3
RD	19	10.7 (0.5)	7.7 (.6)	105.3 (15.1)			
High frequency					69.4 (19.9)	75.4 (19.6)	
Low frequency					54.9 (26.0)	44.9 (22.1)	
NA	20	7.5 (0.6)	7.8 (.4)	107.8 (12.9)			
High frequency					85.3 (11.2)	85.3 (13.6)	
Low frequency					75.3 (15.6)	56.5 (15.6)	

(*table continues*)

Table 1 *(continued)*

Study	n	Mean age (months)	Reading level	IQ	Accuracy regular words	Accuracy irregular words	Study conclusion[a]
			WRMT (GE)		No. correct out of 32	No. correct out of 32	
Treiman & Hirsch-Pasek (1985)							4
RD	37	141 (18)	3.57 (1.2)		18.9 (7.4)	16.3 (7.6)	
NA	37	102 (13)			18.9 (7.5)	16.9 (7.0)	
			Schonell (years)	Raven	No. correct out of 18	No. correct out of 18	
Beech & Harding (1984)							4
RD	57	119.0 (16.2)	7.63 (1.0)	97.8 (10.2)	10.8 (5.6)	10.3 (5.7)	
NA	44	86.5 (13.0)	7.67 (1.3)	100.4 (8.6)	11.4 (6.5)	10.8 (6.4)	

Note. Accuracy is reported as the number or percentage of correct or error responses; the number in parentheses is the standard deviation. Schonell = Schonell Graded Word Recognition Test; AE = age equivalent; GE = grade equivalent; RD = individuals with reading disabilities; NA = normally achieving readers; WRMT = Woodcock Reading Mastery Tests; WRAT = Wide Range Achievement Test; BAS = British Ability Scales; PIAT = Peabody Individual Achievement Test; Metropolitan = Metropolitan Achievement Test; Gilmore = Gilmore Oral Reading Test; DST = Decoding Skills Test; SS = standard score; WISC-R = Wechsler Intelligence Scale for Children–Revised; WAIS-R = Wechsler Adult Intelligence Scale–Revised; PPVT = Peabody Picture Vocabulary Test; WISC-R(P) = Wechsler Intelligence Scale for Children–Revised (Performance Scale); WISC-R(V) = Wechsler Intelligence Scale for Children–Revised (Verbal Scale).
[a] 1 = significant regularity effect of equal magnitude for both groups; 2 = significant regularity effect, but greater for NA sample; 3 = significant regularity effect for NA but not for RD; 4 = no significant regularity effect for either group. [b] p estimated to find t and calculate d. [c] Adult readers with disabilities. [d] Low-frequency data used in meta-analysis. [e] Reading level match based on spelling and comprehension. [f] Recalculated from original data. [g] Reading level match based on comprehension. [h] Grade equivalent recorded in paper.

irregular words both predicted significant variance in effect sizes in separate analyses (Qs = 24.55 and 30.22, respectively). Effect size increased with decreasing mean frequencies, whether examined for regular or irregular words.

We next divided the studies into two categories, the top and bottom halves in terms of mean frequency of regular words. This yielded 18 effect sizes in each category. The mean weighted effect size for studies in the top half of the distribution was 0.39, and the 95% confidence interval was 0.26–0.52. For the studies in the lower half, the mean effect size was 0.94, and the 95% confident interval was 0.82–1.06. Thus, even studies that used words of relatively higher frequency had a mean effect size for regularity significantly greater than zero (consistent with results reported in Jared, 1997). However, the mean effect size for these studies was small relative to that for the studies that used lower frequency words. The same calculations for studies divided into the top and bottom halves in terms of mean frequency for irregular words showed the same pattern: d = 0.44 (0.32–0.56) for the high-frequency category and d = 0.83 (0.70–0.96) for the low-frequency category.

The Q-test analysis for irregular words as a predictor of effect size yielded an R value of .50 and and an R^2 value of .25. Therefore, we conclude that, taking into account the weighting associated with each study, irregular word frequency accounted for approximately 25% of the variance in regularity effect sizes. The same analysis with regular word frequency as the predictor variable yielded an R value of .45 and an R^2 value of .20. With both variables entered into the weighted regression equation, the R value was .51 and the R^2 value was .26.

The relationship between mean word frequency for regular and irregular words and regularity effect size was similarly examined, but in separate analyses for the reading disability and normally achieving populations. The mean frequency of regular words predicted variance among effect sizes for both populations when examined individually (Qs = 13.24 and 12.12, respectively), as did the mean frequency of irregular words (Qs = 20.95 and 12.38, respectively). Thus, the finding of an association between increasing regularity effect size and decreasing word frequency characterizes both of the reading populations.

Discussion

This meta-analysis was conducted to test the prediction that the population of individuals with reading disabilities would show reduced effects of spelling-to-sound regularity on single-word reading. The findings most directly relevant to this hypothesis can be summarized as follows. First, both individuals with reading disabilities and normally achieving readers showed clear effects of spelling-to-sound regularity. Second, reading group was not related to regularity effect size. Even the eight studies that, individually, did not support these main conclusions produced a clear regularity effect for individuals with reading disabilities when the results were pooled across the same studies.

In terms of the theoretical framework outlined in the introduction, these results appear somewhat paradoxical. According to the phonological-deficit model, problems with the segmental structure of spoken language are assumed to prevent the normal development of a spelling-to-sound translation routine. This routine requires the efficient use of

Table 2
Effect Sizes for Magnitude of Regularity Effect

Study	*n*	*d*	Variance
Baddeley et al. (1988)			
RD	15	0.78	.144
NA	16	0.75	.134
Beech & Awaida (1992)			
RD	38	0.35	.053
NA	40	0.42	.051
Beech & Harding (1994)			
RD	57	0.08	.035
NA	44	0.09	.046
Ben-Dror et al. (1991)			
RD	18	1.54	.144
NA	20	1.59	.132
Bruck (1988)			
RD	17	1.86	.179
NA	17	2.29	.195
Bruck & Treiman (1990)			
RD	20	0.66	.105
NA	15	0.78	.144
DiBenedetto et al. (1983)			
RD	20	0.17	.100
NA	20	0.31	.101
Frith & Snowling (1983)			
RD	8	0.17	.251
NA	10	1.51	.157
Holligan & Johnston (1988)			
RD	20	1.37	.123
NA	20	1.30	.121
Johnston et al. (1990)			
RD	19	0.41	.104
NA	20	1.05	.113
Manis et al. (1990)			
RD	52	0.60	.040
NA	35	0.39	.058
Murphy & Pollatsek (1994)			
RD	65	1.19	.037
NA	65	1.67	.042
Olson et al. (1985)			
RD	23	0.61	.095
NA	26	0.57	.080
Siegel & Ryan (1988) (younger participants)			
RD	12	−0.02	.167
NA	27	0.30	.075
Siegel & Ryan (1988) (older participants)			
RD	44	0.41	.046
NA	117	0.42	.018
Stanovich et al. (1988)			
RD	19	0.37	.107
NA	20	0.88	.110
Szeszulski & Manis (1987) (younger participants)			
RD	37	0.47	.057
NA	14	0.82	.155
Szeszulski & Manis (1987) (older participants)			
RD	15	0.78	.144
NA	20	0.66	.106
Treiman & Hirsh-Pasek (1985)			
RD	37	0.34	.055
NA	37	0.27	.058

Note. RD = individuals with reading disabilities; NA = normally achieving readers.

sublexical phonological representations. Two predictions are normally assumed to be consistent with this model. First, the model predicts a specific pseudoword reading problem for individuals with reading disabilities. Clear support for this prediction has been found: There are substantial data consistent with a selective pseudoword processing deficit in reading disabilities (Ijzendoorn & Bus, 1994; Rack et al., 1992), and this observation has been taken as support for the phonological-deficit model.

Second, the phonological-deficit model has been taken to predict that the spelling-to-sound regularity effect should be reduced or absent in children with reading disabilities even when they are able to read words at the same level as younger, normally achieving readers. This second prediction derives from the assumption that the normal use of a sublexical route produces the widely observed advantage for regular over irregular items. If this phonological route is impaired in those with reading disabilities, as proposed by the phonological-deficit model, then there is no reason to expect a word recognition advantage for regular versus exception words. The present meta-analysis, however, yielded strong evidence against this second prediction: Our results reveal clear evidence of word regularity effects in normally achieving readers and those with reading disabilities, the magnitude of which is not predicted by reading group. Thus, the observed pattern of empirical findings, taken as a whole (i.e., support for a pseudoword reading deficit but not for a reduced regularity effect in people with reading disabilities), cannot easily be explained by the phonological-deficit model interpreted within the classical, dual-route framework.

How, then, is this paradoxical pattern of findings to be explained? One possibility is that the populations of individuals with reading disabilities have not been the same in pseudoword reading experiments and experiments that have examined spelling-to-sound regularity effects (e.g., see Stanovich et al., 1988). For example, the reading disability could have been less severe in populations that have exhibited normal-sized regularity effects and more severe in populations that have exhibited impaired pseudoword reading. Alternatively, different age groups may have been used in the different sets of studies. However, the results of our meta-analysis showed that, within the age span studied, age did not predict variability in effect sizes. Furthermore, the studies used in the research syntheses on pseudoword reading in people with reading disabilities and the present study largely overlap. Thus, for the majority of studies included in the present meta-analysis, other syntheses have found that these same groups of individuals with reading disabilities do demonstrate a pseudoword reading deficit. It therefore appears difficult to explain the apparently paradoxical results in terms of characteristics of the participant groups.

An alternative possibility is that inadequate methodology has been used in the studies that have not reported reduced effects of spelling-to-sound regularity in groups with reading disabilities. Methodological failings could, for example, involve floor or ceiling effects or inadequate control of stimulus characteristics. Clear overall effects of spelling-to-sound regularity were obtained, however, for both reading populations, and these effects varied with word frequency. These observations, along with the finding that there was significant heterogeneity among effect sizes, would make it difficult to argue that there was not significant variation in effect sizes to be predicted by reading group. With regard to stimulus characteristics, it is possible that earlier studies were less likely to control for lexical characteristics that might have been correlated with spelling-to-sound regularity (purely orthographic regularity, as indexed by measures such as positional bigram frequency). On this account, apparent effects of spelling-to-sound regularity might really be effects of some other variable, and hence the failure of such effects to interact with level of reading disability would not be relevant to the phonological deficit model. This interpretation seems unlikely, however, in the light of our finding that larger effects of spelling-to-sound regularity were associated with more recently published studies (which one might reasonably expect to be associated with improved methodology and stimulus materials).

An alternative explanation for the lack of a differential effect of spelling–sound regularity is that the predicted trend toward attenuated regularity effects in the population of individuals with reading disabilities is obscured by heterogeneity within this population. Specifically, it has long been speculated that there are subtypes within this group. If phonological deficits characterize only one of several subtypes of reading disability, then any predicted difference based on the phonological-core deficit model will be statistically diluted by the other subtypes. It is unlikely, however, that this factor could fully account for any null result. First, it is already apparent that, even if reliable subtypes can be demarcated (see Castles & Coltheart, 1993; Manis, Seidenberg, Doi, McBride-Chang, & Peterson, 1996; Stanovich, Siegel, & Gottardo, 1997), phonological deficits will characterize the most frequent subtypes (Fletcher et al., 1994; Share, 1995; Share & Stanovich, 1995; Stanovich & Siegel, 1994; Stanovich et al., 1997). Second, other deficits (in comparison with reading-level controls), such as phonological awareness deficits and pseudoword reading deficits, have not been diluted beyond statistical detection.

A final suggestion is that deficits in individuals with reading disabilities are more likely to be observed when the phonological demands of the task are greater (e.g., Holligan & Johnston, 1988). It might be suggested, for example, that pseudoword reading places greater demands on phonological abilities than does the reading of regular and irregular real words. Such an account would need independent specification of precisely how and why pseudoword reading is a more demanding task with particularly high requirements for intact phonological representations. In the next section, we argue that cognitive models of reading within a connectionist framework can provide just such an account. In summary, we have argued elsewhere (e.g., Brown, 1997; Metsala & Brown, 1998) that the observed pattern of empirical findings associated with reading disability may be explained in terms of the computational capacity of a reading-learning system (Brown & Loosemore, 1994, 1995) or in terms of the representations given to such a system (Brown, 1997). On this account, pseudoword reading is a more appropriate task for detecting impaired phonological representations than is word reading. More specifically, we suggest that recent connectionist models of reading can explain why impaired phonological representations lead to impaired pseudoword reading but not to reduced spelling-to-sound regularity effects. In other words, we suggest that connectionist models can explain the paradoxical pattern of results (impaired pseudoword reading with normal-sized regularity effects) observed in individuals with reading disabilities.

Connectionist models of reading development (e.g., Plaut et al., 1996; Seidenberg & McClelland, 1989) provide an alternative to the traditional dual-route approach with its focus on the use of rules for applying predetermined spelling–sound correspondences. Connectionist models emphasize instead the learned association between inputs (e.g., the orthographic forms of words) and outputs (e.g., word pronunciations) without the use of explicit rules (Rumelhart & McClelland, 1986). Much research has demonstrated that the nature of the representations with which a connectionist model of reading is provided has a major impact on the model's performance (e.g., Harm, Altmann, & Seidenberg, 1994; Hulme, Snowling, & Quinlan, 1991; Plaut et al., 1996). More specifically, it appears that phoneme-based representations are of particular importance in pseudoword reading, because they allow a connectionist network to capture generalizations at the level of graphemes and phonemes more easily (e.g., Brown, 1997; Harm et al., 1994; Norris, 1994; Plaut et al., 1996). Thus, a network will learn more easily if it is provided with appropriately structured phonemic output representations (Hulme et al., 1991).

To explain this account of the reading pattern of people with reading disabilities, we begin with a brief description of the basic principles of operation of connectionist reading networks. We emphasize the importance for such models of the way the orthographic forms of words (and pronunciations of those words) are represented to the network as patterns of simulated neural activity. We then describe how different connectionist models of reading have made different assumptions concerning the nature of phonological representations and show that models that have used certain types of phonological representations can be viewed as "impaired" in their phonological representations. These models, unlike models with "unimpaired" phonological representations, behave just like children with reading disabilities in that they exhibit a selective impairment in pseudoword reading but show normal effects of spelling-to-sound regularity. We conclude that computational insights derived from the study of connectionist models of reading offer a potential explanation for the apparently paradoxical pattern of empirical findings outlined here.

Connectionist networks are normally made up of large numbers of simplified "artificial neurons" that are richly interconnected. Each artificial neuron (or "unit") is connected to some, although generally not all, of the other units in the network. Every unit has an "activation level" associated with it. The interconnections are used to communicate the activation level of one unit to another, and the activation level is modified as it passes through the connection, depending on the "strength" of that connection. Each unit's level of activation is determined by the sum of the activations that it receives from other units to which it is connected. Broadly speaking, a unit's activation level is proportional to the amount by which the total activation coming into the unit is higher than a threshold value.

Such networks become of psychological interest when patterns of activation over the units represent something meaningful, such as the phonological form of a word. For example, one set of units, designated "input units," might be used to represent the written forms of words. Each different word would then be represented as a different pattern of activation on the input units. Similarly, every possible pronunciation of a word can be represented as a different pattern of activity of a set of "output units." Precisely how a word's spelling or pronunciation is represented as a pattern of activity over the units differs between models, and we discuss this in more detail subsequently.

What can such networks do? Because the input units (representing word spellings) and output units (representing word pronunciations) are interconnected, the presence of a pattern of activation on the input units (representing a spelling) will cause a pattern of activation to appear on the output units (representing a pronunciation). The precise pattern formed on the output units will depend on the strengths of all of the connections in the network.

If the network can learn the appropriate set of connection strengths, then input patterns that represent particular word spellings can cause formation of a pattern of activity on the network's output units that corresponds to the correct pronunciation for an item. A reading model network can learn associations between pairs of patterns (spellings and pronunciations) simply by being repeatedly exposed to the pairs: All of the learning takes place by slow modification of connection strengths in the course of "experience." At the end of learning, the network is, in most cases, able to produce the correct output (pronunciation) in response to a particular input (spelling). This learning ability has led to a widespread interest in these models within the psychology of reading as well as many other areas of psychology.

The Seidenberg and McClelland (1989) model was the first comprehensive and computationally explicit account of single-word reading within a connectionist framework, and it accounted for an impressive range of empirical data. However, the model was criticized for poor pseudoword reading performance (Besner et al., 1990).

Subsequent research has suggested that the deficient pseudoword reading of the model could be ascribed to its possession of "impaired" phonological representations (Plaut et al., 1996). This is consistent with subsequent work showing that improved pseudoword reading can be obtained in connectionist models if more fine-grained input and output representations, which allow the network to capture generalizations at the level of graphemes and phonemes more easily, are used (e.g., Brown, 1997; Bullinaria, 1995; Norris, 1994; Plaut et al., 1996).

What do we mean by an impaired phonological representation in the context of a connectionist model? We first need to show how the phonological and orthographic forms of words can be represented as the network's inputs and outputs. We illustrate using orthographic representations (phonological representations follow similar principles).

The model of reading developed by Seidenberg and McClelland (1989) used a modification of a method that involves dedicating units to represent each ordered triple of letters or phonemes contained in the words to be represented. (The modifications involved the use of distributed representations, in which each unit participates in the encoding of many different triples, and the use of triples of phonetic features rather than phonemes themselves. Although these modifications are essential to the successful operation of the implemented model, we can ignore them for the purposes of illustration.) The orthographic form of a word such as *give,* for example, could be represented by "switching on" input units representing the four triples *_gi* + *giv* + *ive* + *ve_* (where "_" signifies a word boundary). A similar representation operates at the phoneme level (although only three units would be needed). With this type of triple-based representation, the model showed a good fit to adult spelling-to-sound regularity effects but was slightly impaired on pseudoword reading, a similar pattern, although less extreme, to that associated with reading disability.

An obvious question, therefore, concerns the features of the model that lead to its slightly impaired performance on pseudowords. This appears to be at least partly due to what Plaut et al. (1996) referred to as the *dispersion problem.* In a triple-based representation, graphemes (and phonemes) are effectively given different representations depending on where in a triple they occur. Thus, the letter *t* at the end of a triple has, for the model, nothing in common with a *t* occurring at the start of a triple. As far as the model is concerned, they might as well be different letters. This impairs the ability of the model to learn generalizations between graphemes and phonemes after a given amount of training, because the same grapheme-to-phoneme correspondence must be learned separately in several different contexts. Thus, the ability of the model to learn correspondences between graphemes and phonemes is impaired as a result of the model's "impaired" representations (Plaut et al., 1996). The model nevertheless shows normal effects of spelling-to-sound regularity in word reading (Seidenberg & McClelland, 1989).

If this account is correct, models in which individual phonemes and graphemes have their own unique representations should do better at pseudoword reading. And, indeed, there is now ample evidence that this is so (see Brown, 1997; Bullinaria, 1995; Coltheart et al., 1993; Norris, 1994; Phillips, Hay, & Smith, 1993; Plaut et al., 1996; Seidenberg, Plaut, Petersen, McClelland, & McRae, 1994; Sejnowski & Rosenberg, 1987). It is clear, therefore, that there is a relationship between the types of representations given to a reading model during learning and the model's eventual pseudoword reading performance. Impaired phonological representations lead to impaired pseudoword naming but preserved effects of spelling-to-sound regularity.

It has therefore been suggested that the phonological representations used in the original Seidenberg and McClelland (1989) model can be seen as analogous to impaired phonological representations in children with reading disabilities (e.g., Brown, 1997). The lack of sufficiently "fine-grained" phonological representations will prevent the easy acquisition of spelling–sound correspondence information at the level of graphemes and phonemes, and the result is a model that exhibits normal effects of spelling-to-sound regularity but impaired pseudoword reading.

Brown (1997) examined the issue directly by comparing the performance of two small "toy" connectionist models that differed in the quality of their orthographic and phonological representations. The "impaired representation" model was given triple-based representations such as those described earlier, and the "normal representation" model was given representations of individual graphemes and phonemes (similar to those used in the model of Plaut et al., 1996; see Brown, 1997, for more details of the implementation and results). Both models were given a small vocabulary of words (both regular and irregular) and were required to learn the pronunciations.

An analogy to a reading-level match was used in comparing the performance of the models: Results were scaled so that the models performed equally well on regular words. The ability of each of the models to read irregular words and pseudowords was then examined.

The results confirmed the hypotheses outlined earlier. Each model performed worse on irregular than regular items, and this performance reduction was of approximately equal magnitude in the impaired and unimpaired models. However, when pseudoword reading performance was examined, the reduction in performance was substantially greater for the model with impaired phonological representations.

Thus, the results of computational modeling work within a connectionist framework support the suggestion that impaired phonological representations will lead to impaired pseudoword reading but will not lead to reduced effects of spelling-to-sound regularity. This pattern is exactly the pattern of results that characterizes the performance of children with reading disabilities.

Conclusion

On the basis of our meta-analysis, we have shown that individuals with reading disabilities do show spelling-to-sound regularity effects and that a difference in the magnitude of this effect between those with reading disabilities and normally achieving readers is not supported in a quantitative synthesis of the literature. This goes against the prediction of the phonological-deficit model of reading disabilities as interpreted within the context of dual-route models of reading development.

However, we have argued that equivalent regularity effects across the reading populations are consistent with the phonological-deficit account of reading disability interpreted in the light of recent connectionist models of reading. Furthermore, these models are consistent with the proposal that difficulties in phoneme-based representations underlie reading difficulties in children with reading disabilities (e.g., Elbro, 1996; Fowler, 1991; Metsala, 1997b; Metsala & Walley, in press; Stanovich, 1991). If connectionist models are provided with "impaired" phonological representations, they, like the population of individuals with reading disabilities assessed in our meta-analysis, show impaired pseudoword reading but normal spelling-to-sound regularity effects. The reason appears to be that the use of small-grained units (e.g., graphemes and phonemes) is particularly important in the reading of unfamiliar items (pseudowords) and, by extension, particularly important in the early stages of reading development, when most words are still unfamiliar.

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