

## Research Report

### MOVEMENT SEQUENCING AND PHONOLOGICAL FLUENCY IN (PUTATIVELY) NONIMPAIRED READERS

Claudia Carello,<sup>1</sup> Valerie Marciarille LeVasseur,<sup>1</sup> and R.C. Schmidt<sup>2</sup>

<sup>1</sup>University of Connecticut and Haskins Laboratories and <sup>2</sup>College of the Holy Cross

**Abstract**—*Reading-disabled children often have accompanying deficits in motor coordination. Rather than assuming impairment of a shared neural mechanism, we conjecture that coordination difficulties that undermine normal speech would also undermine development of phonological awareness, which is necessary for reading fluency. Non-impaired readers who vary in fluency, therefore, should also covary in coordination. Reliable interrelationships between phonological decoding skills and the speed and variability of sequentially tapping the fingers of one hand (either dominant or nondominant) were, indeed, found for college undergraduates. Reading measures that do not emphasize phonological decoding did not show the same connection. Characterizing phonological decoding as a skill and the long-term consequences of failure to master that skill suggest that it could benefit from practice even in high-literacy populations.*

Although reading seems like a quintessentially cognitive activity, the constellation of tasks that impaired readers do or do not find troublesome belies that intuition. Metacognitive tasks are a problem for impaired readers only when linguistic segments are the focus (Fowler, 1991). Indeed, the specific designation "reading disabled" applies to individuals who have poor reading skills compared with others of similar general intelligence. Perhaps surprisingly, however, reading-disabled children often have accompanying deficits in motor coordination. Compared with age-matched control children, dyslexics are slower, more variable, or more prone to errors in a variety of manual coordinations (Denckla, 1985; Gladstone, Best, & Davidson, 1989; Wolff, 1999; Wolff, Michel, Ovrut, & Drake, 1990) and balance tasks (Nicolson & Fawcett, 1990).

Why should reading deficits be so narrowly linguistic yet be linked to something so seemingly far afield as coordinated movement? We pursue a rationale that focuses on the challenge facing all beginning readers, with or without impairment. According to the *phonological-awareness hypothesis* (I.Y. Liberman, 1973), in order to map a sequence of visual forms into a sequence of phonemes, the aspiring reader must first become explicitly aware that the spoken word can be analyzed into a sequence of phonemes. The difficulty is that those phonemes are not neatly sequenced acoustically. Vocal gestures necessarily overlap, obscuring the very sequence that the listener and the beginning reader need to extract. The difficulty, therefore, concerns more than simply the temporal order of discrete elements because those elements are interwoven in a temporally continuous stream (A.M. Liberman, 1993; Wolff, 1999). An appreciation of coarticulated sequencing is a challenge for speakers, listeners, and, ultimately, readers. The ability to segment words phonologically is a powerful predictor of future reading success (Brady & Shankweiler, 1991; Lundberg, Frost, & Petersen, 1988), even among

illiterates and former illiterates (Lukatela, Carello, Shankweiler, & Liberman, 1995; Morais, Bertelson, Cary, & Alegria, 1986).

Here is the link between reading and coordination: Decoding skills are dependent on phonological representations whose precision may have been compromised by imprecise phonological productions, however subtle. To the extent that speech production and skilled movement share the requirement of coordinating a variety of muscles over time and space, less fluid manual coordination may be a signature of less fluid productions, which, consequently, are less supportive of fluent decoding.<sup>1</sup> This perspective characterizes reading fluency in terms of level of decoding skill. To the extent that coarticulated sequencing is a skill, individuals will be more or less expert. To the further extent that sequencing movement segments and sequencing phonemic segments both exploit that skill, fluent readers ought to be more coordinated than less fluent readers throughout the spectrum of fluency.

In two experiments, we examined this conjecture with college students whose reading ability would be considered clinically unimpaired (although their childhood status is unknown). In Experiment 1, participants were recruited from a high-literacy population of college students; in Experiment 2, a pseudohomophone identification task was used to preselect samples of college students who were distinct with respect to the level of their phonological decoding skill. The motor coordination tasks required participants to tap computer keys with either the dominant or the nondominant hand, using just the index finger on a single key or an ordered sequence of the four fingers on four adjacent keys. The kind of bimanual task on which dyslexics show an impairment (asynchronous tapping of the index fingers of the two hands) was also used. All participants were administered two standard reading tests to assess their phonological decoding skills and comprehension independently. Reading rate was measured within one of these tests.

#### EXPERIMENT 1

The high-literacy sample consisted of 50 undergraduates at the College of the Holy Cross whose Scholastic Assessment Test (SAT) verbal scores ranged from 500 to 710, with an average of 616. They were administered two tests of reading ability. The National Adult Reading Test, or NART (Nelson & O'Connell, 1978), comprises two lists of words that participants must read aloud. One list contains 20 long, regular words (10 common, 10 rare) that are easily decoded (NART I) and 50 irregular words (25 more familiar, 25 less familiar) that are more difficult to decode (NART II). The Nelson-Denny Reading Test Form E (Brown, Bennett, & Hanna, 1981) assesses comprehension with literal and interpretive questions about eight passages. Cut-time administration was used with a time limit of 15 min. This test also provided an index of reading rate by having participants mark the line of text they had reached

Address correspondence to Claudia Carello, Center for the Ecological Study of Perception and Action, 406 Babbidge Rd., U-20, University of Connecticut, Storrs, CT 06269-1020; e-mail: claudia.carello@uconn.edu.

1. This is so whether fluency is taken to imply speed, accuracy, or automaticity.

## Movement and Fluency

in the first passage upon a signal from the experimenter (at the 1-min mark).

For single-finger tapping, the index finger of the dominant or nondominant hand was placed on the space bar of a computer keyboard. The experimenter gave the signal to begin, and the participant tapped that key as fast as possible for 5 s. The participant used the opposite hand for the next trial and alternated on subsequent trials (starting hand was counterbalanced across participants). In all, there were five trials for each hand. The sequential task required that four keys be tapped in order. For the right hand, the index, middle, ring, and little fingers were to tap the "V," "B," "N," and "M" keys in order, beginning with "V"; for the left hand, the fingers were to tap the "V," "C," "X," and "Z" keys in order, also beginning with "V." The instruction was again to tap as fast as possible, this time for 10 s. Once more, the participant used the opposite hand for the next trial and alternated on subsequent trials, for a total of five trials for each hand. For bimanual tapping, participants were to alternate between tapping the "S" key with their left index finger and the "L" key with their right index finger, again as fast as possible for 5 s for a total of five trials.

A short break was provided between the different tapping tasks. Participants always began with the single-finger task and ended with the sequential task. For each task, intertap intervals (ITIs) and the standard deviations of those intervals (including those that resulted from a key-press error) were recorded. For the single-finger and sequential tasks, these measures were obtained separately for the dominant and nondominant hands.

Dependencies between coordination and reading were evaluated in simple regressions of the ITI and standard deviation from each tapping task with respect to each of three regressors: SAT score, total NART errors, and Nelson-Denny errors. The only significant relationship involved the sequential tapping task and the NART decoding score. Significant simple regressions were found for ITI using the dominant hand,  $r = .31$ ,  $F(1, 48) = 4.96$ ,  $p = .03$ ; ITI using the nondominant hand,  $r = .28$ ,  $F(1, 48) = 4.19$ ,  $p < .05$ ; standard deviation using the dominant hand,  $r = .41$ ,  $F(1, 48) = 9.56$ ,  $p < .0035$ ; and standard deviation using the nondominant hand,  $r = .29$ ,  $F(1, 48) = 4.26$ ,  $p < .05$ . All other  $F$ s had a value less than or equal to 1. The nature of the relation between reading and movement was as expected: The fewer errors that readers had made on the decoding task, the faster and more consistent they were at the sequential tapping task. This dependency did not involve the comprehension measures of reading (SAT or Nelson-Denny test), and it did not appear with the nonsequential tasks.

## EXPERIMENT 2

Given that Experiment 1 revealed a connection between phonological decoding skills and sequential finger movements, in the second experiment (which used the same tasks), we explicitly recruited participants so that two extremes of decoding skill level would be included. The Olson Pseudohomophone Test (Olson, Forsberg, Wise, & Rack, 1994) consists of 60 triplets of nonsense letter strings. One of each triplet is a pseudohomophone—that is, a misspelling of a real word that would, nonetheless, sound like that word if pronounced according to the grapheme-phoneme correspondence rules of English (e.g., "kat" sounds like *cat*, "poal" sounds like *pole*). Participants are instructed to circle which member of each triplet "would sound like a real word if sounded out" without actually pronouncing any of the letter strings. This test was administered to 500 introductory psychology students at the University of Connecticut. Good readers were recruited from those who

made no errors; poor readers were recruited from those whose performance was no better than chance (33% correct). When these individuals appeared for testing, they were asked to provide their SAT verbal scores, and then both groups were administered the same reading tests and coordination tasks as in Experiment 1. In order to achieve clear group differences with respect to reading fluency, we further limited good readers to those who performed well on the NART decoding tasks. These selection criteria yielded 11 poor decoders (whose SAT scores ranged from 420 to 610, with an average of 528) and 11 good decoders (whose SAT scores ranged from 500 to 650, with an average of 586). Tapping ITIs and standard deviations were recorded as before, along with key-press errors.

A 2 (good vs. poor readers)  $\times$  2 (single vs. sequential tapping)  $\times$  2 (dominant vs. nondominant hand) analysis of variance (ANOVA) was conducted on ITIs. The main effect of tapping task was significant,  $F(1, 20) = 14.60$ ,  $p < .001$ , with single-finger tapping faster (169 ms) than sequential tapping (218 ms). There was also an effect of hand dominance,  $F(1, 20) = 15.62$ ,  $p < .001$ , with the dominant hand tapping faster (189 ms) than the nondominant hand (199 ms). The numerical difference between good readers (184 ms) and poor readers (204 ms) did not reach significance,  $F(1, 20) = 2.43$ ,  $p < .15$ , but its influence

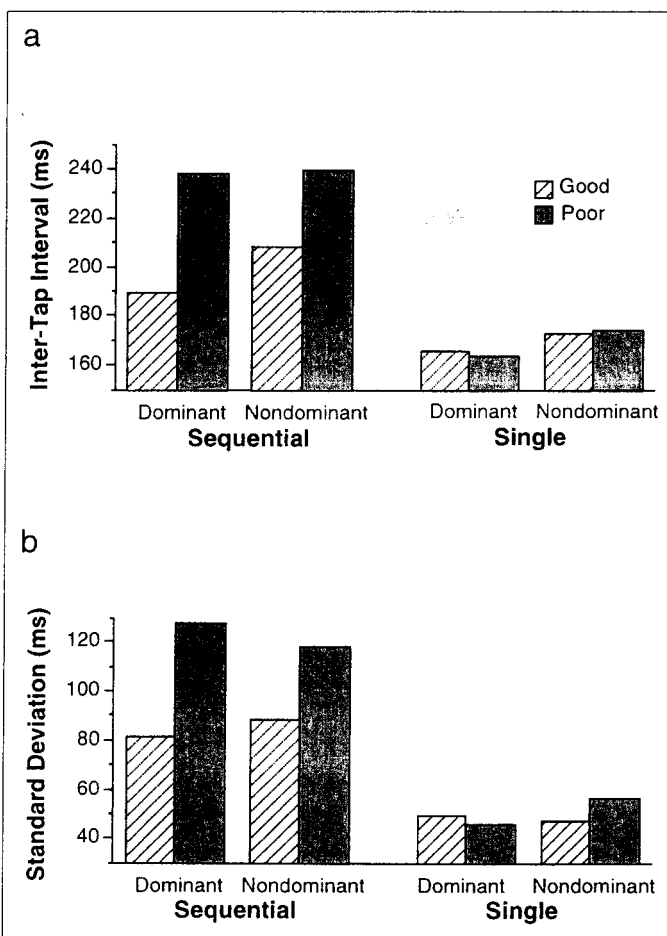
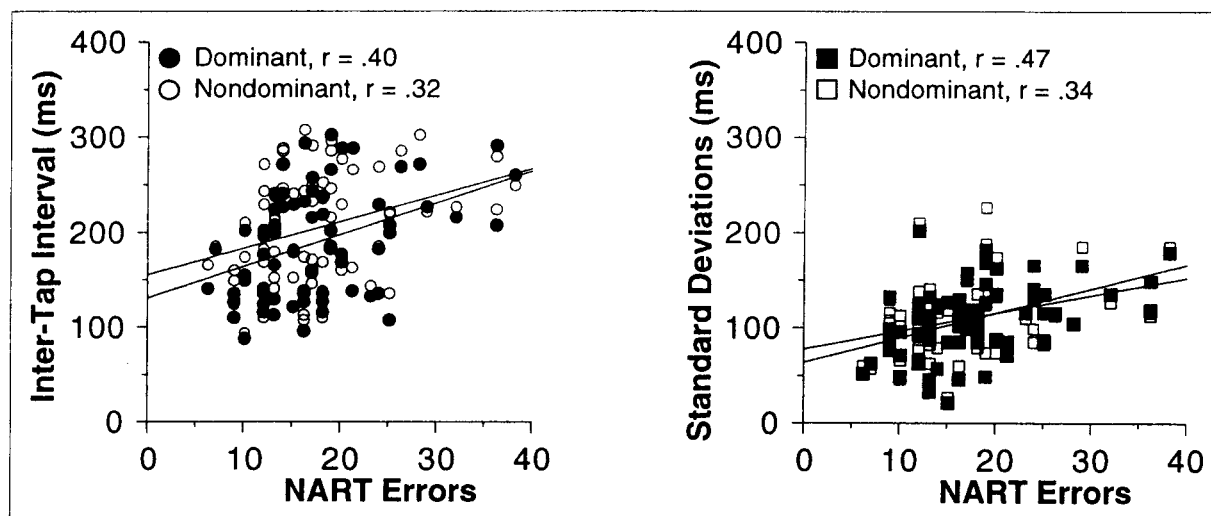


Fig. 1. Intertap interval (a) and variability of tapping (b) of good and poor readers in the sequential and single-finger tapping tasks. Results are shown separately for the dominant and nondominant hand.



**Fig. 2.** Intertap interval (left) and variability of tapping (right) as a function of the number of errors on the National Adult Reading Test (NART; Nelson & O'Connell, 1978) for the 72 participants from both experiments. Separate regression lines and  $r$  values indicate trends for the dominant and nondominant hand.

was seen in the significant Fluency  $\times$  Hand Dominance  $\times$  Task interaction,  $F(1, 20) = 6.39, p < .02$ . In particular, poor readers tapped more slowly than good readers, but only in the sequential tapping task (Fig. 1a). Moreover, the fluency effect was larger for the dominant hand than for the nondominant hand (or, alternatively, poor readers did not show a difference between the dominant and nondominant hands).

A parallel ANOVA on standard deviations was consistent with the preceding analysis. The main effect of reading fluency was significant,  $F(1, 20) = 5.47, p < .03$ , indicating that good readers tapped with less variability (66 ms) than poor readers (87 ms). The task difference was also significant,  $F(1, 20) = 60.62, p < .0001$ , with single-finger tapping less variable (50 ms) than sequential tapping (104 ms). The effect of hand dominance was not significant,  $F < 1$  ( $SD_{\text{dominant}} = 76$  ms,  $SD_{\text{nondominant}} = 77$  ms), nor were the interactions of hand dominance with reading fluency or tapping task,  $F < 1$ . The interaction of reading fluency and tapping task was significant,  $F(1, 20) = 6.69, p < .02$ , as was the Fluency  $\times$  Hand Dominance  $\times$  Task interaction,  $F(1, 20) = 6.38, p < .02$ . Consistent with the analysis of ITIs, the analysis of standard deviations showed that poor readers were more variable than good readers, but only in the sequential tapping task; the fluency difference was exaggerated for the dominant hand (Fig. 1b). A parallel ANOVA on the key-press errors revealed no significant differences,  $F < 1$ .

Bimanual tapping was analyzed separately (because it did not include hand dominance as a separable condition). One-way ANOVAs showed no difference due to reading fluency for ITIs,  $F < 1$  (good decoders averaged 132 ms, poor decoders averaged 132 ms), or standard deviations,  $F = 1$  (good decoders averaged 39 ms, poor decoders averaged 45 ms).

The continuity across experiments is apparent in the significant simple regressions ( $p < .01$ ) of sequential movement measures on a phonological decoding score (Fig. 2). The interrelationships among the whole variety of measures were assessed by a principal components factor analysis using the reading scores common to both Experiments 1 and 2 (i.e., not the pseudohomophone test) and tapping data for all 72 participants. The analysis was restricted to factors with eigen-

values greater than 2 (meaning that a factor was included only if it doubled the variance accounted for). Table 1 shows the loadings of each of the variables on the three independent factors thus extracted. The square of a factor loading represents the proportion of variance of that variable predicted by that factor. The distribution of factor loadings lends further support to the hypothesized relationship between sequential tapping and phonological decoding: The measures of sequential tapping and phonological decoding all loaded strongly on Factor 1, which seems related to coarticulated sequencing. Moreover, the loadings were consistent with the analyses of results from Experiments 1 and 2 in that sequential tapping was distinct from the other movement tasks, which distributed on the other, less well-defined factors. The standard deviations of both single and bimanual tapping were best predicted by Factor 2, whereas the ITIs for these tasks were predicted by Factor 3. The reading tests that were less overtly phonological than the NART loaded most highly on Factor 2 or 3, not on Factor 1.

## DISCUSSION

Consistent with previous observations, the present experiments showed a reliable relation between reading and movement. The data show that this link characterizes readers who generally would be considered unimpaired (i.e., university undergraduates) but whose fluency—as measured by reading rate, comprehension, and decoding—varies. The strongest link observed was between phonological decoding skill and sequential movement skill.

Clearly, manual dexterity does not cause phonological awareness nor vice versa. Rather, we assume some (coarticulated sequencing) skill underlies both. As noted, mastering phonological awareness is inherently difficult under ordinary circumstances. Delay in the development of phoneme awareness seems to accompany underexposure to spoken language, for example, because of low socioeconomic status (Nittrouer, 1996) or hearing difficulties (Campbell & Burden, 1995; Nittrouer, 1996). It has been argued that a smaller than usual lexicon

**Table 1.** Factor loadings of reading tests and tapping tasks for participants in Experiments 1 and 2

Measure	Factor		
	1	2	3
Reading			
Scholastic Assessment Test	-.281	<b>.521</b>	.464
Nelson-Denny comprehension	.335	-.361	<b>-.425</b>
Reading rate	-.222	<b>.377</b>	.116
National Adult Reading Test: I (easier decoding)	<b>.498</b>	-.312	-.435
National Adult Reading Test: II (more difficult decoding)	<b>.641</b>	-.408	-.379
Sequential tapping			
ITI: dominant hand	<b>.610</b>	-.349	.148
ITI: nondominant hand	<b>.577</b>	-.303	.225
SD: dominant hand	<b>.792</b>	.234	-.212
SD: nondominant hand	<b>.685</b>	.294	-.074
Single-finger tapping			
ITI: dominant hand	.288	-.418	<b>.713</b>
ITI: nondominant hand	.310	-.382	<b>.698</b>
SD: dominant hand	.478	<b>.756</b>	.116
SD: nondominant hand	.522	<b>.728</b>	.075
Bimanual tapping			
ITI	.308	-.276	<b>.656</b>
SD	.451	<b>.781</b>	.084

Note. Boldface indicates the factor with the highest loading for each variable. ITI = intertap interval.

results in “fuzzy” phonological representations and, hence, defective phonological awareness (Fowler, 1991; Studdert-Kennedy, 1987, in press). One could imagine that less than usual fluidity in coordinating the articulators would have related consequences for phonological awareness. For example, less articulate children might be less likely to engage in conversation than their more articulate counterparts, thereby reducing their exposure to spoken language. Or their less precise productions may result in phonological representations that are less precise. This conjecture is consistent with the observation that the coordination difficulties of dyslexics extend to speaking as well (e.g., syllable repetition—Wolff, Michel, & Ovrut, 1990; production of tongue twisters—I.Y. Liberman, Shankweiler, & Liberman, 1985; pronunciation accuracy—Scarborough, 1990; distinctness—Elbro, Borström, & Petersen, 1998).<sup>2</sup>

Neural rationales for the reading-coordination link typically focus on impairment of a general mechanism thought to be shared by speaking and motor coordination (e.g., generative assembly—Corballis, 1991; hierarchical organization—Greenfield, 1991; temporal resolution—Hammond, 1982; automatizing skills—Nicolson & Fawcett, 1990). Given that the link extends continuously into a range of reasonably fluent readers, however, impairment per se seems too severe. A more subtle disruption is likely.

The power law of practice suggests that even highly learned skills can be improved asymptotically with continued practice (Provins, 1997). From this understanding, an implication of the present data is that train-

2. Imprecise phonological representations would also compromise rapid automatized naming (Wolf & Bowers, 1999), which may play a more prominent role in languages other than English (e.g., Wimmer, Mayringer, & Landerl, 2000).

ing in phonological decoding skills ought to continue to improve reading fluency even among putatively unimpaired readers. A compatible neurobiological view speculates that such training might improve the “functional connectivity” among supporting cortical areas (Pugh et al., 2000, p. 55). Given the long-term consequences of disfluency (Brady & Shankweiler, 1991), such training might fruitfully be pursued beyond primary school.

**Acknowledgments**—This research was supported by grants from the National Institutes of Health (HD 01994, awarded to Haskins Laboratories) and the National Science Foundation (SBR 97-28970, awarded to M.T. Turvey), as well as a Howard Hughes Medical Institute grant awarded to the College of the Holy Cross. We thank M. Studdert-Kennedy, M.T. Turvey, and Ken Pugh for helpful discussion and comments.

## REFERENCES

- Brady, S.A., & Shankweiler, D.P. (Eds.). (1991). *Phonological processes in literacy: A tribute to Isabelle Y. Liberman*. Hillsdale, NJ: Erlbaum.
- Brown, J.I., Bennett, J.M., & Hanna, G. (1981). *The Nelson-Denny reading test: Examiner's manual*. Chicago: Riverside Publishing.
- Campbell, R., & Burden, V. (1995). Pre-lingual deafness and literacy: A new look at old ideas. In B. de Gelder & J. Morais (Eds.), *Speech and reading* (pp. 109–123). East Sussex, England: Erlbaum Taylor & Francis.
- Corballis, M.C. (1991). *The lopsided ape: Evolution of the generative mind*. New York: Oxford University Press.
- Denckla, M.B. (1985). Motor coordination in dyslexic children: Theoretical and clinical implications. In F. Duffy & N. Geshwind (Eds.), *Dyslexia: A neuroscientific approach to clinical evaluation* (pp. 187–196). Boston: Little, Brown.
- Elbro, C., Borström, I., & Petersen, D.K. (1998). Predicting dyslexia from kindergarten: The importance of distinctness of phonological representations of lexical items. *Reading Research Quarterly*, 33, 36–60.
- Fowler, A. (1991). How early phonological development might set the stage for phoneme awareness. In S.A. Brady & D.P. Shankweiler (Eds.), *Phonological processes in literacy: A tribute to Isabelle Y. Liberman* (pp. 97–117). Hillsdale, NJ: Erlbaum.

- Gladstone, M., Best, C.T., & Davidson, R.J. (1989). Anomalous bimanual coordination among dyslexic boys. *Developmental Psychology*, 25, 236-246.
- Greenfield, P.M. (1991). Language, tools, and brain: The ontogeny and phylogeny of hierarchically organized sequential behavior. *Behavioral and Brain Sciences*, 14, 531-595.
- Hammond, G.R. (1982). Hemispheric differences in temporal resolution. *Brain Cognition*, 1, 95-118.
- Liberman, A.M. (1993). In speech perception, timing is not what it seems. *Annals of the New York Academy of Sciences*, 682, 264-271.
- Liberman, I.Y. (1973). Segmentation of the spoken word. *Bulletin of the Orton Society*, 23, 65-77.
- Liberman, I.Y., Shankweiler, D., & Liberman, A.M. (1985). The alphabetic principle and learning to read. In D. Shankweiler & I.Y. Liberman (Eds.), *Phonology and reading disability: Solving the reading puzzle* (pp. 1-33). Ann Arbor: Michigan University Press.
- Lukatela, K., Carello, C., Shankweiler, D., & Liberman, I.Y. (1995). Phonological awareness in illiterates. *Applied Psycholinguistics*, 16, 463-487.
- Lundberg, I., Frost, J., & Petersen, O. (1988). Effects of extensive program for stimulating phonological awareness in preschool children. *Reading Research Quarterly*, 23, 263-284.
- Morais, J., Bertelson, P., Cary, L., & Alegria, J. (1986). Literacy training and speech segmentation. *Cognition*, 24, 45-64.
- Nelson, H.E., & O'Connell, A. (1978). Dementia: The estimation of premorbid intelligence levels using the New Adult Reading Test. *Cortex*, 14, 234-244.
- Nicolson, R.I., & Fawcett, A.J. (1990). Automaticity: A new framework for dyslexia research? *Cognition*, 35, 159-182.
- Nittrouer, S. (1996). The relation between speech perception and phoneme awareness: Evidence from low-SES children and children with chronic OM. *Journal of Speech and Hearing Research*, 39, 1059-1070.
- Olson, R., Forsberg, H., Wise, B., & Rack, J. (1994). Measurement of word recognition, orthographic, and phonological skills. In G. Reid Lyon (Ed.), *Frames of reference for the assessment of learning disabilities: New views on measurement issues* (pp. 243-277). Baltimore: Paul H. Brookes.
- Provins, K.A. (1997). The specificity of motor skill and manual asymmetry: A review of the evidence and its implications. *Journal of Motor Behavior*, 29, 183-192.
- Pugh, K.R., Mencl, W.E., Shaywitz, B.A., Shaywitz, S.E., Fulbright, R.K., Constable, R.T., Skudlarski, P., Marchione, K.E., Jenner, A.R., Fletcher, J.M., Liberman, A.M., Shankweiler, D.P., Katz, L., Lacadie, C., & Gore, J.C. (2000). The angular gyrus in developmental dyslexia: Task-specific differences in functional connectivity within posterior cortex. *Psychological Science*, 11, 51-56.
- Scarborough, H.S. (1990). Very early language deficits in dyslexic children. *Child Development*, 61, 1728-1743.
- Studdert-Kennedy, M. (1987). The phoneme as a perceptuo-motor structure. In A. Allport, W. Prinz, & E. Scheerer (Eds.), *Language perception and production* (pp. 67-84). New York: Academic Press.
- Studdert-Kennedy, M. (in press). Deficits in phoneme awareness do not arise from failures in rapid auditory processing. *Reading and Writing*.
- Wimmer, H., Mayringer, H., & Landerl, K. (2000). The double-deficit hypothesis and difficulties in learning to read a regular orthography. *Journal of Educational Psychology*, 92, 668-680.
- Wolf, M., & Bowers, P.G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology*, 91, 415-438.
- Wolff, P.H. (1999). A candidate phenotype for familial dyslexia. *European Child and Adolescent Psychiatry*, 8, III/21-III/27.
- Wolff, P.H., Michel, G.F., & Ovrut, M. (1990). The timing of syllable repetitions in developmental dyslexia. *Journal of Speech and Hearing*, 33, 281-289.
- Wolff, P.H., Michel, G.F., Ovrut, M., & Drake, C. (1990). Rate and timing precision of motor coordination in developmental dyslexia. *Developmental Psychology*, 26, 349-359.

(RECEIVED 5/8/01; REVISION ACCEPTED 9/28/01)