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Speech Perception Deficits in Poor Readers: Auditory Processing or Phonological Coding?

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Poor readers are inferior to normal-reading peers in aspects of speech perception. Two hypotheses have been proposed to account for their deficits: (i) a speech-specific failure in phonological representation and (ii) a general deficit in auditory "temporal processing," such that they cannot easily perceive the rapid spectral changes of formant transitions at the onset of stop-vowel syllables. To test these hypotheses, two groups of second-grade children (20 "good readers," 20 "poor readers"), matched for age and intelligence, were selected to differ significantly on a /ba/–/da/ temporal order judgment (TOJ) task, said to be diagnostic of a temporal processing deficit. Three experiments then showed that the groups did not differ in: (i) TOJ when /ba/ and /da/ were paired with more easily discriminated syllables (/ba/–/sa/, /da/–/ʃa/); (ii) discriminating nonspeech sine wave analogs of the second and third formants of /ba/ and /da/; (iii) sensitivity to brief transitional cues varying along a synthetic speech continuum. Thus, poor readers' difficulties with /ba/–/da/ reflected perceptual confusion between phonetically similar, though phonologically contrastive, syllables rather than difficulty in perceiving rapid spectral changes. The results are consistent with a speech-specific, not a general auditory, deficit. © 1997 Academic Press

Reading is a complex skill and there are many reasons that children may fail. The most firmly established correlate of reading disability is a deficiency

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in skills related to phonological processing. Phonological processing entails the segmental analysis of words for ordinary speaking and listening, as well as the metaphonological skills required for explicitly analyzing the sound structure of speech into the phonemic components represented by the alphabet. Many studies have shown poor readers to be significantly inferior to their normal reading peers in ". . . perceptual discrimination of phonemes, phonological awareness tasks involving the manipulation of phones within words, speed and accuracy in lexical access for picture names, verbal short-term memory, syntactic awareness and semantic processing on tasks of listening comprehension" (Olson, 1992, p. 896). Many, if not all, of these weaknesses may arise, directly or indirectly, from a deficit in speech perception. Several independent lines of research point to speech perception as a source of subtle, but ramifying deficit in reading-impaired children and adults.

The nature and origin of the perceptual deficit have been a matter of debate for over 15 years. One account sees it as purely linguistic, specific to speech and closely related to the deficit in verbal working memory, also often observed in poor readers (e.g., Bradley & Bryant, 1991; Brady, Shankweiler, & Mann, 1983; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). Accordingly, poor readers are said to have normal auditory capacities, but, for unknown reasons, to be less efficient in transforming linguistic input, whether spoken or written, into the phonological code necessary for working and long-term verbal memory. The assumption here is that both reading and listening require lexical items to be held in working memory long enough to extract syntactic structure and meaning from the strings of which they are part. Deficient phonological access or storage may then show up as an impairment in reading and listening, perhaps even masquerading as a syntactic deficit (Shankweiler & Crain, 1986).

An alternative account also acknowledges the difficulty as phonological, but sees it as stemming from a general auditory deficit in "temporal processing." Tallal (1980), the original proponent of this account, asserts that reading-disabled children cannot easily process brief and/or rapidly changing acoustic events, whether speech or nonspeech. They therefore have difficulty in judging the temporal order not only of brief, rapidly presented nonspeech tones, but also of stop–consonant–vowel syllables contrasting in their initial formant transitions. The difficulty subtly interferes with overall speech perception and so with normal language development, including learning to read.

The Speech-Specific Hypothesis

At least three independent bodies of evidence are consistent with a speech-specific interpretation of the perceptual deficit: studies of categorical perception, of speech perception under demanding conditions, and of verbal memory span.

Categorical Perception

Reading-impaired children have characteristically deviant patterns of identification and discrimination on tests of categorical perception with synthetic speech sounds. For example, Godfrey, Syrdal-Lasky, Millay, and Knox (1981), comparing performances on two synthetic continua, /ba/–/da/ and /da/–/ga/, found that dyslexic subjects were significantly less consistent than normals in identification, even at the extremes of the continua. Other studies have reported similar results for /ba/–/da/ (Reed, 1989; Steffens, Eilers, Gross-Glen, & Jallad, 1992; Werker & Tees, 1987), for /pʌ/–/tʌ/ (De Weirdt, 1988), and for /sa/–/sta/ (Steffens et al., 1992). Inconsistent identification can also give rise to deviant patterns of discrimination along synthetic continua. For example, poor readers may be less accurate than good readers on between-category, but not on within-category discrimination, suggesting that poor readers cannot easily exploit the phonological contrast that normally enhances discrimination across a phoneme boundary (De Weirdt, 1988; Godfrey et al., 1981; Pallay, 1986; Werker & Tees, 1987). In short, the poor readers' difficulties in all these studies seem to have been primarily in identifying phonetically similar, though phonologically contrastive, synthetic syllables. Such results suggest that speech categories may be, for unknown reasons, broader and less sharply separated in reading disabled than in normal children.

Speech Perception under Demanding Conditions

A variety of tests has found poor readers to be less successful than good readers at recognizing spoken words under demanding conditions. An effective way to increase the difficulty of repetition tasks and to reveal reading-group differences is to reduce the familiarity of stimuli by using pseudowords (Apthorp, 1995; Brady, Poggie, & Rapala, 1990; Gathercole & Baddeley, 1993; Hansen & Bowey, 1994; Snowling, Goulandris, Bowlby, & Howell, 1986; Taylor, Lean, & Schwartz, 1989). A subject then necessarily relies on the phonological representation of novel input to formulate and execute a correct response. Recent results have confirmed that poor readers are less accurate at pseudoword repetition than both chronological-age matched good readers and reading-age matched controls (Stone & Brady, 1995). Reading group differences have also been reported when the perceptual difficulty of tasks has been increased by presenting time-compressed speech (Freeman & Beasley, 1978; Pallay, 1986; Watson & Rastatter, 1985), synthetic speech or speech produced by infants (Lieberman, Meskill, Chatillon, & Shupack, 1985), and by embedding words in noise (Brady et al., 1983; Snowling et al., 1986). For example, poor readers were significantly worse than good readers at repeating naturally spoken monosyllabic words presented in noise, but no worse when the same stimuli were presented without noise (Brady et al., 1983). By contrast, with nonspeech sounds (e.g., environmental sounds such as clapping, knocking on a door, etc.), both groups were worse on the noisy condition, but to the same degree. These results also are consistent with the notion that phonological categories are broader and less well separated among disabled than among normal readers: Poorly defined categories would presumably be more vulnerable to signal degradation by noise than well-defined categories.

In a related study of normal adults, Rabbitt (1968) found poorer recall of digits correctly perceived in noise than of digits correctly perceived in quiet. In accord with a limited capacity model of working memory, Rabbit argued that adding noise to the signal necessitated increased use of resources, so that fewer resources were available for storing items in memory. Brady et al. (1983) link their perceptual results to Rabbitt's short-term memory findings, and hypothesize that poor readers' inferior performances on both speech-in-noise and verbal working memory stem from relatively coarse-grained phonological storage.

Verbal Memory Span

Poor readers often have shorter verbal memory spans than do good readers of comparable age, and their memory deficits are specific to speech: When stimuli are neither words nor easy to represent linguistically by verbal labels, recall has not been found to be related to reading ability. (For review and discussion, see Brady, 1991; Perfetti, 1985; Wagner & Torgesen, 1987.) This lack of correlation has been observed in memory tasks with nonsense figures and unfamiliar writing systems as well as on a standard test of visual pattern recall, the Corsi Block Design Test (Gould & Glencross, 1990; Katz, Shankweiler, & Liberman, 1981; Liberman, Mann, Shankweiler, & Werfelman, 1982; Rapala & Brady, 1990; Vellutino, Pruzek, Steger, & Meshoulam, 1973). The difference is not, however, a matter of input modality (visual vs. auditory): On verbal tests both good and poor readers display essentially the same patterns of errors whether the list to be recalled is heard or read (Shankweiler et al., 1979). Therefore, rather than attribute the poor readers' memory deficit to the coincidence of low level dysfunctions in both auditory and visual systems, as does Tallal (e.g., Tallal, 1990; Tallal, Sainburg, & Jernigan, 1991), the speech-specific hypothesis attributes it to a deficit in the phonological representation common to both modes of input.

The General Auditory Hypothesis Critically Examined

A more general account attributes the phonological deficits of reading disabled children and certain other clinical populations to an impaired rate of auditory processing: Defective children are simply slower than normals in apprehending the auditory structure of a signal. If children are slower, their deficit can show up in at least two ways: (i) They can be poor at perceiving signals that follow one another rapidly (i.e., that have short interstimulus intervals (ISIs); (ii) they can be poor at perceiving signals that are very brief. If the two properties, brief signal and short ISI, are combined, as in consonant formant transitions followed immediately by a vowel, children with this deficit will be doubly disadvantaged. Thus, rapid spectral changes, such as formant transitions at the onset of stop consonant–vowel syllables, pose a special problem for these children. Tallal draws on her findings with developmental aphasics (Tallal & Piercy, 1973, 1974, 1975) and aphasic adults (Tallal & Newcombe, 1978) to support this position.

Defining Temporal Perception

Before considering the hypothesis in detail, we must clarify terminology. First, we should distinguish between capacities often confounded in the literature: namely, perceiving the temporal properties of events (duration, sequence, relative timing, rhythm), on the one hand, and rapidly identifying or discriminating between very brief events, on the other. Only a deficit in the former can properly be considered a deficit in "temporal analysis," "temporal processing," or "temporal perception." Difficulties in perceiving very brief events and/or events with very brief intervals between them indicate a deficit not in temporal perception, but in the perception of rapidly presented information. We should not confuse rate of perception with perception of rate. Perception is temporal if the defining property of the perceived event is temporal; it does not become temporal by virtue of being effected rapidly.

The second important distinction in terminology is between identification and discrimination. To identify a stimulus is to assign it a specific response, such as pressing a certain button or saying its name. To discriminate between stimuli is merely to indicate that they are different in some respect. Identification therefore entails discrimination, but not vice versa. For temporal order judgment (TOJ), discrimination alone is not enough: Identification is required. Errors are therefore ambiguous, unless we have independent evidence of correct identification. The difficulty is obvious from the standard format of TOJ tests in which pairs of stimuli (1, 2) are presented for ordering in the combinations: 1–1, 2–2, 1–2, 2–1. All errors where the same stimuli are judged as different, or different stimuli are judged as the same, necessarily involve errors of identification. Only errors of reversal (e.g., 1–2 for 2–1) may be pure errors of temporal judgment. The reader should bear this ambiguity in mind throughout our discussion and reports on TOJ tests below. Arguably, all the supposed difficulties in "auditory temporal perception," or actual difficulties in perceiving rapidly presented information, so far reported for both reading-impaired and specifically language-impaired children, can be traced to difficulties in stimulus identification. Tallal has repeatedly acknowledged this fact (e.g., Tallal, 1980, p. 193; Tallal & Piercy, 1973, p. 396; Tallal et al., 1991, p. 365), and Reed (1989, pp. 287–289) makes the same point.

Developmentally Aphasic Children and Aphasic Adults

In the first of a series of studies, Tallal and Piercy (1973) found developmentally aphasic children (n = 12) to be significantly impaired, in comparison to an equal number of age-matched, normal controls, on tasks involving rapid auditory perceptual processing. The dysphasic, or language-impaired, children had difficulty with

TOJ for pairs of complex tones differing in fundamental frequency (100 vs. 305 Hz). The impaired children made significantly more TOJ errors than normal controls when the tones were short (75 ms) rather than long (250 ms), and/or when the interval between the tones (ISI) was short (150 ms) rather than long (300 ms). The authors viewed these findings as evidence that developmental aphasics process auditory stimuli more slowly than normals.

On the hypothesis that, if children had trouble perceiving rapid auditory events, it would be evident in their perception of speech, Tallal and Piercy (1974) extended their research to verbal stimuli characterized by brief and rapid spectral changes. Their stimuli were: the synthetic syllables, /ba/ and /da/, for which the brief (approx. 40 ms) second and third formant transitions at onset are critical cues to consonant place of articulation; two synthetic three-formant steady-state vowels, /ɛ/ and /ae/; and the two long tones of the previous study. All stimuli were 250 ms in duration. Repeating their earlier procedure, the investigators found that only 5 of the 12 dysphasic subjects reached identification training criterion with /ba/ and /da/, and only 2 of these 5 reached criterion on same/different discrimination of these stimuli at a long ISI; only these 2 therefore were tested on TOJ at short ISIs. By contrast, all 12 controls readily reached training criterion on /ba/–/da/ and performed perfectly on discrimination and TOJ at all ISIs. On the same tasks with the 250 ms vowels and tones, the two groups did not differ significantly. We emphasize that the dysphasic children's difficulties were not shown to be with TOJ, on which only 2 of them were tested (both doing well), but with the identification and discrimination of /ba/ and /da/.

In a further study, Tallal and Piercy (1975) showed that these same children had no difficulty with /ba/–/da/ when their F1, F2 and F3 transitions were extended from 43 to 95 ms. In this study all 12 aphasic children and their matched controls reached criterion on identification, and on TOJ and discrimination at a long ISI. Even when ISI was reduced, dysphasics continued to perform as well as normals. Thus, improved TOJ at short ISIs followed improved identification, suggesting again that the difficulty was with the latter rather than the former. That dysphasics did worse when the syllables incorporated brief formant transitions was viewed as consistent with the earlier findings for brief nonspeech tones. Taken together the two findings suggested to the authors that (i) ". . . it is the brevity not the transitional character of this component of synthesized stop consonants, which results in the impaired perception of our dysphasic children" (Tallal & Piercy, 1975, p. 73), and (ii) the impairment was due to a general auditory deficit, not specific to speech. Notice, however, that the authors did not establish the auditory basis of the dysphasic children's difficulties with /ba/–/da/ by demonstrating equivalent difficulties for appropriate nonspeech control patterns with brief and rapidly changing onset frequencies. The claim that the deficit was general and auditory rather than phonetic and specific to speech was therefore unsubstantiated, and has remained so.

No one, so far as we know, has replicated the results of Tallal and Piercy (1975) with specifically reading-impaired children, but Tallal and Newcombe (1978) did observe improved identification of /ba/–/da/ with lengthened transitions (from 40 ms to 80 ms) in 4 of 10 adult aphasics. Attempts to replicate these results have not been successful, however. Two studies, with a combined total of 25 adult aphasic subjects, failed to find that lengthened transitions improved either identification or discrimination of stop consonant place of articulation (Blumstein, Tartter, Nigro, & Statlender, 1984; Riedel & Studdert-Kennedy, 1985). We should note, moreover, that even if the advantage due to lengthened transitions were better attested than it is, its interpretation would be uncertain. The standard finding in the acoustic phonetic literature is that the perceived manner of syllable-initial stop consonants shifts from stop to glide when formant transitions are lengthened (Borden, Harris, & Raphael, 1994, Chapter 6). Improved identification and discrimination by aphasic subjects due to lengthened transitions may then reflect either facilitated auditory processing, as Tallal and Piercy (1975) assert, or increased phonetic distance across a phonological contrast.[3]

Auditory Temporal Perception and Phonological Decoding

We turn next to the paper in which Tallal (1980) extended her hypothesis concerning the perceptual deficits of dysphasic children to children with reading impairments (cf., Tallal (1984) and Tallal, Miller, and Fitch (1993), for example, who also propose extending the hypothesis to reading-impaired children). She tested 20 reading-impaired children on a battery of tests, including verbal and performance IQ, five reading tests, and two nonspeech auditory perceptual tests. The last were the short ISI discrimination and TOJ tests with 75-ms complex tones differing in fundamental frequency (100 vs. 305 Hz), described above. Tallal compared the performance of the 20 reading-impaired children on the auditory tests with that of 12 normal controls from a previous study (Tallal, 1976). Eleven of the reading-impaired children performed normally; only 9 fell below the worst control.

Despite this variability, Tallal found significant rank-order correlations between nonverbal auditory perception and all five reading tests. The highest correlation was between tone TOJ and a Nonsense Word Reading Test, evaluating decoding skill (Spearman's $R = .81$, $p < .001$). Tallal argued that the children's difficulties in identifying brief, rapidly presented tones related to their difficulties in reading by appealing to her previous findings with dyspha-

[3] Riedel and Studdert-Kennedy (1985), who modeled their synthetic syllables on those of Tallal & Piercy (1975), found that when transitions were increased from 30 to 82 ms, identifications reported by their aphasic subjects included, in addition to /ba/–/da/: /wa/–/la/, /bwa/–/dla/, /wa/–/da/ and /ra/–/ja/. The diversity of response was probably due to the absence of systematic variations in prevoicing, normally present in natural or well-synthesized /ba/–/wa/ and /da/–/ja/ contrasts.

sic children who had difficulty both with brief tones and (by hypothesis) with brief formant transitions at the onset of /ba/ and /da/ (Tallal & Piercy, 1973, 1974, 1975). If we assume that the reading-impaired children of Tallal (1980) suffered from this same syndrome of deficits, we have ". . . a possible basic perceptual mechanism that may underlie some difficulties in analyzing the phonetic code efficiently, and ultimately in learning to read" (p. 196). The supposedly defective mechanism is that engaged for ". . . the analysis of rapidly changing acoustic information . . . in formant transitions . . . [D]-ifficulty in analyzing rapid information may lead to difficulty in analyzing speech at the phonemic level . . . [and so to] some of the difficulties . . . poor readers . . . have segmenting and recoding phonemically" (p. 196).

Yet several questions arise. First, the reading-impaired children's performance on tone TOJ was not significantly worse than their performance on tone discrimination. From this finding Tallal (1980) inferred (as she had earlier inferred for her developmental aphasics) that their ". . . difficulty with temporal pattern perception may stem from a more primary [sic] perceptual deficit that affects the rate at which they can process perceptual information" (p. 193). In other words, the difficulty may not have been with "auditory temporal perception" itself (as the title of the paper implies), but with identifying the tones correctly, when they were presented in rapid succession.

Second, the reading-impaired children's difficulties in identifying brief tones at short ISIs do not warrant the inference that they would have had similar difficulties with /ba/ and /da/. To be sure, Reed (1989), the only researcher to have tested specifically reading-impaired children on both speech and nonspeech tasks in the Tallal paradigm, did find that such children performed significantly worse than normal controls on TOJ for both brief tones and stop consonants. And at least two other studies have reported poor performance by disabled readers on tone TOJ (e.g., Bedi, 1994) and on stop-consonant discrimination at short ISIs (Hurford & Sanders, 1990). But we have no reason to suppose that the two weaknesses reflect the same underlying discriminative deficit, because tones and syllables contrast on entirely different acoustic dimensions. The tones are discrete, steady-state events, contrasting in fundamental frequency; the transitions of synthetic /ba/ and /da/ are continuous spectral sweeps, contrasting in spectral locus and direction. (For a critique of the equation of tone sequences with formant transitions, see Studdert-Kennedy and Mody, 1995.)

Finally, the proposal that difficulty in identifying /ba/ and /da/ should be attributed to difficulty in "the analysis of rapidly changing acoustic information" is precisely the hypothesis that Tallal and Piercy (1975) tested with dysphasic children and, as we have seen, rejected in their conclusion that ". . . it is the brevity, not the transitional character" (p. 73) of formant transitions that causes difficulty. Yet no subsequent experiment has established, by means of an appropriate nonspeech control, that rapid acoustic changes are indeed difficult to perceive for either specifically language-impaired or specifically reading-impaired children.

In fact, the only relevant study known to us does not even support the claim that reading-impaired children are likely to have difficulty with the brevity, let alone the spectral changes, of formant transitions. Pallay (1986) manipulated the duration of F1 transitions along two synthetic continua: one ranging from /ba/ (30-ms transitions) to /wa/ (100-ms transitions) and the other, a nonspeech control, ranging across the isolated F1 transitions of the /ba/–/wa/ continuum. Second-grade reading-impaired children and matched normal controls identified the stimuli as /ba/ or /wa/ for the speech series, and as "long" or "short" for the nonspeech series. There was no significant difference between normal and poor readers in the positions of their category boundaries on either series. In other words, poor readers did not need a longer F1 transition than normal controls to identify stimuli either as /wa/ or as "long." We should emphasize that the manner contrast, /ba/–/wa/, unlike the place contrast, /ba/–/da/, does call for a temporal judgment. For while place information is largely carried by a pattern of spectral change in F2 and F3, stop-glide manner information is largely carried by the duration of the F1 transition into the vowel (Liberman, Delattre, Gerstman, & Cooper, 1956). Here, then, in the only study ever to call on reading-impaired children to identify both speech sounds contrasting in their temporal properties and an appropriate set of nonspeech controls, the children displayed completely normal capacities, both auditory and phonetic.

In sum, no direct evidence for a temporal-processing deficit in poor readers has been reported. However, a number of studies have found that poor readers may have difficulties in discriminating or identifying /b/–/d/ (e.g., Godfrey et al., 1981; Hurford & Sanders, 1990; Reed, 1989; Steffens et al., 1992; Werker & Tees, 1987). An auditory account of that effect, attributing it to a deficit in some aspect of so-called temporal processing, has not yet been subjected to direct test. Such a test was a main purpose of the present study.

The Present Study

Experiment 1a served to select a group of poor readers who had difficulty with synthetic /ba/–/da/ TOJ in a test modeled after Tallal's, and a group of good readers who had no such difficulty; both groups were also tested on /ba/–/da/ discrimination. Selection was necessary to ensure that the poor readers did indeed have difficulty with /ba/–/da/ TOJ, because both Tallal (1980) and Reed (1989) found poor readers whose TOJ performance fell within the normal range. Experiment 1b determined whether the poor readers' apparent difficulties with TOJ and discrimination remained when the syllables to be judged were highly contrastive, and so readily identifiable. If the difficulties vanished for readily identifiable syllable contrasts, we could conclude that errors on /ba/–/da/ TOJ were due to difficulties in identifying the syllables rather than in judging their temporal order.

Experiment 2 was a nonspeech discrimination control for Experiment 1a, using sine wave patterns corresponding to the center frequencies of F2 and

F3 in synthetic /ba/ and /da/. If poor readers displayed the same effects of reduced ISI on discrimination of nonspeech control patterns as they had on discrimination of the full syllables, we could conclude that their difficulties might indeed arise in the auditory processing of rapid spectral changes; on the other hand, if effects of ISI, and group differences, disappeared, we could conclude that poor readers' difficulties with /ba/–/da/ were not auditory, but phonetic; that is, specific to the perception of speech.

Yet whatever the outcome of Experiment 2, it would be of interest to know whether poor readers' difficulties extended to other phonological contrasts carried by brief formant transitions. Experiment 3 therefore compared good and poor readers on sensitivity to the frequency extent of rapid F1 transitions varying along a synthetic continuum from /seI/ to /steI/. If poor readers were less sensitive to transitional information than are good readers, we would expect them to need a more extensive transition in order to detect the presence of a stop between fricative and vowel. Alternatively, we might expect, from the results of a previous study with this continuum (Nittrouer, 1992), in which 3-, 4-, and 5-year-olds proved more rather than less sensitive to formant transition variations than 7-year-olds and adults, that this final test would afford a measure of developmental delay in the speech perception of 8-year-old impaired readers. If neither of these outcomes occurred, we could conclude that poor readers did not differ from good readers in their sensitivity to the extent of formant transitions.

GENERAL METHOD

Subjects

The subjects consisted of 40 second-grade children (mean grade level: 2.5 yrs), between the ages of 7;0 and 9;3 years, from a public school district in south-central Connecticut. These were drawn from a pool of 220 children screened for the study. The large pool was necessitated partly by school requirements that all members of a class participate, partly by the study's stringent criteria for performance and for statistical matching of the groups.

Overview of Selection Criteria

Because two of the central goals were to study whether problems on TOJ tasks stem from difficulties with identification and whether less skilled readers have difficulty on both speech and nonspeech tasks, it was essential to select poor readers who could meet an identification training criterion for /b/ and /d/, yet who made errors on the speech TOJ task. These demands ruled out a number of poor readers (n = 10), who like over half of Tallal's (1980) subjects on tone TOJ, failed to make errors on /ba/–/da/ TOJ. For reasons detailed below, the remaining subjects reading below grade level were matched as a group (n = 20) in age and in verbal and nonverbal IQ scores with a group of better readers (n = 20). The combined set of criteria, and some

TABLE 1
Mean (*M*) and Standard Deviation (*SD*) for Good and Poor Readers on Each of the Selection Criteria

	Good readers		Poor readers		
	M	*SD*	*M*	*SD*	*t*
Age (months)	95.9	5.3	97.0	6.6	0.61
PPVT-R (standard scores)	98.5	7.7	97.4	7.7	0.43
WISC-R (standard scores)	105.9	9.2	106.3	14.2	0.33
Word identification[a]	4.4	0.8	2.1	0.3	11.97*
Word Attack[a]	8.9	4.6	1.9	0.4	6.80*
/ba/–/da/					
TOJ (errors[b])	0.0	0.0	7.4	4.4	7.59*
Discrimination (errors[b])	0.0	0.0	5.8	3.9	6.65*

[a] Grade equivalent scores.
[b] Errors out of 36 trials per subject, across three short ISIs combined.
* $p < .001$.

additional screening requirements, disallowed many subjects, but resulted in a well-matched set of participants for whom differences on the experimental measures were interpretable.[4] Table 1 lists means and standard deviations on the selection criteria for the two groups.

Reading

Reading performance was assessed with the Word Attack and Word Identification subtests of the Woodcock-Johnson Reading Mastery Test–Revised (Woodcock, 1987). These measures were selected because of converging evidence that the major reading deficits for poor readers are difficulties in decoding and in word recognition (e.g., Olson, Forsberg, Wise, & Rack, 1994; Rack, Snowling, & Olson, 1992; Stanovich, 1991). To ensure appropriate classification, an individual was included as a skilled or unskilled reader only if his or her scores on the two Woodcock subtests both categorized the child as a skilled reader or as a less skilled reader. Because reading ability is normally distributed, and because dyslexia is not a discrete clinical category

[4] In accordance with the criteria detailed in the Subjects section, 122 subjects were eliminated from the study for: borderline reading scores that did not fall clearly within the skilled or less skilled reading groups (n = 28); high PPVT-R or WISC-R scores (n = 60); hearing difficulty, bilingualism, or documented attention-deficit disorder (n = 32); school absence (n = 2). The remaining 98 subjects comprised 66 good readers and 32 poor readers. From these we eliminated: 29 good readers and 2 poor readers due to lack of match on IQ or age; good readers with at least one TOJ error (n = 13); and poor readers with fewer than three TOJ errors (n = 10). Four good readers were then dropped at random to form two matched groups with n = 20.

(e.g., Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992; Stanovich & Siegel, 1994), our goal was to test groups of 20 subjects each, well separated in reading level, but conforming to the other selection criteria described below. The less skilled readers selected were all at least five months behind midyear grade level in their reading; the good readers were at least five months above grade level. The two groups did not overlap on their reading scores as measured by the Woodcock subtests. We note, further, that these measures tend to overestimate reading skill, as may be judged from the fact that 17 of the poor readers had been identified by their school's reading coordinator as having reading difficulties, and were receiving supplemental reading instruction.

IQ

Studies have shown that poor readers with low IQ perform worse than poor readers with normal IQ on the Tallal nonspeech tone task (Jorm, Share, Maclean, & Matthews, 1986). Therefore, to avoid potential problems of IQ confounds, we selected children who differed in reading ability but whose IQs (as estimated by the Peabody Picture Vocabulary Test–Revised (PPVT-R) (Dunn & Dunn, 1981)) and by the Block Design subtest of the Wechsler Intelligence Scale for Children–Revised (WISC-R) (Wechsler, 1974) were in the normal range and were fairly comparable. The inclusion range was specified as scores from 80–120, although, because of difficulty in finding poor readers who met all the specified criteria, two children with Block Design scores of 135 were included. Thus the groups were closely matched on receptive language and on nonverbal IQ.

Temporal Order Judgment on /ba/–/da/

As noted above, the groups were further defined on the basis of their performance on Tallal's /ba/–/da/ TOJ task. Only poor readers who made a minimum of three errors out of 36 trials (8%) on the three short ISIs combined, and good readers who scored 100% correct on the same were included. We would have preferred a higher minimum error rate for the poor readers, but were compelled to settle for an arbitrary 8%, an average of one error in each block of 12 trials at each ISI, by the shortage of poor readers making substantial numbers of errors.[5] Nonetheless, the groups were well separated on /ba/–/da/ TOJ at short ISIs: the good readers' mean number of errors was zero, the poor readers' mean number of errors differed significantly from zero. As

[5] Performance on the /ba/–/da/ TOJ task is far from normally distributed either within or across the populations of good and poor readers. Of the 40 good readers tested on 36 trials each, 27 (67%) made no errors at all, 35 (87%) made fewer than three errors, and only 5 (12%) made three or more errors; by contrast, of the 31 poor readers tested, 1 (3%) made no errors, 10 (32%) made fewer than three errors, and 20 (65%) made three or more errors.

indicated in Table 1, the mean number of errors on /ba/–/da/ discrimination at short ISIs was also zero for the good readers and also differed significantly from zero for the poor readers.

The selection of subjects on the basis of performance on /ba/–/da/ TOJ was an essential part of the experimental design, both to ensure that the poor readers displayed behavior consistent with the deficit that Tallal (1980) proposes may underlie difficulties in segmenting and recoding speech phonemically and to ensure that the good readers differed significantly from the poor readers in this respect. We emphasize that this aspect of the experimental design precluded either good readers or poor readers from being fully representative samples of the good and poor reading populations. Rather, they were samples from experimentally defined populations of good readers who make no errors on Tallal's task and of poor readers who make at least 8% errors on that task. Because the main goal of the study was to test a hypothesis concerning the cause of errors on the task, these were appropriate target populations.

Age

The skilled and less skilled readers were matched on age to control for potential developmental factors on performance.

Additional Criteria

All subjects came from middle-income families, had no history of emotional, neurological, or attentional disorders, and were monolingual, native speakers of English (i.e., English was the predominant language spoken in the home). They had normal hearing (25 dB SPL at 500 Hz, and 20 dB SPL at 1000, 2000, 4000, 6000, and 8000 Hz) and no dialect-related consonant substitutions or omissions relevant to the stimuli being used in the study. Except for two good readers, who were ambidextrous, all subjects were right-handed. Handedness was determined by an abbreviated five-question checklist drawn from Annett's (1970) original set of criteria for handedness. The checklist consisted of the following questions: Which hand do you use for the following activities: writing, brushing your teeth, throwing a ball, swinging a bat, hammering a nail? Subjects were considered right handed, if they used their right hand for all five tasks. Written consent was obtained from the parents of all participants.

Procedures

All testing was done individually in a quiet room in the children's schools. After the screening tests, qualified subjects met with the experimenter three more times; each session lasted about 45 minutes. Four speech perception tasks (one not reported here) and one non-speech perception task were administered over the course of the study. The final screening test, using Tallal's TOJ task, was carried out as Part a of Experiment 1. Stimuli were presented through TDH-39 headphones at a comfortable listening level. Subjects were rewarded with colorful stickers and/or pencils.

EXPERIMENT 1

Experiment 1a was a portion of the subject-selection process, intended to establish a significant difference between good and poor readers on TOJ at short ISIs for /ba/–/da/ in the standard Tallal task. Experiment 1b was designed to determine whether the apparent TOJ deficit of the poor readers in 1a might arise from difficulties in identifying /ba/ and /da/ at rapid rates of presentation due to their close acoustic-phonetic similarity rather than from a deficit in judgments of temporal order itself. If this were so, we would expect their difficulties to disappear when the syllables were presented in more easily discriminable pairs, such as /ba/–/sa/ and /da/–/ʃa/. Notice that while /ba/–/da/ differ on a single phonetic feature (place), /ba/–/sa/ and /da/–/ʃa/ differ on three features (place, manner, voicing). Experiment 1b therefore tested discrimination and TOJ for these stop-fricative combinations.

Method

Stimuli

The syllables /ba/, /da/, /sa/ and /ʃa/ were generated on the Haskins serial synthesizer on a VAX 11/780. The stimuli /ba/ and /da/, each 250 ms in duration, were composed of three formants with no release burst. Values of the stimulus parameters were identical to those used by Reed (1989) in her successful replication of Tallal's experiments (Tallal, 1980; Tallal & Stark, 1981). The two syllables had identical steady-state portions with F1 at 750 Hz, F2 at 1200 Hz, and F3 at 2350 Hz. The bandwidths of the three formants were 90 Hz, 90 Hz, and 130 Hz, respectively. Each syllable started with F0 at 121 Hz rising to 125 Hz in 40 ms and falling to 100 Hz at syllable end. Whereas F1 began at 200 Hz for both syllables, reaching its steady-state value in 25 ms, F2 and F3 onsets differed for the two syllables. For /ba/, the second and third formants began at 825 Hz and 2000 Hz, respectively, reaching their steady states in 35 ms. For /da/, F2 began at 1500 Hz and F3 at 2630 Hz, both reaching their steady states in 35 ms.

The /sa/ and /ʃa/ stimuli were each 400 ms long, the frication noise lasting 150 ms and the vowel formants 250 ms (Tallal & Stark, 1981); /sa/ had a fricative noise high-pass cut-off at 4100 Hz, /ʃa/ at 2800 Hz. Relative amplitude of the frication noise rose from 20 to 35 dB over the first 50 ms, and then fell to 30 dB over the last 50 ms of the frication duration. The vocalic portions were identical for both sounds, the formant frequency values being the same as those of the steady-state vocalic portions of /ba/ and /da/.

Procedure

The sequence and structure of the training and test procedures exactly followed those of Tallal (1980), with minor adaptations incorporated by Reed

(1989) in her successful replication of Tallal's work. Experiment 1a consisted of a TOJ task and a discrimination task with a stimulus pair also used by Tallal, /ba/–/da/ (Tallal & Piercy, 1974). In Experiment 1b subjects repeated the TOJ and discrimination tasks, this time with a different stimulus pair in which for half of each subject group the pair was /ba/–/sa/ and for the other half of each group the pair was /da/–/ʃa/. The order of presentation of TOJ and discrimination was counterbalanced across subjects within a group. Following Tallal's protocol, a written log of subjects' responses was maintained throughout the session.

Experiment 1a

Identification training. Subjects were told that they would hear two syllables, /ba/ and /da/. Their task was to identify these syllables by pointing to a red dot on the board before them if they heard /ba/, to a green dot if they heard /da/. Each child was presented with six repetitions of the syllable /ba/, followed by six repetitions of the syllable /da/ to familiarize him or her with the sounds and the correct responses. Training then continued for up to 48 trials, 24 of each stimulus quasi-randomly presented one at a time with the restriction of a maximum of three of one type in succession and an unlimited interval for responding. For this identification training only (i.e., not for any of the subsequent tasks), the experimenter switched after the first two subjects, to a "point and say" response, because this seemed to engage the child's attention more fully and to increase response consistency. When subjects reached a criterion of 12 correct out of 16 consecutive trials ($p < .001$, binomial test), they proceeded to one or the other of the next two tasks.

Temporal order judgment training and test. Here the subject was first trained to respond to two stimuli presented in succession with a 400 ms ISI by pointing to the red and green dots in the correct order of presentation of the two sounds. There were four possible orders: 1–1, 1–2, 2–1, 2–2 (where 1 and 2 represent /ba/ and /da/, respectively). Four demonstrations by the experimenter were followed by 8 training trials with feedback and by 24 further trials without feedback, to a criterion of 12 correct out of 16 consecutive trails. All subjects reached criterion and were then given an additional 36 TOJ test trials at reduced ISIs: A series of 12 two-stimulus patterns was presented at each of three shorter ISIs, viz., 100, 50, 10 ms. The series were presented in the same order of decreasing ISI for all subjects.

Discrimination training and test. A same/different task was used. A subject was initially presented with 6 examples of identical syllable pairs (either /ba/–/ba/ or /da/–/da/), at ISIs of 400 ms and was instructed to point to two blue dots (i.e., two dots of the same color) after each trial. Then came 6 examples of trials with different syllables, for which the subject was instructed to point to two differently colored dots (a blue dot and a yellow dot). Next, 48 trials consisting of an equal number of identical and different syllable pairs, were presented in a quasi-random order, with the proviso that there be a maximum of three of a kind in succession. Training continued to a criterion of 12 correct out of 16 consecutive trials. All subjects reached criterion and were then tested for discrimination with the same series of 12 trials at each of the three short ISIs as were used in the TOJ task (i.e., 100, 50, and 10 ms).

Experiment 1b

As noted above, for half the subjects in each group, the TOJ and discrimination tasks were repeated with the stimulus pair /ba–sa/, and for the other half they were repeated with the stimulus pair /da/–/ʃa/. Ideally, each subject should have completed these tasks with both stimulus pairs, but this would have made the procedure unacceptably long. Once again, the order of presentation of the TOJ and discrimination tasks was counterbalanced within the groups of good and poor readers, and the subjects had to respond by pointing.

Results and Discussion

Training

In Experiment 1a (/ba/–/da/) only 4 of the good readers, but 14 of the poor readers, made at least one error during one or more of the three training segments. The mean numbers of errors and the differences between the group means were very small. The training means (with standard deviations in parentheses) for good readers were 0.2(0.4) on identification, 0(0) on discrimination, and 0.1 (0.2) on TOJ; for poor readers they were 1.1(1.7) on identification, 0.6(0.9) on discrimination, and 1.0(1.3) on TOJ. Because the data clearly did not meet the assumptions of normality and homogeneity of variance, we compared the groups nonparametrically across the three training segments combined. The difference between the number of good readers (4) and poor readers (14), making at least one error was significant ($\chi^2_{(1)}$ = 10.10, $p < .01$).

By contrast, in Experiment 1b good and poor readers performed equally well on identification and TOJ training with stimulus pairs /ba/–/sa/ or /da/–/ʃa/, making no errors at all. Performance on discrimination training was almost error-free too, with the exception of a single error by one poor reader in the /da/–/ʃa/ subgroup. Thus, there were no significant differences between the groups on any of the training segments for the stop-fricative contrast.

Perception at Short ISIs

Figure 1 displays the mean number of errors on discrimination and TOJ of /ba/–/da/ at short ISIs by the two groups. Whereas errors increase monotonically with decreases in ISI for the poor readers on both tasks, good readers were unaffected by the change in ISI, and their performance was identical on the two tasks. Although more errors might be expected on TOJ (chance: 25%) than on discrimination (chance: 50%), poor readers made more errors

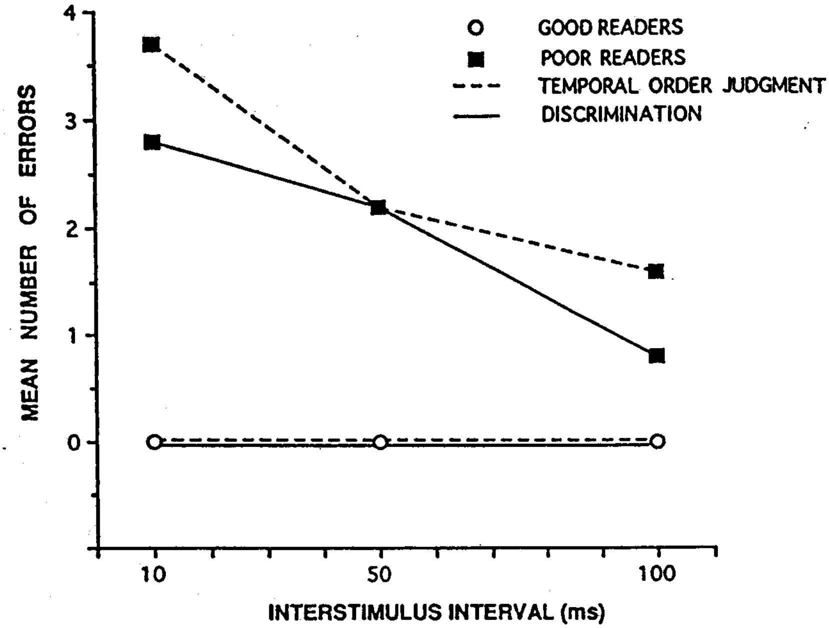

FIG. 1. Mean number of errors by good and poor readers as a function of ISI on /ba/–/da/ discrimination and temporal ordering tasks.

on TOJ than on discrimination only at 100 and 10 ms, not at the intermediate ISI of 50 ms. A two-way ANOVA (Task × ISI) for the poor readers yielded a significant main effect of ISI ($F(2,38) = 11.26$, $p < .001$), an effect just short of significance for task ($F(1,19) = 4.30$, $p = .052$), and no significant interaction between the two variables $F(2,38) = 1.64$, $p > .05$). Thus, ISI had the same effect on both tasks.

When the syllable pair was changed to /ba/–/sa/ or /da/–/ʃa/, poor readers performed almost as well as the controls with the exception of one temporal ordering error and two discrimination errors, all at the shortest ISI and on syllable pair /da/–/ʃa/. Good readers continued to make no errors at any ISI. Overall, there was no difference between good and poor readers on discrimination and temporal ordering at short ISIs for the stop-fricative contrast.

In summary, the two groups were selected to differ significantly on overall /ba/–/da/ TOJ; they also differed significantly on overall /ba/–/da/ discrimination (Table 1). Yet there was no significant difference between their performances on the same tasks with stimulus pairs /ba/–/sa/ or /da/–/ʃa/. These findings demonstrate that the poor readers' difficulties with /ba/–/da/ TOJ do not reflect a general problem with temporal order analysis: Poor readers judge temporal order accurately, even at rapid rates of presentation, if they can identify the items to be ordered. Perhaps, then, their difficulties with /ba/–/da/ are phonological. As noted earlier, these syllables differ on a single phonetic feature. If poor readers have broader, less well separated phonological categories than normal, such pairs may be difficult to discriminate and, for TOJ, to identify under time pressure. Nonetheless, it is still possible that their similarity is acoustic rather than phonetic. Experiment 2 was designed to resolve this issue.

EXPERIMENT 2

This experiment was a nonspeech control condition for Experiment 1a, required to determine whether the poor readers' difficulties with /ba/–/da/ were indeed auditory in origin. The stimuli were frequency modulated sine wave patterns following the center frequencies of the second and third formants of synthetic /ba/ and /da/; as may be recalled from the description of the stimuli for Experiment 1, /ba/ and /da/ differed in F2 and F3, but not in F1. Because sine wave syllables composed of second and third formant analogs, without a first formant analog, are not heard as speech, even by listeners instructed to listen to the sounds as speech (Remez, Rubin, Pisoni, & Carrell, 1981), these stimuli constituted acoustically matched, but perceptually distinct, nonspeech controls. The sine wave patterns were presented for identification training, discrimination training at 400 ms ISI, and discrimination at short ISIs in exactly the same sequence and numbers of stimuli as for the syllables in Experiment 1. Both for reasons of time and because (as in Tallal, 1980) there were no significant differences between discrimination and TOJ at short ISIs in Experiment 1a, we omitted TOJ for these nonspeech control patterns. If the poor readers' deficit were auditory rather than phonetic, we would expect them to display the same effects of ISI on the nonspeech control as on /ba/–/da/, and again to perform significantly worse than good readers. If the deficit were specific to speech, the nonspeech control patterns should yield no effect of ISI and no group differences.

Method

Stimuli

Nonspeech stimuli were generated on the Haskins sine wave synthesizer through a VAX 11/780. The two stimuli, each 250 ms in duration, were each composed of two sine waves with durations and frequency trajectories identical to those of the center frequencies of F2 and F3 in the synthetic /ba/ and /da/ described above. Perceptually, they did not resemble their speech models. Listeners judged them to be unfamiliar nonspeech sounds and assigned them the descriptive labels of "up" and "down," respectively. The selection of these labels was based on a pilot run of the stimuli with four normal children who unanimously preferred "up"/"down" over "high"/"low."

TABLE 2
Mean (*M*) and Standard Deviation (*SD*) of Errors to Criterion on Training Tasks by Good and Poor Readers, under Speech and Nonspeech Conditions

	Good readers				Poor readers			
	Speech		Nonspeech		Speech		Nonspeech	
Task	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Identification	.2	.4	6.4	3.5	1.1	1.7	7.3	4.5
Discrimination at 400 ms ISI	0.0	0.0	2.2	2.9	0.6	0.9	2.0	2.4

Procedure

The procedures were those of the identification training, discrimination training at 400 ms ISI, and discrimination at short ISIs of Experiment 1a. For identification training the red dot and the green dot were replaced by an upward-pointing and a downward-pointing arrow, respectively, to match the "up" and "down" identification labels.

Results and Discussion

Training: Identification and Discrimination

To facilitate comparison between speech (Experiment 1a) and nonspeech (present experiment), Table 2 lists, for each group, the mean number of errors to criterion for identification training and discrimination training, under each condition. Both groups found the nonspeech stimuli harder, as indicated by the increase in errors. On identification training the mean increase in errors was equal for the two groups (6.2); on discrimination training the mean increase was slightly greater for good readers (2.2) than for poor (1.4). Separate two-way analyses of variance (Group × Condition (Speech/Nonspeech)) for identification training and for discrimination training yielded the same pattern of results: A main effect of Condition for both identification ($F(1,38) = 96.04, p < .001$) and discrimination ($F(1,38) = 15.68, p < .01$): no effects of Group (identification: $F(1,38) = 1.64, p > .05$; discrimination: $F(1,38 = .17, p > .05$), and no significant interactions (identification: $F(1,38) = 0, p > .05$; discrimination: $F(1,38) = 0.7, p > .05$).

The main effects of condition, combined with the absence of both main effects of group and interactions between group and condition, indicate that, while both groups found nonspeech more difficult than speech, training was not significantly harder for one group than for the other. The lack of group differences in learning to identify and discriminate the sine wave patterns would not be expected if the poor readers' difficulties with /ba/–/da/ were indeed due to a general deficit in perceiving "rapid acoustic changes."

Discrimination at Short ISIs

On nonspeech discrimination, the poor readers (mean errors across ISIs = 1.4, *SD* = 1.5) slightly outperformed the good readers (mean errors across ISIs = 2.3, *SD* = 1.9). The two groups performed similarly with no effect of ISI over the two longer values (100 ms and 50 ms), but good readers showed a sharp increase in errors at the shortest ISI. A two-way ANOVA (Group × ISI) found no significant difference between Groups ($F(1,38) = 3.5$, $p > .05$), and no main effect of ISI ($F(2,76) = 2.42$, $p > .05$), but a significant interaction between group and ISI ($F(2,76) = 4.12$, $p < .02$), reflecting the effect of the shortest ISI on good readers, and the lack of such an effect on poor readers. However, a post hoc *t*-test of the difference between the shortest ISI and the mean of the two longer ISIs for the good readers fell short of significance by the conservative criterion of Scheffé ($t(19) = 2.75$, $p > .05$). Thus, ISI had no significant effect on nonspeech discrimination for either group. (For evidence that the lack of group differences in errors on nonspeech discrimination cannot be attributed to regression to the mean from the extreme error scores on speech discrimination reported in Experiment 1a, see the Appendix.)

To illustrate the differences between speech (/ba/–/da/) (Experiment 1a) and nonspeech (Experiment 2), Fig. 2 plots discrimination errors of the two groups as a function of ISI for the two conditions. The most striking features of the figure are: (i) a strong effect of condition for the good readers, but a relatively weak effect for the poor readers; (ii) no effect of ISI on either condition for the good readers (see Scheffé test above); (iii) a strong effect of ISI on speech, but not on nonspeech, for the poor readers. A three-way ANOVA (Group × ISI × Stimulus Condition) on the error data, with ISI and Stimulus Condition as within-subject variables, confirms this description: Significant main effects of Condition ($F(1,38) = 12.33$, $p < .001$) and ISI ($F(2,76) = 10.91$, $p < .0001$), but not of Group ($F(1,38) = 2.56$, $p > .10$); significant two-way interactions between Group and Condition ($F(1,38) = 34.52$, $p < .0001$) and between Group and ISI ($F(2,76) = 3.15$, $p < .05$), and a significant three-way interaction among Group, ISI and Condition ($F(2,76) = 8.45$, $p < .001$). Thus, the effects of both condition and ISI are different for the two groups. For the poor readers, the seemingly weak effect of condition and the strong effect of ISI on speech, but not on nonspeech, is confirmed by a two-way ANOVA across Experiments 1a and 2 (Condition × ISI) for these readers alone: No effect of Condition ($F(1,19) = 3.43$, $p > .05$), but a significant effect of ISI ($F(2,38) = 8.15$, $p < .01$), entirely due to its strong effect on speech, as indicated by a significant ISI by Condition interaction ($F(2,38) = 4.90$, $p < 02$). Thus, whatever difficulties were induced in the poor readers by increasingly rapid presentation of synthetic stop-vowel syllables were not similarly induced by the nonspeech control patterns.

These results demonstrate that the poor readers' difficulties with /ba/–/da/

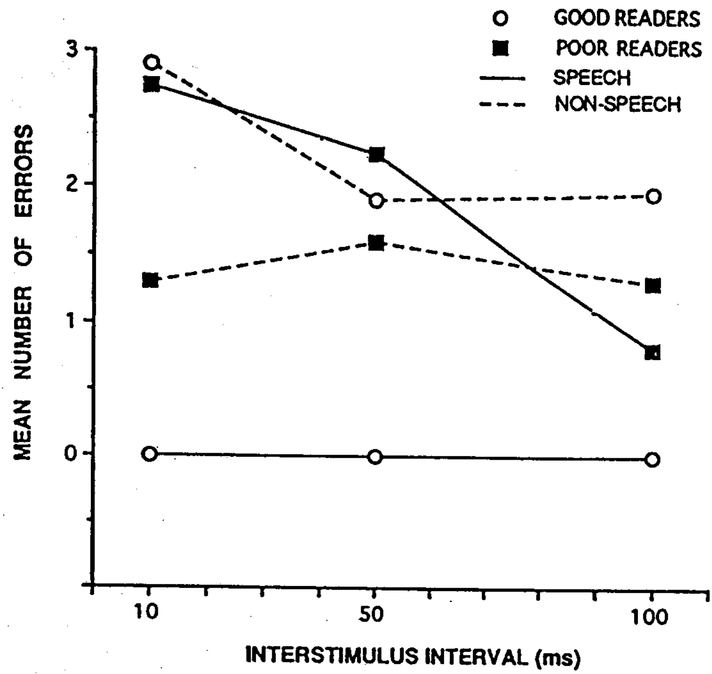

FIG. 2. Mean number of errors by good and poor readers as a function of ISI on speech (/ba/–/da/) and nonspeech discrimination.

discrimination were specific to speech, and cannot be attributed to a general auditory deficit in the perception of brief patterns of rapidly changing acoustic information. Nonetheless, it still seemed possible that the poor readers' difficulty with /ba/–/da/ might be specific to phonetic processing of brief formant transitions. Accordingly, we undertook Experiment 3.

EXPERIMENT 3

Two salient cues specify the presence of a stop consonant in a fricative-stop cluster, as in the word *split*, /splIt/ (Fitch, Halwes, Erickson, & Liberman, 1980) or in the word *stay*, /steI/ (Best, Morrongiello, & Robson, 1981). First, a sharp drop in energy (i.e., silence) after the fricative indicates that the vocal tract has closed. Second, a sharp rise in F1 energy and frequency after the silence indicates that the tract is opening. The duration of the silence and the extent of the F1 frequency rise (i.e., of the F1 transition) are reciprocally related and additive in their perceptual effect. In synthetic speech they "trade:" A given probability of hearing a stop can be determined either by a brief silence and a relatively extensive F1 frequency rise, or by a longer silence and a less extensive F1 frequency rise.

Morrongiello, Robson, Best, and Clifton (1984) exploited these facts in a study of 5-year-old children and adults. Their subjects identified members of two series of syllables ranging from /seI/ to /steI/. Each syllable consisted of a natural /s/ frication concatenated with a vocalic portion synthesized to sound either strongly or weakly as /deI/: The stronger /deI/ was cued by a lower F1 onset frequency, and so a more extensive F1 transition to its steady state, the weaker /deI/ was cued by a higher F1 onset and so a less extensive F1 transition. Various amounts of silence were inserted between the noise and the transitions to generate two /seI–steI/ continua, one with the high F1 onset, one with the low. Children and adults did not differ in their identification functions on the low F1 series. But on the high F1 series children needed less silence to hear a stop than adults, indicating that they weighted the less extensive F1 transition more heavily relative to the silence than the adults did. The authors concluded that 5-year-olds were more sensitive to rapid intrasyllabic formant transitions than adults. Nittrouer (1992) reached the same conclusion for 3-, 4-, and 5-year-olds, compared with 7-year-olds and adults on identification of a /seI/–/steI/ continuum. (For theoretical interpretation of such findings, see Nittrouer, Studdert-Kennedy & McGowan, 1989.)

Precisely the opposite result was reported by Tallal and Stark (1978) for a group of language-impaired children, tested on a /sa/–/sta/ continuum, with fixed F1 transition extent and varying silent intervals between frication offset and vowel onset. These children needed a significantly longer silent interval between fricative and vowel than normal children to shift their judgments from /sa/ to /sta/; in other words, they were less sensitive to (or weighted less heavily) the extent of F1 transition than normals. A similar result was reported by Steffens et al. (1992) for adult subjects with familial dyslexia. Such results are consistent with Tallal's expectation that dyslexics and language-impaired children should display reduced sensitivity to brief acoustic events.

The present experiment was a variation of the above studies. Instead of fixing F1 onset frequency and varying silence, we followed Nittrouer (1992), fixing the silent interval and manipulating F1 onset frequency. If the 8-year-old poor readers behaved perceptually like the 5-year-olds of Morrongiello et al. (1984) and of Nittrouer (1992), they would require a higher F1 onset frequency (i.e., a less extensive F1 transition) to hear a stop than normals. On the other hand, if the poor readers' difficulties with /ba/–/da/ in Experiment 1 stemmed from a general deficit in the phonetic processing of brief formant transitions, they would require a lower F1 onset frequency (i.e., a more extensive F1 transition) than good readers to switch their judgments from /seI/ to /steI/. Finally, if poor readers were neither more nor less sensitive than good readers to variations in the extent of F1 transitions, we could conclude that they were neither developmentally delayed nor had difficulty in processing rapid formant transitions. Such an outcome would suggest that poor readers' difficulties with /ba/–/da/ did not stem from acoustic properties of the syllables.

Method

Stimuli

The stimuli were drawn from a /seI–steI/ continuum, each step made up of a natural sample of /s/ frication noise, followed by a synthetic vocalic portion. These stimuli, identical to those used by Nittrouer (1992), were modeled after those of Best et al. (1981) and Morrongiello et al. (1984). The duration of the frication noise was 120 ms and that of the vocalic portion 300 ms, accompanied by a falling F0 from 120 to 100 Hz. F3 fell from 3196 to 2694 Hz in the first 40 ms, remained there for the next 120 ms and rose to 2929 Hz over a 90-ms period where it remained steady for the last 50 ms. F2 remained constant at 1840 Hz during the first 160 ms and then rose to 2240 Hz over the next 90 ms, where it remained steady for the final 50 ms. F1 onset varied from 211 to 611 Hz in 50 Hz steps, reaching 611 Hz over the first 40 ms, where it remained for the next 120 ms. Then F1 fell to 304 Hz over 90 ms where it stayed for the final 50 ms. A silent gap of 20 ms was inserted between the /s/ noise and each following vocalic segment.

Procedure

Subjects were trained to a 90%-correct criterion with 10 repetitions of good exemplars from the two categories. They were then presented with the test stimuli, one at a time, in a random order, with an unlimited interval in which to respond; there was a total of 90 trials (9 tokens × 10 repetitions per token). The stimuli were presented by a Compaq 386 portable computer (IBM clone) through a 901F Frequency Devices filter and TDH-39 headphones. Subjects responded both by saying aloud what they heard and by pointing to a picture of a little girl with an empty blurb balloon for the word "say" and of a man appearing to admonish a dog with a raised hand for "stay." Responses were registered directly to the computer by the experimenter.

Results and Discussion

Figure 3 displays the mean probability of /steI/ responses as a function of F1 transition onset frequency for the two groups. The two functions are very similar, although poor readers seem to have a somewhat shallower slope. Close inspection reveals that the shallower appearance is largely due to the slope between stimuli 4 and 5 where the poor readers' function crosses that of the good readers.

Cumulative normal distributions were fit to individual data by the method of least squares (Finney, 1964) and yielded means and standard deviations of the individual distributions. The mean is an estimate of the phoneme boundary, the value of the F1 transition for which *say* and *stay* responses are equally likely; the standard deviation corresponds to the reciprocal of the slope of the cumulative function. Whereas the good and poor readers have almost the same mean phoneme boundaries (398 (39.1) and 396 (45.5) Hz,

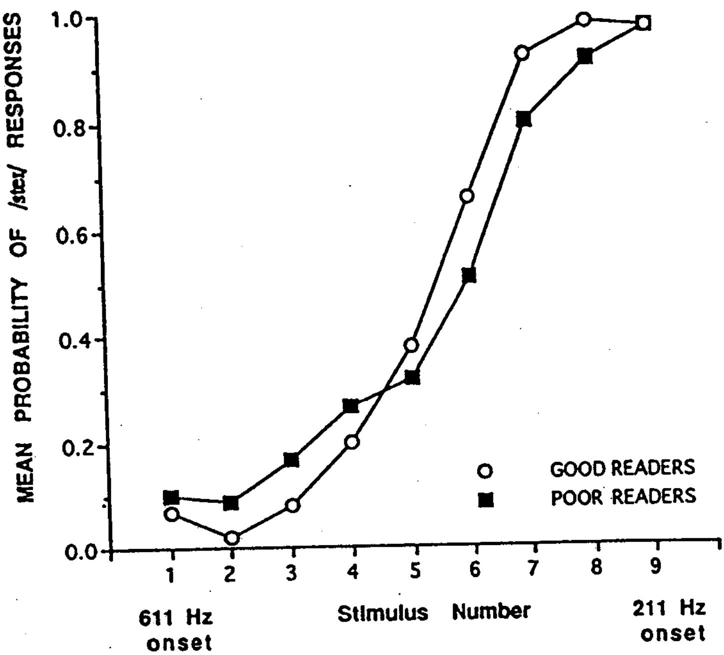

FIG. 3. Mean identification functions for /sel–stel/ in good and poor readers. Stimulus numbers refer to F1 onset-frequencies ranging from 611 to 211 Hz in 50-Hz steps.

respectively, with standard deviations in parentheses), the former have steeper mean slopes (15.5 (6.9) vs. 12.4 (9.5) Hz). The differences between the groups were not significant, however, in either phoneme boundary ($t(38) = .18$, $p > .05$) or slope ($t(38) = 1.16$, $p > .05$).

Individual data of several subjects were not well fit by the cumulative normal curve, throwing doubt on the propriety of probit analysis. An alternative, though coarser, measure of response to F1 onset variations was therefore computed, namely, the total number of stay responses across the continuum. Once again, the groups did not differ significantly: The mean number of stay responses by the good readers (42.3) was almost equal to that of the poor readers (41.1) ($t(38) = .47$, $p > .05$). Good and poor readers were also equally variable on this measure: Both groups had the same standard deviations (7.7).

These results demonstrate that, unlike the language-impaired children of Tallal and Stark (1978) and the adult dyslexics of Steffens et al. (1992), the poor readers of the present study were not less sensitive than normals to the F1 transition: They did not require a more extensive transition in order to hear a stop in a syllable-initial /s/-stop cluster. Also, unlike the poor readers of previous studies described in the introduction, the poor readers were no less consistent than good readers in identifying synthetic syllables distributed along a continuum. Perhaps this was because the contrast here was between the presence and absence of a full segment marked by several features rather than between segments differing on a single feature, as in earlier studies. This interpretation fits neatly with the results of Experiment 1, where poor readers' difficulties with a single feature contrast (/ba/–/da/) vanished for triple feature contrasts (/ba/–/sa/, /da/–/ʃa/).

In any event, the poor readers of this study, despite their demonstrated difficulties with /ba/–/da/ discrimination and TOJ, clearly did not suffer either from the general auditory deficit posited by Tallal (1980) or from a corresponding domain-specific, phonetic deficit in the perception of brief formant transitions. Nor did they exhibit the developmental delay, suggested by the findings of Morrongiello et al. (1984) and of Nittrouer (1992), in the form of heightened sensitivity to transitions. In other words, the reading-impaired children were completely normal, as sensitive to a very brief acoustic event in speech as they had proved to be in nonspeech (Experiment 2).

GENERAL DISCUSSION

The general auditory account of phonological deficits in both language-impaired and reading-impaired children (e.g. Tallal et al., 1991, pp. 369–370) makes two independent claims: (i) The basic deficit is in "temporal processing;" (ii) the deficit is general rather than specific to speech. The present study lends no support to either of these claims for reading-impaired children.

We should acknowledge, however, that the study has certain limitations. First, due in part to the rigorous criteria for subject selection, the poor readers were less severely impaired than those of Tallal (1980), whose children were reading at least one year below grade level. Yet the poor readers did display precisely the difficulties with /ba/–/da/ TOJ that Tallal (1980) proposed as symptomatic of a phonological disorder and that Reed (1989) subsequently observed in some reading-impaired children. Whether the difference in reading level is a serious concern depends therefore on how likely it is that identical difficulties with /ba/–/da/ TOJ stem from different perceptual deficits in more severely impaired than in less severely impaired readers. We do not find this likely. As noted in the Subjects section, several large-scale studies converge on the conclusion that reading ability is normally distributed with no qualitative difference between those who are simply less skilled and those who meet standard criteria as reading-disabled (e.g., Shaywitz et al., 1992; Stanovich & Siegel, 1994). If this is so, the results of the present experiments can be generalized to specifically reading-impaired children who have difficulty with /ba/–/da/ TOJ, regardless of their degree of reading impairment. Whether the results can also be generalized to specifically language-impaired children, whose difficulties are not confined to reading, is a question for future research incorporating the nonspeech controls that previous studies of such children have omitted (e.g., Tallal & Piercy, 1974; Tallal & Stark, 1981;

Tallal, Miller, Bedi, Byma, Wang, Nagarajan, Schreiner, Jenkins, & Merzenich, 1996).

A second limitation of this study (and of any other study designed to test Tallal's hypothesis) is that its results cannot disprove the hypothesis: They can merely fail to support it where support would be expected. Yet we should not forget that the hypothesis of a general auditory deficit underlying difficulties with rapid stop–vowel syllable perception is purely speculative and without experimental support. No one has ever shown that either language-impaired or reading-impaired children have difficulty in discriminating both brief, rapidly changing speech sounds (formant transitions) and acoustically matched nonspeech control patterns. The concurrent difficulties with both /ba/–/da/ and tone TOJ, reported by Reed (1989) for impaired readers, do not fill the gap, because rapidly presented pairs of discrete, complex tones, differing in fundamental frequency (pitch), do not qualify as acoustically matched controls for the rapid continuous sweeps of formant transitions, differing in spectral weight (timbre). Nor can we attribute concurrent tone and stop–vowel difficulties to some more general deficit in, say, speed of auditory stimulus classification (cf. Nicholson & Fawcett, 1994). Instead, such evidence as we have in this regard seems to favor the notion of independent deficits in different aspects of speech and nonspeech discriminative capacity. We briefly consider this proposal in the following sections.

Difficulty in Identification Stems from a Deficit in Discriminative Capacity, Not in Temporal Processing

From one of her earliest papers (Tallal & Piercy, 1973, p. 396), to a recent paper 18 years later, Tallal has repeatedly acknowledged that the ". . . sequencing deficit . . . in dysphasic children is . . . secondary . . . to the more primary [sic] deficit in . . . discrimination of rapidly presented stimuli" (Tallal et al., 1991, p. 365). In other words, the deficit is in stimulus discrimination, and so a fortiori in identification, not in TOJ itself. Experiment 1b of the present study, in which apparent TOJ errors vanished for readily identifiable syllables, merely confirms therefore what Tallal herself would predict.

Yet descriptions of the deficit as one of "temporal processing" persist, maintained by a shift in the locus of the supposedly defective "temporal processing" from the judgment of sequence (TOJ) to the judgment of rapid spectral change. Thus, in the very paper from which the above quotation is drawn, we also read of ". . . basic temporal processing deficits which interfere . . . with adequate perception of specific verbal stimuli which require resolution of brief duration formant transitions, resulting in disordered language development" (p. 363). The phrase "specific verbal stimuli" evidently refers to stop–vowel syllables, such as /ba/ and /da/. Here, then, perception of a contrast between syllables with identical temporal properties (duration, rate of spectral change), but differing in the frequencies and directions of spectral change at syllable onset, is deemed "temporal," simply because the critical spectral shift is of "brief duration." The passage nicely illustrates the confusion between temporal perception and rapid perception to which we referred in the introduction. (For fuller analysis than is possible here of Tallal's concept of "temporal processing," see Studdert-Kennedy & Mody, 1995.)

Yet, even if we set aside the seemingly trivial, though conceptually and substantively critical, issue of terminology, the claim that poor readers find /ba/–/da/ difficult to identify because these syllables ". . . require resolution of brief duration formant transitions," is not only without experimental support, but is also at odds with the results of the present study. In Experiment 3 poor readers, chosen precisely for their difficulties with /ba/–/da/ TOJ, were asked to detect the presence or absence of a stop consonant between a syllable–initial fricative and vowel; they proved no less sensitive than good readers to small variations in the frequency extent of brief *F*1 transitions. And in Experiment 2, where the brief transitions were in nonspeech sine waves, the poor readers discriminated between them as well as good readers. Nor, finally, are /ba/ and /da/ difficult for poor readers because they are acoustically similar: The nonspeech sine waves were as acoustically similar as the syllables on which they were modeled. The source of the difficulty, then, is evidently phonetic: /ba/ and /da/ are difficult to discriminate and identify at rapid rates of presentation because, although phonologically contrastive, they are phonetically similar. As earlier remarked, /ba/ and /da/, like /sa/ and /ʃa/, which language-impaired children may also find difficult to discriminate (Tallal & Stark, 1981), differ on a single phonetic feature.

How, then, is this deficit in speech perception related to the difficulty with nonspeech TOJ, repeatedly reported for reading-impaired children?

Nonspeech Tone Temporal Order Judgment

As we saw in the introduction, some relation seems to obtain between performance on rapid nonspeech tone TOJ and phonological decoding skill in reading, but the relation is at best statistical and its functional basis is obscure. Tallal's (1980) view that difficulty with tone TOJ is one symptom of a general deficit in "temporal processing," of which difficulty with /ba/–/da/ TOJ is another, is undermined by the present finding that the latter is neither general nor "temporal," but specific to speech and a consequence of difficulty in identification at rapid rates of presentation.

That tone TOJ itself may not be a reliable measure of general temporal processing is also strongly suggested by recent work of Watson and Miller (1993). These authors studied a sample of 94 undergraduates, 24 of whom were diagnosed as reading disabled, on a battery of 35 tests assessing nine factors potentially relevant to reading skill. They found no significant differences between normal and reading-disabled subjects in intelligence, simple auditory discrimination (pitch, loudness), or in nonverbal "auditory temporal processing," as measured by discrimination thresholds for (i) tone duration around a 100 ms, 1 kHz standard, (ii) interpulse intervals differing from a

40 ms standard, and (iii) presence of an embedded 10- to 200-ms tone in a nine tone sequence. They did find, however, highly significant differences on tests of speech perception, short- and long-term verbal memory, phoneme segmentation, and of TOJ for tones of 550 and 710 Hz, varying in duration from 20 to 200 ms, with no silent gap between tones.

Yet, upon entering tone TOJ into a linear structural relations analysis in combination with the three tests of temporal discrimination described above, Watson and Miller (1993) found no relation between nonverbal temporal processing and either phonological skills or reading itself. They therefore concluded: "Overall, these results indicate that the phonological processing variables are highly associated with speech perception, and that nonverbal temporal processing does not explain a significant amount of variance in the phonological variables independent of speech perception and intelligence" (p. 859).

Two points concerning Watson and Miller's study deserve emphasis. First, the three tests that call for judgments of a temporal dimension (duration), and therefore have clear face validity as measures of temporal processing, did not separate normal from disabled readers. Second, tone TOJ, a test that calls in the first instance for judgment of a nontemporal dimension (fundamental frequency), and only secondarily for judgment of temporal sequence, did separate normal from impaired readers, but did not cluster with tests of temporal processing.

We are left then with the puzzle of why tests calling for rapid identification of the relative pitch of nonspeech tones separate, at least statistically, normal from impaired readers. A new approach to this puzzle comes from a recent experimental study by Nicholson and Fawcett (1993, 1994). These authors compared groups of dyslexics, aged 15 and 11 years, with chronological age (CA) and reading age (RA) controls on selective choice reaction time (SCRT) to pure tones differing in pitch, and on reaction time in a lexical decision task. They found that the dyslexics were significantly slower than CA controls (though not than RA controls) on SCRT to tones (a "quantitative deficit" in speed of decision), and significantly slower even than RA controls on lexical decision for words, but not for nonwords (a "qualitative deficit" in speed of lexical access).

The SCRT results suggested a general slowdown in processing speed; but this could not account for the "qualitative" difference between words and nonwords in speed of lexical decision. The authors therefore concluded that: "Phonological deficits must still be posited over and above any putative deficits in information processing speed" (Nicholson & Fawcett, 1994, p. 45). In other words, they proposed that the lexical decision effect stemmed from two independent deficits: ". . . a phonological deficit in lexical access speed, together with a nonphonological deficit in stimulus classification speed" (p. 46).

The co-occurrence of phonological impairment and other cognitive problems is not at odds, of course, with the real-world circumstance of multiple deficits in reading-disabled children. For example, it is now recognized that roughly 40% of such children may have an independent co-occurring "attention-deficit-disorder" (Shaywitz, Fletcher & Shaywitz, 1994). Presumably, phonological deficits are present in every poor reader (Shankweiler, Crain, Katz, Fowler, Liberman, Brady, Thornton, Lundquist, Dreyer, Fletcher, Stuebing, Shaywitz, & Shaywitz, 1995). Co-occurring nonphonological deficits are evidently more variable in occurrence, as shown by the repeated finding that some poor readers fall within the normal range on tone TOJ (e.g., Bedi, 1994; Reed, 1989; Tallal, 1980).

CONCLUSION

Deficits in speech perception among reading-impaired children are domain specific and phonological rather than general and auditory in origin. Such children's difficulties with /ba/–/da/ TOJ (when they are present) arise from difficulty in identifying the phonological categories of phonetically similar speech sounds rather than from deficits either in temporal order judgment itself or in processing the brief acoustic changes of formant transitions. The full nature, origin, and extent of the perceptual deficit remain to be determined. For example, how poor readers' deficits in speech perception relate to their characteristically impaired phonological awareness, and so to reading, is a question we must leave to future research.

APPENDIX

An anonymous reviewer questioned the validity of the comparison between good and poor readers on nonspeech discrimination because, by selecting good readers who made no errors on /ba/–/da/ TOJ, we had truncated "the variability expected in normal children" and so had invited in any test of "another sound contrast, regression to the mean . . . in both groups, as is seen in the data." We should note, first, that, the most important finding of Experiment 2 was not the lack of a main effect for group, for which regression might perhaps be called to account (although see below), but the lack of a significant effect of ISI on nonspeech for the poor readers. This result, taken with the highly significant effect of ISI on speech in Experiment 1a, demonstrates that the poor readers' difficulties with rapid stimulus presentation were confined to speech; a two-way ANOVA across Experiments 1a and 2 for the poor readers alone confirms this conclusion (see main text). Notice further that the regression hypothesis cannot predict the different effects of ISI across conditions, because subjects were selected by speech TOJ errors summed across ISIs, not separately for each ISI.

As for the regression hypothesis itself, comparison of the error distributions in the parent populations of good and poor readers with those in the experimental samples demonstrates that the hypothesis is implausible. The distributions of errors on /ba/–/da/ discrimination, like those on /ba/–/da/ TOJ, were positively skewed for both the 40 good readers and the 31 poor readers from whom the final selection of subjects was made. The positive skews are indicated by the fact that in each distribution the mean was greater than the median. For the good readers ($n = 40$), the median was actually indeterminate because 30 (75%) of the subjects made no errors at all, while the mean was 1.4 (pulled up from 0.4 by two mavericks who made more errors than any poor reader, viz., 17 and 21); for the poor readers ($n = 31$), the median was 2.7, the mean 3.9 (as compared with 6.2 and 7.4 respectively, for the poor readers selected for the experimental group ($n = 20$)). Thus, the children selected to participate as good and poor readers were from opposite extremes of two quite differently weighted distributions of speech errors. Yet on the nonspeech test, in a shift that the regression hypothesis would not predict, the two groups not only came closer together, but switched their relative positions, so that the good readers now made more errors than the poor readers. We see this in the values of the means and medians on the nonspeech test: for good readers a median of 6.0 and a mean of 6.7, for poor readers a median of 2.5 and a mean of 4.0. Thus the nonspeech mean for the poor readers was indeed numerically compatible with regression; that is, on the nonspeech test, the mean error rate for poor readers did shift to a less extreme value, almost equal, in fact, to the mean of the distribution of speech errors on /ba/–/da/ discrimination in the parent population. Yet for the good readers (who were presumably more susceptible to regression, because drawn entirely from the floor of their distribution), the shift was not to a less extreme value closer to the population mean, but to an even more extreme value (i.e., even further from the mean than zero), at the opposite end of their distribution. Such a shift is not toward the mean, but past the mean, from the nonskewed end to the skewed end of a heavily skewed distribution. Regression is surely not a plausible explanation for a shift of this magnitude.

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