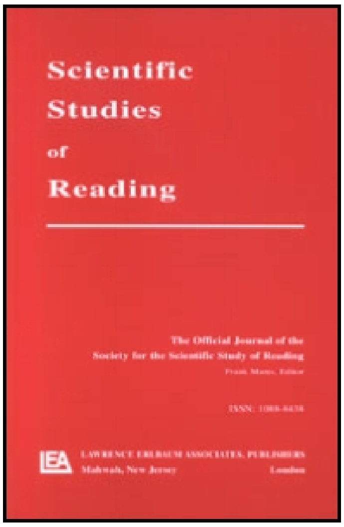

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Visual Processing Deficits in Children With Slow RAN Performance

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Two groups of 8- to 10-year-olds differing in rapid automatized naming speed but matched for age, verbal and nonverbal ability, phonological awareness, phonological memory, and visual acuity participated in four experiments investigating early visual processing. As low RAN children had significantly slower simple reaction times (SRT) this was entered as a covariate in all subsequent data analyses. Low RAN children were significantly slower to make same/different judgments to simple visual features, non-nameable letter-like forms and letters, with difference in SRT controlled. Speed differences to letter-like forms and letters disappeared once RTs to simple visual features were controlled. We conclude that slow RAN children have difficulty in discriminating simple visual features that cannot be explained in terms of a more general speed of processing deficit, a deficit in making same/different judgments, or to differences in word reading ability.

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Slow performance on rapid automatized naming tasks has long been known to be associated with poor reading performance (Denckla & Rudel, 1974, 1976; Spring & Capps, 1974), with RAN performance of children with dyslexia differing from that of age-matched average readers (Bowers, Steffy, & Tate, 1998), "garden-variety" poor readers (Badian, 1994; Wolf & Obregon, 1992) and readers with other learning disabilities (Ackerman & Dykman, 1993).

In recent years, various explanatory accounts of this relationship have been advanced: that both slow RAN and poor reading index an underlying problem in phonological processing (Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; Wagner & Torgesen, 1987; Wagner et al., 1997); that slow RAN is an index of generally slow processing speed that also affects the development of reading skills (Kail, 1991; Kail & Hall, 1994; Kail, Hall, & Caskey, 1999); and that slow RAN indexes a deficit in nonphonological processes, possibly a problem with orthographic processing (Ackerman & Dykman, 1993; Badian, 1993; Blachman, 1984; Bowers & Wolf, 1993; Felton & Brown, 1990; Manis, Seidenberg, & Doi, 1999; Wolf & Bowers, 1999). This latter view has come to be known as the double deficit theory of dyslexia, which proposes that children with dyslexia can be assigned to one of three subgroups: those with a phonological deficit, those with a RAN deficit, and those (the most severely affected) with deficits in both phonological processing and RAN. Bowers (1995); Bowers and Wolf; and Powell, Stainthorp, Stuart, Garwood, and Quinlan (2007) all have provided evidence of the existence of these three postulated subgroups in typically developing populations and those with dyslexia.

Bowers and Newby-Clark (2002) have suggested that poor RAN performance may have a negative impact on the integration of the visual information relating to the sequence of letters in words, which may then result in limitations on the development of an extended orthographic lexicon.

Despite the many studies that have been carried out to demonstrate and investigate the nature of the relationship between RAN performance and reading, relatively few studies have sought to investigate the cognitive processes that are involved in performing RAN tasks. A number of studies (Cobbold, Passenger, & Terrell, 2003; Georgiou, Parrila, & Kirby, 2006; Neuhaus, Foorman, Francis, & Carlson, 2001) separated RAN response times into two components, articulation time and pause time, and showed that it is the latter component that relates most closely to reading levels. Pause time is interpreted as a measure of retrieval time from phonological memory. However, Clarke, Hulme, and Snowling (2005) failed to replicate this result when the reading measure used was exception word reading. Clarke et al. noted that better readers paused more strategically (i.e., more often at the ends of lines) than poorer readers, and they suggested that differences in RAN may in part reflect differences in strategic control that result from differences in reading practice and experience.

Of the four RAN tasks (picture naming, color naming, digit naming, letter naming) it is the alphanumeric tasks (RAN letters and digits), which are most strongly associated with reading performance (Neuhaus & Swank, 2002). The letter and number stimuli differ from the color and picture stimuli in being selected from a closed set of items, all of which are composed from a small set of visual features, that is, lines and curves in different orientations. The RAN letter task would appear to have a more direct relationship with reading because both involve the processing of letters per se. The flowchart (see Figure 1) provided by Wolf, Bowers, and Biddle (2000) of the processes that are likely to be involved in RAN proposes that one of the first stages in RAN performance involves visual processing. However,

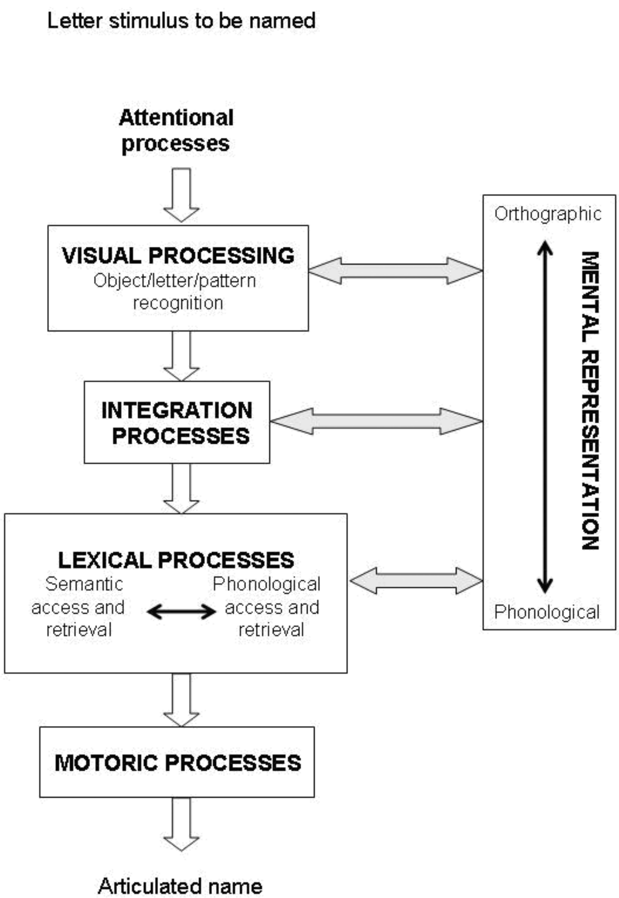


FIGURE 1 Model of visual naming. Adapted from Wolf, Bowers, and Biddle (2000). Reprinted by permission of SAGE Publications.

possibly because of the impact of Vellutino's (1979) devastating critique of studies investigating visual perceptual processing deficits in dyslexia, until recently there have been fewer investigations of prelexical visual processing in children with dyslexia or those showing typical development. This despite Venezky's (1993) point that the fact that

> the reader interacts with the text, integrates previously acquired knowledge with local text information, and generates hypotheses about what might occur next in the text does not negate the critical initiation role played by the letters, words, punctuation, and other graphic characteristics of the page. (p. 3)

Lachmann and van Leeuven (2007) have recently argued that many of the tasks used to investigate visual processing deficits in children with dyslexia may not be sufficiently sensitive to detect anomalies. To our knowledge there is no research as yet that has focused specifically on letter identification processes in children identified as having RAN deficits. That is, it is simply not known whether children with RAN deficits have problems with the early visual processing of letters.

Vellutino (1979) made a systematic review of the published research that implicated a visuo-perceptual deficit in dyslexia. He found that much of the research up to that time was flawed because of poor methodology. For example, few studies included a control group, and little attention was paid to matching for socioeconomic status or cultural background. Groups of poor readers often included children with low IQ, neurological problems, or emotional problems, which rendered conclusions about a visuo-perceptual deficit which was specific to poor reading performance unreliable. The majority of the studies reviewed by Vellutino used tasks of matching to standard and figure drawing such as the Bender Visual Motor Gestalt Task (Bender, 1938) as indices of a perceptual deficit. It is questionable whether such tasks are able to assess performance at the very first stage of visual processing since they clearly involve a degree of higher level cognitive processing. Vellutino argued that because of flawed methodology, claims that a visuo-perceptual deficit was implicated in poor reading performance had to be treated with caution. His laboratory therefore instigated a systematic experimental investigation of the perceptual deficit hypothesis using carefully controlled stimuli with appropriate control of participants. In this series of experiments no significant differences were found between participants with and without dyslexia on tasks involving the processing of visual stimuli such as words, scrambled letters, items composed of Hebrew letters, and geometric designs. It was therefore concluded that visuo-perceptual difficulties were not implicated in dyslexia. However, the tasks used in these experiments (including copying and copying from memory) required much more than visual perception. Because no differences were found in performance across groups on these tasks, Vellutino concluded that visual perception in children with dyslexia must be intact. However, this conclusion needs to be treated with some caution because of the rather complex nature of the tasks used and the failure to measure response times.

Vellutino's critique notwithstanding, there is more recent evidence suggesting that children with dyslexia do show visual and visual-attentional deficits. For example, Lovegrove, Martin, and Slaghuis (1986) proposed that a large percentage of disabled readers had a low-level visual deficit. Although they acknowledged that the impact of this deficit on reading was not known, they argued that its association with reading disability merited further investigation.

In a developmental experimental study, Willows, Kruk, and Corcos (1993) found that younger children with a reading disability were slower and less accurate at deciding whether two unfamiliar letters (Hebrew for non-Hebrew speakers) were the same or different. Stein and Walsh (1997) argued from their studies that children with developmental dyslexia may have deficits in the adequate processing of fast incoming sensory information across all modalities. They suggested that the underlying cause of such deficits may be found at a lower level than the perceptual and cognitive systems that have been investigated in psychological research. In addition, Hari and Revall (2001) proposed that the observed deficits may be the result of children with dyslexia having sluggish attentional shift, which can impair rapid stimulus sequence processing regardless of the modality. However, Bosse, Tanturier, and Valdois (2007) have recently suggested that the visual attention span disorder is not a universal characteristic and might be a separate, independent cognitive disorder leading to word reading difficulties. In addition, Pammer and Kevan (2007) have proposed that low-level visual sensitivity is a significant contributor to word reading with the possible result some children with dyslexia may show impaired visual sensitivity. However, in their study investigating this they measured phonological processing but not RAN performance.

In short, though a phonological deficit has been firmly established as a cause of some children's dyslexia, there is now sufficient evidence to hypothesize that early visual perceptual processes may also be implicated in word reading difficulties. The rapid naming deficit associated with dyslexia is well established, and though we cannot gainsay that phonological processes are involved in RAN performance, the potential role that visual perceptual processes may play remains largely uninvestigated. This is therefore a potentially fruitful area for research, especially as the cognitive processes that Wolf et al. (2000) proposed operate in performing the RAN letter naming task can be directly related to the cognitive processes proposed to operate in the lexical reading route of the Dual Route Cascade (DRC) model of visual word recognition (see Figure 2, RAN and DRC lexical processes). Given this direct relationship, an understanding of the sources of difficulty underlying slow performance on the RAN letter naming task might transfer directly to related reading difficulties.

The DRC model incorporates the McClelland and Rumelhart (1981) model of lexical access. This proposes three levels of representation: visual features, letters,

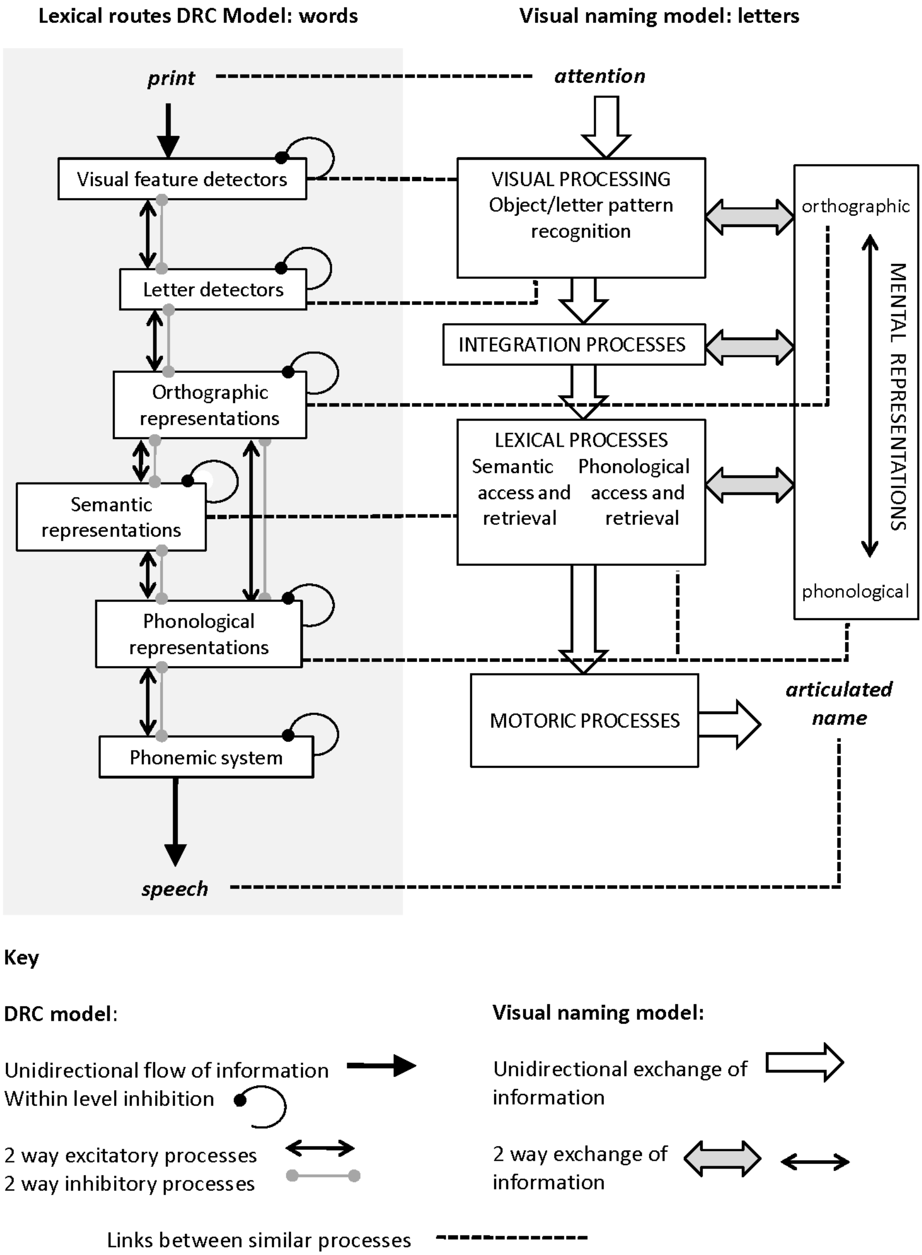


FIGURE 2 RAN processes compared with the Dual Route Cascade (DRC) model.

and words. Lexical access is achieved through processes of activation and inhibition between and within these three levels. If we adopt this model, then the first stage in processing letters in both reading and RAN alphanumeric tasks is visual feature identification.

In this study we report the data from four experiments designed to investigate whether children with a single RAN deficit showed compromised performance when processing visual stimuli relative to children who showed normal performance on RAN tasks. We also report the data from control measures of visual and auditory reaction time tasks.

EXPERIMENT 1: SIMPLE REACTION TIME

Method

Participants. To select criterion groups for the study, the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999) and the British Ability Scales Word reading test was administered to a total of 1,010 children in Years 3 and 4 (equivalent to U.S. Grades 2 and 3) in nine state-funded primary schools in an urban area to the west of London, UK (Powell et al., 2007).

The RAN letters and RAN digits subtests from the CTOPP were administered to assess naming speed. Both these two subtests require participants to name as quickly as possible two 4 × 9 arrays containing repetitions of six letters or digits. Phonological awareness was assessed using the elision and blending subtests of the CTOPP. Elision requires the participant to say out loud the word that results from the deletion of a designated sound (e.g., "Say *cup* without saying /k/"). Blending requires the participant to combine a sequence of discrete phonemes to form a word (e.g., "What word do these sounds make? m-a-d." Phonological memory was assessed using the memory for digits subtest and the nonword repetition subtest. The CTOPP manual gives procedures for calculating composite scores for RAN, Phonological Memory (PM), and Phonological Awareness (PA) by summing the standard scores for the two measures of each construct. However, because the instrument was not standardized on a UK population composite scores for RAN, PM, and PA were calculated by summing the raw rather than the standard scores.

Word reading ability was assessed using the British Ability Scales (BAS) single word reading task (Elliot, Murray & Pearson, 1983). This task requires the participants to read aloud single words of increasing difficulty. Only correct pronunciations of words were accepted, and testing was abandoned if the children made more than 10 successive errors as detailed in the manual.

These data were use to select 154 children to form two groups: a low RAN group and a group of matched control children. The 75 children comprising the low RAN group were further subdivided into a younger and an older group: 36 younger children in Year 4 (equivalent to U.S. Grade 3) and 39 older children in Year 5 (equivalent to U.S. Grade 4). They were identified as having a RAN deficit (defined as RAN performance of at least 1 standard deviation below the mean) and normal phonological awareness (defined as performance not less than 1 standard deviation below the mean). The control group was also further subdivided into a younger and an older group consisting of 36 children in Year 4 and 43 in Year 5. They were selected to show normal phonological awareness as defined above and normal RAN performance (defined as scores not less than 1 standard deviation below the mean). In addition each child in each of these two control groups was selected as a match for a low RAN child in the respective younger and older groups on the basis of age, verbal, and nonverbal ability as measured respectively by the Vocabulary and the Block Design subtests of the Wechsler Intelligence Scale for Children, Third Edition Revised (WISC–III–R; Wechsler, 1992), and on visual acuity as measured on the Freiburg Visual Acuity Test (Bach, 1996).

Table 1 shows the mean performance of the four groups on these tests. These data were analyzed using independent t tests to verify the accuracy of the matching procedure. No significant differences were found between groups on any of these control measures. There were differences on BAS word reading; for the younger groups, $t(70) = 2.55$, $p = .03$, and for the older groups, $t(80) = 2.79$, $p = .007$. In each case the control children were significantly better readers than the low RAN children.

Materials and measures. As we intended to measure both speed and accuracy in later visual feature judgment experiments (see next), and as there have been suggestions that slow RAN is an index of generally slow speed of processing (Kail, 1991), we first administered a simple reaction time (SRT) task to all children. Any observed SRT differences between groups could then be statistically controlled in subsequent data analysis. A computerized test of SRT was developed using E-prime experiment presentation software (Schneider, Eschman, & Zuccolotto, 2002). The task was presented using a Dell Latitude D800 laptop computer with an Intel Pentium processor (1400MHz) and a 15” color screen. The children were required to make a key-press response following the appearance of a target stimulus on the screen and the time taken to do this was measured. The target stimuli were six color drawings of monsters.

Procedure. The ethics committee of the School of Psychology and Human Development, Institute of Education, scrutinized and passed the project. Informed parental consent was obtained from the parents via letters sent out from the schools. The children were told that they were free to withdraw at any time. No child chose to do so.

TABLE 1
Mean (*SD*) Raw Scores on PA, PM, and RAN Core Subtests of the Comprehensive Test of Phonological Processing, Chronological Age, Scaled Scores on the Block Design and Vocabulary Subtests of the WISC–III–R, and BAS Word Reading Standard Scores and Raw Scores for Low RAN and Controls Groups

	Younger (Year 4)		*Older (Year 5)*	
	Low RAN[a]	*Controls*[b]	*Low RAN*[c]	*Controls*[d]
PA (raw score)	20.285	20.47	20.41	19.93
	(4.89)	(5.24)	(4.82)	(4.45)
PM (raw score)	18.92	18.86	20.51	20.14
	(3.76)	(2.69)	(3.52)	(2.88)
RAN (raw score in msec)	117.07	78.67	102.79	70.74
	(15.01)	(12.95)	(15.26)	(10.14)
Age at initial screening (Years 3 and 4)	7:12	7:21	8:22	8:20
	(0:15)	(0:23)	(0:25)	(0:23)
WISC–III–R				
Block Design (s.s.)	9.06	8.69	9.15	8.40
	(4.06)	(3.98)	(3.93)	(3.49)
Vocabulary (s.s.)	11.19	10.86	10.54	9.98
	(3.47)	(3.21)	(3.56)	(3.04)
Visual acuity	16.33	17.97	18.50	16.93
	(6.37)	(5.260	(5.07)	(4.16)
BAS Word Reading (s.s.)	118.42	135.56	134.15	149.46
	(32.04)	(26.43)	(30.41)	(26.62)
Range	58–172	69–188	49–199	72–184
BAS Word Reading (raw scores)	52.64	62.72	61.67	70.44
	(18.80)	(14.47)	(16.26)	(12.07)

Note. PA = Phonological Awareness; PM = Phonological Memory; WISC–III–R = Wechsler Intelligence Scale for Children, Third Edition Revised; BAS = British Ability Scales.
[a]*n* = 36. [b]*n* = 36. [c]*n* = 39. [d]*n* = 43.

Each participant saw a welcome screen displaying the six pictures of monsters that acted as target stimuli and the following instructions, “Hello. When you see one of these monsters, press the spacebar as quick as you can.” After ensuring that the child understood the instructions, the experimenter initiated a block of six practice trials, followed by two blocks of experimental trials. For both practice and experimental blocks, each trial began with the presentation of a black fixation cross in the center of a white screen for 500 msec, followed by a lag, followed by the appearance of the target stimulus. The duration of the lag was varied to prevent the children anticipating the moment when the stimulus appeared on the screen and was 300, 600, or 900 msec. Each lag duration occurred equally often and in random order, as did each of the six target stimuli. The target remained in the center of the screen until the participant made a spacebar response, which initiated the next trial. There was a short break of approximately 1,000 msec between trials. There were 18 trials in each of the two experimental blocks.

Results and Discussion

Raw scores for the simple reaction time task are given in Table 2.

SRT task data were analyzed in a two-way analysis of variance (ANOVA), with Group and Year as between-group factors, and mean RT as the dependent variable. There was a significant main effect of Group, with the low RAN group being significantly slower than the controls, $F(1, 150) = 4.25$, $p < .05$, $\eta^2 = .028$. There was also a significant main effect of Year, with significantly slower RTs in Year 4 than Year 5, $F(1, 150) = 7.02$, $p < .02$, $\eta^2 = .039$. The interaction between Group and Year was not significant, $F(1, 150) < 1$, *ns*. These data show that the children with a single RAN deficit had significantly slower response times when they were required to detect the appearance of a stimulus. This finding would appear to be in accord with Kail's position that RAN performance may index a general speed of processing deficit. Because of this difference in the groups it was necessary to control for SRT when analyzing the reaction time data from subsequent experiments.

EXPERIMENT 2: VISUAL FEATURES SAME/DIFFERENT JUDGMENT TASK (PARTS A, B, & C)

Method

Participants. The participants in this experiment were the same children who took part in the simple reaction time experiment just reported. The experiment was carried out at the beginning of the following academic year: Thus the younger groups were in Year 4 (equivalent to U.S. Grade 3) and the older groups were in Year 5 (equivalent to U.S. Grade 4).

Materials and measures. A computerized visual feature discrimination experiment was developed using the E-prime software and presented using the laptop

TABLE 2
Mean (*SD*) Reaction Times (msec) for Experiment 1 (Simple Reaction Time)

	Younger (Year 4)	*Older (Year 5)*
Low RAN	370.68 (77.40)	337.24 (58.57)
Control	341.33 (59.01)	323.64 (62.04)

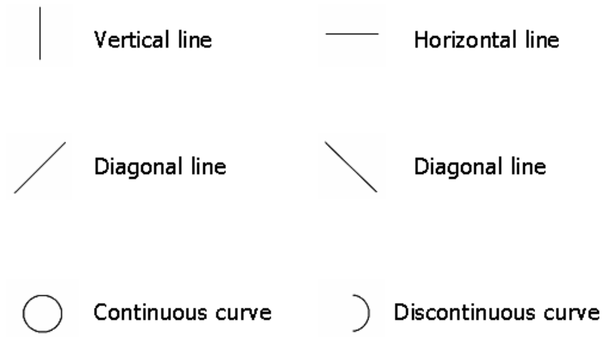


FIGURE 3 Simple visual features stimuli used in Experiment 2(a).

computer just described. This was in three parts (a, b, and c). Pairs of stimuli were presented on the screen, and the children were required to decide whether the stimuli were the same or different. The stimuli stayed on the screen until a key-press response was made. Speed and accuracy data were collected.

The stimuli for Experiment 2(a) (see Figure 3) were simple visual features of which letters are composed. Sixty pairs of stimuli were prepared, 30 of which were "same" trials (5 for each stimulus), and 30 were "different" trials (each combination of the six stimuli, with each combination occurring twice to allow for both possible left–right positions of the two stimuli).

The seven stimuli for Experiment 2(b) (see Figure 4) were based on the letter-like forms designed by Gibson, Gibson, Pick, and Osser (1962) and included

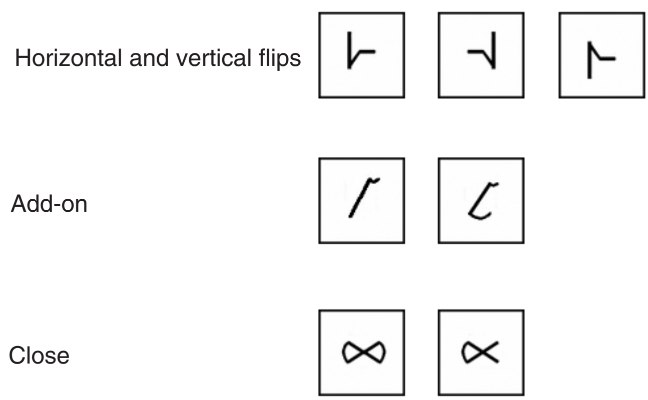


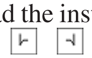
FIGURE 4 Letter-like form stimuli used in Experiments 2(b) and 3 (from Gibson et al., 1962).

transformations that were letter-like, that is, horizontal and vertical flips, forms with an add-on feature, and forms that involved open or closed elements.

Eighty-four pairs of stimuli were prepared as target stimuli. There were 42 “same” trials, involving six pairs of each of the seven letter-like forms, and 42 “different” trials, involving each combination of all forms, with each combination occurring twice to allow for both possible left–right positions of each pair.

The seven stimuli for Experiment 2(c) were real letters. The lowercase letters b, d, p, n, m, c, and o were selected. These shared similar characteristics to the letter-like forms used as stimuli in Experiment 2(b). There were reversals (b, d, p), add-ons (n, m), and open and closed curves (c, o). Eighty-four pairs of letters were prepared as target stimuli. There were 42 “same” trials, involving six pairs of each of the seven letters, and 42 “different” trials, involving each combination of all letters, with each combination occurring twice to allow for both possible left–right positions of each pair.

Procedure. The procedure was the same for each part of the experiment. For 2(a) the children saw a welcome screen with the instructions, “You are about to see a screen with 2 pictures on it like this: \ / If the two pictures are the same, press the blue key. If they are different, press the red key.” The experimenter determined that the children understood the task, pointing out that to be considered the same, the two pictures comprising each pair “had to be not just the same shape but also pointing in the same direction,” a constraint that was further reinforced by the experimenter during the practice trials. There were 10 practice trials, selected at random for each individual participant from the total of 60 stimulus pairs, each of which was followed by encouraging corrective feedback. There followed three blocks of 20 experimental trials, allowing for the presentation of all 60 stimulus pairs, in random order, with feedback (percentage correct, and mean RT) given at the end of each experimental block. (Ten of the items were therefore presented once in practice and once in the experiment, though because these 10 items were randomly selected they differed for each participant.) Each trial commenced with the presentation of a fixation cross for 500 msec followed by a pair of stimuli, which remained visible until a key-press response was made. Children pressed the blue key (the L key covered with a blue sticker and presented as the “blue key”) if they thought the two features were the same, and the red key (the A key covered with a red sticker and presented as the “red key”) if they thought they were different. For left-handers the required key-press response was reversed (red, A key for “same” responses; blue, L key for “different” responses) so that all participants responded “same” with their dominant hand. Speed and accuracy measures were recorded.

The procedure was the same for 2(b) and 2(c) with the exception that the initial welcome screen for Part b had the instructions “You are about to see a screen with two pictures on sit like this:  . If the two pictures are the same, press the blue key. If the two pictures are different, press the red key." For 2(c), the word "letters" was substituted for "pictures" and two letters replaced the letter-like forms.

Results and Discussion

Accuracy and latency scores and adjusted RT scores after controlling for SRT scores are given in Table 3.

We initially present the results for each part of this experiment separately.

A two-way ANOVA was carried out on the accuracy data for Experiment 2(a) (simple visual features), with Group and Year as between-group factors, and proportion correct responses as the dependent variable. There were no main effects of Group or Year and no interaction, Fs$(1, 150) = 0.53$, 1.36 and 0.78, respectively.

A two-way analysis of covariance (ANCOVA) was carried out on the RT data, with Group and Year as the between-group factors, SRT as the covariate, and

TABLE 3
Mean (*SD*) Accuracy Scores (Proportion Correct), Mean Reaction Times for Correct Responses (msec) and Adjusted Means (and Standard Errors) After Controlling for Simple Reaction Time (SRT) Measures (Experiment 1) for Experiment 2 Same/Different Judgment Task: (a) Simple Visual Features, (b) Letter-Like Forms and (c) Letters

	Younger (Year 4)		*Older (Year 5)*	
	Low RAN	*Control*	*Low RAN*	*Control*
Simple Visual Features (Expt. 2(a))				
Proportion correct	0.92	0.92	0.94	0.93
	(0.06)	(0.06)	(0.04)	(0.06)
RTs to correct responses (msec)	1083.61	960.76	1002.87	856.87
	(262.79)	(208.47)	(255.19)	(204.50)
M (*SE*) after controlling for SRT	1055.59	960.15	1007.77	875.46
(Expt. 1) (msec)	(38.21)	(37.35)	(35.91)	(34.58)
Letter-like forms (Expt. 2(b))				
Proportion correct	0.92	0.92	0.91	0.93
	(0.06)	(0.05)	(0.08)	(0.07)
RTs to correct responses (msec)	1120.12	980.56	985.86	897.40
	(461.97)	(210.95)	(240.72)	(244.79)
RTs (*SE*) after controlling for	1104.30	981.05	988.62	905.69
SRT (msec)	(51.33)	(50.17)	(48.24)	(46.45)
Letters (Expt. 2(c))	.94	.94	.93	.93
Proportion correct	(.05)	(.03)	(.06)	(.07)
RTs to correct responses (msec)	938.69	959.20	1028.40	911.31
	(194.76)	(41.23)	(39.65)	(39.59)
RTs (SE) after controlling for	921.45	855.33	895.79	798.65
SRT (msec)	(30.71)	(30.01)	(28.86)	(27.79)

mean RTs for the correct responses as the dependent variable. Analysis revealed that after controlling for SRT there was still a main effect of Group, $F(1, 149) = 9.62$, $p < .01$, $\eta^2 = .06$. There was no main effect of Year, $F(1, 149) = 3.22$, $p = .08$, and no interaction between Group and Year, $F(1, 149) < 1$, *ns*.

The accuracy data from this part of the experiment showed that there were no differences between the groups in their ability to make an accurate decision as to whether the pairs of stimuli were the same or different. This would appear to be a task which demanded very little processing capacity and indeed the performance of all groups was close to ceiling. On the surface these data support Vellutino's claims that individual differences in visual perception do not have an impact on reading performance. However, as we previously noted, Vellutino did not include any speeded performance measures. The analysis of the RT data (for correct responses only) showed that, even after controlling for SRT, the children in the low RAN groups were still taking longer to make their decisions about the identity of the pairs of stimuli. These data suggest that a characteristic of this group was that, though they were just as accurate in discriminating between stimuli composed of single basic visual features, they required significantly longer (on average, 115 msec) to make that decision after controlling for differences in SRT. The children in the low RAN groups had been selected because they had a significant deficit in RAN performance. These results suggest that over and above a general speed deficit, these children had a particular problem with speeded discrimination, which could possibly result from a deficit in this aspect of visual perception.

A two-way ANOVA was carried out on the accuracy data for Experiment 2(b) (letter-like forms), with Group and Year as between-group factors, and proportion correct responses as the dependent variable. There were no main effects of Group or Year and no interaction, all Fs $(1, 150) < 1$, *ns*.

A two-way ANCOVA was carried out on the RT data, with Group and Year as the between-group factors, SRT as the covariate, and mean RTs for the correct responses as the dependent variable. Analysis revealed that after controlling for SRT there was a main effect of Group, $F(1, 149) = 4.37$, $p = .04$, $\eta^2 = .038$. The children in the low RAN groups were significantly slower to make a decision about the letter-like forms even after controlling for their slower SRT performance. There was a marginally significant main effect of Year, $F(1, 149) = 3.71$, $p = .056$, $\eta^2 = .024$. There was a tendency for Year 4 children to be slower than Year 5 children. There was no significant interaction, $F(1, 149) < 1$, *ns*.

A further ANCOVA was carried out on these data with RTs for Experiment 2(a) (simple visual features) added as a further covariate. When these data were added as a covariate, the effects of both Group and Year were no longer significant, Fs$(1, 148) = 0.63$ and 1.57, respectively. The adjusted means and standard errors are presented in Table 4. As with Experiment 2(a), there were no differences between the groups in their accuracy levels. However, when responding at speed the low RAN groups were again significantly slower to discriminate this time be-

TABLE 4
Adjusted Mean Reaction Times (*SE*) for Correct Responses (msec) for Visual Discrimination of Letter-Like Forms (Experiment 2(b)) and Visual Discrimination of Letters (Experiment 2(c)) After Controlling for Simple Reaction Time (SRT), and RTs for Discrimination of Simple Visual Features (Experiment 2(a))

	Younger (Year 4)		*Older (Year 5)*	
	Low RAN	*Control*	*Low RAN*	*Control*
Letter-like forms				
RTs (*SE*) after controlling for SRT and RTs for Expt. 2(a) (msec)	1054.83 (47.14)	987.32 (45.34)	967.08 (43.74)	961.42 (43.03)
Letters				
RTs (*SE*) after controlling for SRT and RTs for Expt. 2(a) (msec)	1023.67 (32.76)	965.93 (31.51)	1003.01 (30.40)	961.90 (29.90)

tween the more complex unfamiliar non-nameable stimuli than the control groups even after controlling for SRT. These results would again seem to confirm Kail's position. Nevertheless, when RTs for simple visual feature discrimination obtained from Experiment 2(a) were entered as a covariate, there were no longer any significant differences between the groups. This suggests that the between-group differences in discrimination between the more complex, non-nameable letter-like forms were accounted for by differences in discriminating between the stimuli composed of very basic visual features since the group differences on the more complex measure became nonsignificant when visual feature discrimination speed was covaried.

A further two-way ANOVA was carried out on the accuracy data for Experiment 2(c), with Group and Year as between-group factors, and proportion correct responses as the dependent variable. There was no main effect of Group or Year, Fs(1, 150) = .001 and 1.114, *ns*, and no interaction, $F(1, 150) = .694$, *ns*.

A two-way ANCOVA was carried out on the RT data, with Group and Year as the between-group factors, SRT as the covariate, and mean RTs for the correct responses as the dependent variable. Analysis revealed that after controlling for SRT there was a main effect of Group, $F(1, 149) = 7.65$, $p = .006$, $\eta^2 = 0.049$. The low RAN groups were significantly slower to make a decision about the letters even after controlling for their slower simple reaction time performance. There was no main effect of Year, $F(1, 149) = 1.92$, $p > .05$. There was no interaction, $F(1, 149) < 1$, *ns*.

A further ANCOVA was carried out on these data with RTs for Experiment 2(a) (simple visual features) added as a further covariate. When these data were added as a covariate, the difference between the groups was no longer significant, $F(1, 148) = 1.14$, *ns*.

The accuracy data showed that there were no group or age differences when judging whether two letters were the same or different. These data suggest that the differences between the groups in their performance on the RAN task were not due to a priori differences in letter identification per se. Given that these children were in either their fourth or fifth year of reading instruction and had not been identified as having any specific problem, this is not a surprising finding. The letters were familiar nameable stimuli. Nevertheless, as with the results from the earlier parts of the experiment, the low RAN groups were significantly slower to judge whether the two letters were the same or different. However, again this difference was no longer significant when the RT performance for Experiment 2(a) was controlled for. These results suggest that the low RAN children do have a difficulty in discriminating between the basic visual features that make up letters, which is not accentuated by added complexity or compensated for by familiarity or nameability.

Further Analyses

As is noted from Table 1, though the low RAN children were in mainstream schools and not identified as having any specific problems with reading, nevertheless their mean word reading was significantly poorer than that of the control group. Therefore it remains a possibility that their slowness in discriminating between simple visual features might be the result of their poorer word reading. We therefore decided to conduct a further two-way ANCOVA with SRT and BAS word reading raw scores as the covariates and the RTs for Experiment 2(a) (simple visual feature discrimination) as the dependent variable. The adjusted mean RTs and standard errors after controlling for BAS word reading performance are shown in Table 5. There was a main effect of group after controlling for SRT and BAS word reading, $F(1, 148) = 7.53$, $p = .007$, $\eta^2 = .074$.

This analysis suggests that the low RAN groups had a significant specific weakness in processing the non-nameable visual features of which letters are composed, which is not accounted for by differences in their reading ability.

EXPERIMENT 3: LETTER-LIKE SHAPES SAME/DIFFERENT JUDGMENT TASK WITH MEMORY COMPONENT

Method

This experiment was designed to investigate whether there was an extra cost to the low RAN children if a memory component was added to the discrimination task.

TABLE 5
Adjusted Mean (*SE*) Reaction Times for Experiment 2(a) After Controlling for SRT and BAS Word Reading Raw Scores

	Younger (Year 4)		*Older (Year 5)*	
	Low RAN	*Controls*	*Low RAN*	*Controls*
RTs (*SE*) after controlling for SRT and BAS word reading	1046.91 (39.85)	960.57 (37.40)	1007.19 (35.97)	882.89 (35.91)

Note. SRT = simple reaction time; BAS = British Ability Scales.

Participants. The participants were the same as for the previous experiments.

Materials and measures. The materials and measures were the same as for Experiment 2b and involved the identical 42 stimulus pairs for the "same" trials, involving 6 pairs of each of the seven letter-like forms, and 42 stimulus pairs for the "different" trials, involving each combination of all forms, with each combination occurring twice to allow for both possible sequential ordering of each pair.

Procedure. This experiment involved the sequential presentation of the same 82 pairs of letter-like forms that were used in Experiment 2(b), and required the children to decide whether each pair of letter-like forms were the same or different. The children saw a welcome screen with the instructions, "You are about to see a screen with 1 picture on it like this: , followed by a screen like this: #####, followed by a screen like this . Press blue if the two pictures are exactly the same. Press red if the two pictures are different." The experimenter determined that the children understood the task and pointed out that to be considered the same, the pictures had to be not just the same shape but also pointing in the same direction. There were 10 practice trials, each of which were followed by encouraging corrective feedback, followed by four blocks of 21 experimental trials, with feedback (percent correct and mean reaction time) given at the end of each block. Each trial began with a fixation point which stayed on the screen for 500 msec. The first of the stimulus pair then appeared on the screen for a duration of 1,000 msec and was then replaced by a pattern mask of ##### for a further 1,000 msec. Then the second of the stimulus pair was displayed and remained on the screen until the child made a key press. As before red was for a "same" response and blue was for a "different" response. To control for order effects, both possible orders for each stimulus pairing were presented. RT and accuracy measures were recorded.

Results and Discussion

The mean accuracy and RT scores are given in Table 6. This table includes the adjusted means after controlling for SRT scores and after controlling for both SRT

TABLE 6
Mean (*SD*) Accuracy Scores (Proportion Correct), Adjusted Mean Reaction Times (Standard Errors) for Correct Responses (msec) for Visual Discrimination of Letter-Like Forms With a Memory Component (Experiment 3) (After Controlling for SRT [Experiment 1] and Adjusted Means [*SE*] After Controlling for SRT and RTs for Discrimination of Simple Visual Features [Experiment 2(a)])

	Year 4		*Year 5*	
	Low RAN	*Control*	*Low RAN*	*Control*
Proportion correct	.87 (.09)	.88 (.06)	.88 (.07)	.90 (.06)
RTs to correct responses (msec)	1103.51 (242.21)	957.57 (243.36)	1026.66 (277.19)	880.61 (241.84)
RTs (*SE*) after controlling for SRT (Expt. 1) (msec)	1085.29 (42.48)	958.13 (41.52)	1029.85 (39.92)	892.50 (38.44)
RTs (*SE*) after controlling for SRT and RTs for Expt. 2(a) (msec)	1023.67 (32.76)	965.93 (31.51)	1003.01 (30.40)	961.90 (29.90)

Note. SRT = simple reaction time.

(Experiment 1) and simple visual feature discrimination RT scores from Experiment 2(a).

A two-way ANOVA was carried out on the accuracy data, with Group and Year as between-group factors, and proportion correct responses as the dependent variable. There was no main effect of Group, $F(1, 150) = 1.93$, *ns*. There was a significant main effect of Year, $F(1, 150) = 4.24$, $p = .04$. There was no significant Group × Year interaction.

A two-way ANCOVA was carried out on the RT data, with Group and Year as the between-group factors, SRT as the covariate and mean RTs for the correct responses as the dependent variable. Analysis revealed that after controlling for SRT there was a main effect of Group, $F(1, 149) = 10.50$, $p < .001$, $\eta^2 = .066$. The low RAN groups were significantly slower to make a decision about the letter-like forms even after controlling for their slower simple reaction time performance. There was no main effect of Year, $F(1, 149) = 2.17$, $p > .05$. There was no interaction, $F(1, 149) < 1$, *ns*.

A further ANCOVA was carried out on these data with RTs for Experiment 2(a) (simple visual feature discrimination) added as a further covariate. When these data were added as a covariate, the differences between the groups were no longer significant, $F(1, 148) = 2.39$, *ns*.

The accuracy data again showed no significant differences between groups for this task. However, there was a main effect of year group. The younger groups made on average two more errors than the older groups. These results reflect an expected modest rise in immediate memory efficiency due to age but do not indicate that the performance of the low RAN groups was compromised by specific limitations in visual short term memory. The group differences in RTs, which were again not significant when controlling for RTs in Experiment 2(a), reflect and confirm the findings from Parts (b) and (c).

EXPERIMENT 4: AUDITORY RT

All the experiments in this study reported so far involved performance when making judgments about visual stimuli. Our analyses led us to conclude that the low RAN groups showed a consistent speed of decision deficit relative to the control children even when controlling for SRT and word reading accuracy. However, it could be argued, as Kail has done, that poor performance on RAN tasks relates to a general speed of processing deficit. We therefore decided to investigate whether the general group differences we had seen in the visual SRT experiment generalized to the auditory modality. To do this we designed an auditory SRT experiment and an auditory same/different judgment experiment using nonlinguistic sounds generated by the computer. Nonlinguistic auditory stimuli were chosen to be appropriate analogs for the very basic visual stimuli used in Experimental 2(a) and ensured that no semantic elements would be involved in the responses.

Experiment 4(a): Auditory SRT

Participants. The same children participated in these experiments, which were carried out while the children were in the spring term of Year 4 and 5 of primary school. One child from the older control group was not available to complete this task.

Materials and measures. A computerized test of auditory simple reaction time was developed using E-prime experiment software (Schneider et al., 2002). A Dell Latitude D800 laptop computer with an Intel Pentium processor (1400 MHz) and a 15” color screen were used to present the task. Six different nonlinguistic sounds were used as test stimuli.

Procedure. The procedure was analogous to that of visual RT task (Experiment 1). The participants were told that this task involved sounds. They would see a welcome screen and sounds would be played via the computer. The instructions were, “Hello, when you hear one of these sounds [6 in all] press the space bar as quickly as you can.” After ensuring that the child understood the instructions, the experimenter initiated a block of six practice trials followed by two blocks of experimental trials. For both practice and experimental blocks, each trial began with the presentation of a black fixation cross in the centre of a white screen. The nonlinguistic sound was presented in random order, with lags of either 300, 600, or 900 msec, selected randomly, between fixation and presentation of the sound.

Results and discussion. The mean auditory RTs are given in Table 7.

A two-way ANOVA was carried out on the data, with Group and Year as between-group factors, and mean RT as the dependent variable. There was no main effect of Group or Year, Fs(1, 149) = .49 and 2.21, *ns*, and no interaction, $F(1, 149) = 1.79$, *ns*.

These results led us to conclude that the speed deficit we had observed in the visual tasks did not generalize to the auditory modality. In the light of these data we would argue that, contrary to Kail's position, poor performance on RAN tasks is not simply an index of a general speed of processing deficit. From the data presented here, the children who were identified as having a RAN deficit only showed a speed deficit when responding to visual stimuli but not when responding to auditory stimuli.

Experiment 4(b): Auditory Same/Different Judgment Task

Having established that the low RAN children did not show significantly slower auditory RTs than the control children, we had to further address the possibility that they were generally slower to make a same/different judgment than the control children regardless of modality. To investigate this we developed an auditory analog of the visual simple features task (Experiment 2(a)). The stimuli selected were computer-generated tones with no semantic element, which varied in frequency, as described next.

Materials. The stimuli for this experiment were nonspeech tones presented through headphones with a 1000 Hz stimulus as the base tone and stimuli of 1015, 1017, 1019, 1021, 1023, 1025, 1027, 1029, 1031, 1033 Hz as the comparison tones.

Procedure. The procedure was analogous to that of Experiment 2(a) but with the pairs of stimuli being presented sequentially. Each stimulus pair started with a base tone of 1000 Hz that lasted for 300 msec. This was followed by an

TABLE 7
Mean (*SD*) Reaction Times (msec) for the Auditory Reaction Time Task (Experiment 4(a))

	Younger (Year 4)	*Older (Year 5)*
Low RAN	554.16	466.73
	(257.46)	(170.59)
Control	490.98	486.32
	(152.77)	(171.30)

interstimulus gap of 300 msec before the second tone, which also had a duration of 300 msec, was presented. The second tone was either the same as the base (1000 Hz) or differed in frequency in various increments. To identify a suitable level of difficulty, pilot work was carried out to find the most appropriate comparison tones. As with the visual experiments, the children pressed the blue key if they thought the two tones were the same and the red key, if different, though this was again reversed for left-handers.

Results and discussion. The mean proportion correct responses and the response times to correct responses are given in Table 8.

A two-way ANOVA was carried out on the data, with Group and Year as between-group factors, and proportion of total responses that were correct as the dependent variable There were no significant main effects of Group or Year, *F*s(1, 149) < 1, *ns*. There were no significant interactions.

A two-way ANCOVA was carried out on the RT data, with Group and Year as the between-group factors and auditory SRT as the covariate. In the RT analysis there were also no significant main effects of Group or Year, *F*s(1, 148) = 3.17, *ns* and < 1, *ns*. There were no significant interactions.

These results suggest that the low RAN children may not differ from the control children in their accuracy or speed to make a decision per se. They did not appear to have a deficit in their speed of response to stimuli presented in the auditory modality, unlike their slower responding to analogous tasks in the visual modality. These findings should be treated with caution, because to identify sufficient participants for the low RAN groups and appropriately matched members of the control groups we used the cut-off point of below –1 standard deviation below the mean for RAN and above –1 standard deviation below the mean for phonological awareness. A buffer zone between the experimental and control groups would have added strength to this no difference finding. However, this would have meant at least doubling the screening population.

TABLE 8
Mean (*SD*) Accuracy Scores (Proportion Correct) and Adjusted Mean RTs for Correct Responses (msec) (SE) for the Auditory Same/Different Judgment Task (Experiment 4(b)) After Controlling for Auditory Simple RT (Experiment 4(a))

	Younger (Year 4)		*Older (Year 5)*	
	Low RAN	*Control*	*Low RAN*	*Control*
Proportion correct	.67	.70	.72	.68
	(.17)	(.18)	(.18)	(.20)
RTs for correct responses	1649.90	1550.58	1628.27	1536.90
	(55.56)	(55.01)	(53.03)	(50.95)

Regression of RAN, SRT, and Visual Feature Discrimination on Word Reading

Having established that the low RAN groups were significantly slower than controls to make visual discriminations, our final aim was to examine more generally the degree to which performance on our visual discrimination task predicted word reading, and whether visual discrimination, along with SRT, mediated the relationship between RAN and reading in our sample. To do this we conducted a hierarchical regression analysis.

Table 9 shows the correlations between the variables, the unstandardized regression coefficients (B), the standardized regression coefficients (β), change in R^2 after each variable was entered into the regression analysis as a separate step, and R, R^2, and adjusted R^2 after entry of all three independent variables. After Step 1, with SRT in the equation, $R^2 = .16$, $F_{\text{inc}}(1, 152) = 2.434$, *ns*. After Step 2, with visual discrimination added to the equation, $R^2 = .040$, $F_{\text{inc}}(1, 151) = 3.891$, $p < .05$. The addition of visual discrimination resulted in a significant increment in R^2. After the final step with RAN added to the equation, $R^2 = .230$, $F_{\text{inc}}(1, 150)$, $p < .001$. Addition of RAN to the equation resulted in a significant increment in R^2. Visual discrimination was no longer significant in the final regression equation.

To summarize, simple reaction time did not predict unique variance in word reading, though interestingly, performance on the visual discrimination task did at Step 2 in the equation. Furthermore when entered last into the regression, RAN still predicted unique variance in word reading, suggesting that the relationship between RAN and reading is not entirely mediated by SRT and performance on the

TABLE 9
Hierarchical Regression Analysis of SRT, (Vis Discrim), and RAN on British Ability Scales (BAS) Word Reading Showing First Order Correlations Between All Variables, Standardized and Unstandardized Coefficients (at the Final Step), and Change in R^2 as well as R, R^2, and Adjusted R^2 (at the Final Step)

Variables	*BAS Reading (DV)*	*SRT*	*Vis Discrim*	*B*	*SE B*	*β at Entry*	*β (in Final Regression Equation)*	ΔR^2
SRT (entered at Step 1)	–.126			.001	.019	.005		.16
Vis Discrim (entered at Step 2)	–.190*	.329***		–.001	.005	–.167*	–.017	.025*
RAN (entered at Step 3)	–.479***	.264**	.369***	–.341	.056	–.475		.190***
							R^2	= .230
							Adjusted R^2	= .215
							R	= .480

Note. BAS = British Ability Scales; SRT = simple reaction time; Vis Discrim = Visual Discrimination. *$p < .05$. **$p < .01$. ***$p < .001$.

visual discrimination task but involves a large number of other possible processes that also need to be dissected out carefully in order to be understood.

These data show that the contribution of RAN performance to word reading is indexing more than just speed.

GENERAL DISCUSSION

The data from this series of experiments provide compelling evidence of a deficit in speed of discriminating simple visual features in children with slow rapid automatized naming. This deficit cannot be accounted for by differences in general speed of processing, because (a) the difference between the low RAN and control groups remained when differences in simple visual RT were controlled for and (b) no differences in speed of processing were found in the auditory modality. Thus the speed of processing deficit was specific to the visual modality in the tasks we administered[1] Nor can the deficit be accounted for by differences in reading ability because the between group differences in speed of visual feature discrimination persisted when differences in reading ability were controlled. Neither does it appear to result from a general slowness in discrimination because no *significant* between group differences were found in an auditory discrimination task.

Differences in speed of letter identification were no longer significant once visual feature discrimination speed was controlled suggesting that any differences in speed of letter identification could be explained by the deficit in visual feature processing speed. This is an important new finding, which might have implications for the ease with which young children learn to identify letters: Letter knowledge is consistently one of the strongest predictors of early reading skill. However, it is not just letter knowledge that is an important predictor of word reading skills; so is phonemic awareness. Both these combine to support knowledge of grapheme–phoneme correspondences. This possible deficit in the speed of letter identification, potentially related to early visual discrimination deficits, may inhibit the ability to map the letter–sound correspondences in the early stages of learning to read. This deficit might also subsequently affect the ease with which children set up representations of words in the orthographic lexicon. This argument is compatible with that of Willows et al. (1993). Both these proposals require further investigation.

For example, Breznitz (2002) suggested that children with deficits in RAN performance take a sequential approach to processing the letters in words, which impacts negatively on the speed with which they can integrate the individual letters into an orthographic unit. This proposal depended on findings from ERP data that the latencies of both P200 and P300 components were slower in auditory-phono-

[1]Following a suggestion by a reviewer we checked whether the RAN effect remained after also controlling for the nonsignificant auditory RT differences. This was the case, $F(1, 147) = 9.375$, $p < .01$.

logical tasks than visual-orthographic tasks in both typically and atypically developing child readers of Hebrew, with the latency difference significantly more pronounced in the children with dyslexia. This led Breznitz to propose that in children with dyslexia visual information has already deteriorated by the time auditory information is available to the system, leading to an impairment in the cross modal integration necessary for word recognition. Their findings were not inconsistent with earlier work with adults by Holmes and Ng (1993), who reported that poor spellers showed inefficient processing related to orthographically structured stimuli. However, recently Moll, Fussenegger, Wilburger, and Landerl (2009) challenged the view that the RAN-reading association is mediated by orthographic processing. Their argument depends on the finding that once nonword reading fluency was entered into regression analysis, the relationship between RAN and word reading fluency was no longer significant. This suggests that it may be the early visual processing of orthography (a necessary stage in both word and nonword reading), which is impaired in children with slow RAN. Our findings that performance on the visual discrimination task predicted unique variance in word reading, over and above any variance due to simple reaction time are consistent with Moll et al.'s account. However, this finding should be treated cautiously, because the proportion of the variance in reading accounted for by performance on the discrimination task, although significant, was extremely small (see Table 9). In addition, the contribution of visual discrimination to word reading was no longer significant after RAN was entered into the equation, indicating that visual discrimination and RAN share common variance in the prediction of word reading.

It is important that other possible component processes be identified and investigated in order properly to understand the relationship between RAN and reading. Furthermore, our results cannot answer questions about causality: At least two causal accounts are feasible. One possibility is that an early problem with visual discrimination leads to deficits in learning to identify and discriminate letters when first learning to read. On the other hand, it could be that early experiences with letters drive visual discrimination ability, particularly of the kind of abstract visual stimuli of which letters are formed and which were utilized in the current research. Further, longitudinal research is necessary to resolve this issue.

An additional issue that should be investigated is the possibility that a visual discrimination problem occurring very early on in the children's educational lives may have resolved by the time children reach the age of our sample, and thus although visual discrimination problems per se are no longer evidenced to any substantial degree, the consequences of early difficulties may be seen in the children's performance on other letter and reading-related tasks. Again, further longitudinal research is required fully to address this possibility.

The results of our experiments also point to the importance of measuring speed as well as accuracy when investigating component processes of word reading skill, as no group differences in accuracy were found in any of the experiments reported here. As we commented previously, a weakness of Vellutino's conclusion that there is not a visuo-perceptual deficit in dyslexia related to the lack of any measurement of response times. Clearly this study did not investigate performance of children with dyslexia so we can make no claims about such children's performance.

Investigation of the processes involved in identifying letters is a promising area for further work to elucidate the relationship between slow RAN and word reading skill. In this connection, Brundson, Coltheart and Nickels (2006) presented a useful and detailed letter processing framework in which initial visual analysis gives sequential access to two levels of abstract letter identification comprising separable font-free representations and case-free representations. This is the level of detail necessary to design experimental investigations of processes involved in slow RAN letter performance which appear to impact on the development of word reading skills.

This study began investigating the relation between possible visual processing deficits and RAN performance when the participants had received a minimum of 2 years reading instruction. They were therefore no longer novice readers. To understand fully the direction of causality between these various skills, there is a need for much wider longitudinal studies, which would enable an investigation of RAN performance and visual processing before reading instruction. At such a point performance on color and object naming would have to be included. Furthermore, though the participants were making good progress in their word reading skills, word reading accuracy was the only measure used in this study. Because speed has been identified as an important factor, it might be interesting to investigate the contribution of word reading speed as well as accuracy and additionally to study the contribution of these processes to comprehension of written texts. Verification of a role for early visual discrimination difficulties in later reading, not only at the single word but also the text level, would have important theoretical and educational implications.

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