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Letter processing and the formation of memory representations in children with naming speed deficits

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Abstract. The ability to recognize letter patterns within words as a single unit is important for fluent reading. This skill is based on previously established memory representations of common letter patterns. The ability to form these memory representations may be impaired in some poor readers, particularly readers with naming speed deficits (NSD). This study explored factors that influence letter processing and the subsequent formation of memory representations of letter strings in children with and without a NSD. Children were presented with a letter string, followed by a probe unit that was either a single letter, a two-letter cluster, or a repetition of the whole string. Children indicated whether or not the probe had been present in the preceding string. Two factors were manipulated: (a) amount of time to process the initial letter string, and (b) level of orthographic structure present in the letter string. Results indicated that overall, children with NSD performed less accurately than children without NSD. However, children with NSD showed no differential benefit in performance as a result of longer time to process a letter string. In addition, all readers were able to make use of the orthographic structure in a letter string to aid performance. Implications of results for establishing memory representations of letter strings are discussed.

Key words: Development of orthographic knowledge, Naming speed deficits, Orthographic representations, Rapid automatized naming

Reading is a complex process that combines various skills and knowledge. While individual word recognition is only one skill involved, it is of great importance. If difficulty is encountered recognizing individual words, few, if any, of the higher order skills such as comprehension, can operate. Fluent reading of individual words involves the recognition of letter patterns within words as a single unit (Adams, 1990). Through practice, letters that frequently occur together become associated into single orthographic units. It is these multi-letter units that are recruited from memory to aid in skillful, fluent reading. The ability to establish these memory representations may be impaired in some readers, particularly poor readers with slow naming speed. Bowers and Wolf (1993; Wolf & Bowers, 1999) suggested that children with slow performance on a Rapid Automatized Naming (RAN) task, process individual letters in a word too slowly to enable associations to form between letters. As a result, these children do not develop good quality representations of orthographic patterns that commonly occur in written English. Slow word recognition and impaired reading development are the outcomes. We explore here factors that influence letter processing and the subsequent formation of memory representations of letter strings in children with and without a naming speed deficit (NSD).

A RAN task measures naming speed of simple visual symbols such as digits, letters, colours, and objects. Research has established that a reliable relation exists between performance on the RAN task and reading skill (e.g., Blachman, 1984; Bowers & Swanson, 1991; Denckla & Rudel, 1976; Korhonen, 1995; Meyer, Wood, Hart, & Felton, 1998; Wolf, Bally, & Morris, 1986). However, while the relationship between RAN performance and reading is well established, it is unclear what underlying processes are driving this relationship. Torgesen, Wagner and colleagues (Torgesen & Wagner, 1998; Torgesen, Wagner, & Rashotte, 1994; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997) have argued that the RAN task measures the ease and speed with which one can access phonological information from long-term memory. Although the RAN task does share some variance with performance on phonological tasks, probably due to the need to access the sound representations and articulate the names of symbols in both tasks (Manis, Seidenberg, & Doi, 1999; Wolf, Bowers, & Biddle, 2000), the RAN task also accounts for unique variance in reading ability that is not accounted for by phonological tasks (e.g., Blachman, 1984; Bowers & Kennedy, 1993; Bowers & Swanson, 1991; Cornwall, 1992; Manis, Doi, & Bhadha, 2000; Manis et al., 1999).

The independence of naming speed and phonological skills in determining reading ability was clearly demonstrated by Bowers (1995, April). She followed a group of readers from Grade 2 to Grade 4 and categorized these children into four groups: those with no deficit in either phonological tasks or naming speed, those with only a naming speed deficit, those with only a phonological processing deficit, and those with a "double deficit" in both naming speed and phonological abilities. Both single deficit groups of children were moderately poor readers, with the double deficit group having the most profound reading disability. Bowers concluded from these results that naming speed was a source of variance in reading ability that was separate from that accounted for by phonological tasks, and that children who have deficits in both naming speed and phonological processing have the most severe reading impairments. This classification has been replicated, (e.g., Lovett, Steinbach, & Frijters, 2000; Manis et al., 2000; Wolf et al., 2002), leading researchers to argue that it is the nonphonological processes underlying the RAN task that mediate its relation with reading (e.g., Manis et al., 1999; Wolf et al., 2000). But what is the nature of the processes that mediate this relationship?

Wolf, Bowers, and colleagues (e.g., Bowers & Wolf, 1993; Wolf & Bowers, 1999; Wolf et al., 2000) conceptualize performance on the RAN task as encompassing an array of time-sensitive cognitive and linguistic subprocesses, many of which are shared with reading. These subprocesses include (a) attentional factors, such as orienting attention to or shifting attention from a stimulus, (b) visual processes, which enable feature detection, and detection of letter and letter patterns, (c) the integration of visual information with stored orthographic and phonological representations, (d) access to and retrieval of phonological labels, and (e) motoric processes resulting in articulation. Precise timing requirements exist both within a single component and in the integration or coordination of multiple subprocesses. The multi-component nature of rapid naming indicates that there are multiple potential sources of breakdown which could result in slower naming speed.

However, precisely how these processes underlying performance on the RAN task are related to reading is unclear. One of several hypotheses outlined by Wolf and Bowers (1999) relates to a disruption in visual processes. In this instance, Wolf and Bowers proposed that performance on the RAN task is related to reading through its effects on orthographic knowledge; that is, RAN is associated with the ease of building up orthographic representations. It is these orthographic representations that facilitate fluent reading (Adams, 1990; Ehri, 1992; Perfetti, 1992). Individual letters within a word must be processed fast enough to enable concurrent processing of sequential letters; if children are not able to identify letters quickly enough for this to occur, the quality of the orthographic representation that is established suffers and in turn contributes to problems in reading. Bowers and Wolf (1993; Wolf & Bowers, 1999) suggested that children with a naming speed deficit are characterized by this slower processing of individual letters. As a result, they are unable to form the associations between letters in a word that form the basis of the good quality orthographic representations that are needed for fluent reading. Thus, even with an equal amount of reading exposure, children with slow naming speed would still have a deficit in orthographic knowledge compared with children without a naming speed deficit.

In support of this hypothesis, deficits in orthographic knowledge have been found with children with naming speed deficits. Bowers, Sunseth, and Golden (1999) found that children in Grade 3 with a naming speed deficit performed less accurately than children without a naming speed deficit on two measures of orthographic knowledge. Similarly, Manis et al. (1999) found that for children in Grades 1 and 2, performance on the RAN task correlated better with three measures of orthographic knowledge, than with measures of phonological awareness. These results support a relation between performance on the RAN task and orthographic knowledge, as suggested by the Bowers and Wolf (1993; Wolf & Bowers, 1999) hypothesis.

However, other research findings have questioned the relationship. In a series of studies, Bowers et al. (1999) devised a "quickspell" task that required readers to report as many letters as they remembered from briefly displayed four letter arrays that varied in their orthographic structure; real words (e.g., name), pseudowords (e.g., pake), and illegal nonwords (e.g., tmln). They expected children with naming speed deficits, compared to peers with normal naming speeds, to be less accurate on all letter strings, but they would show little benefit in reporting letters from real words and pseudowords over illegal nonwords. Children without naming speed deficits, and therefore who have acquired more orthographic knowledge, should benefit from the orthographic structure in words and pseudowords compared with illegal letter strings. However, the results indicated that performance on the RAN task was related to the number of letters reported only in illegal letter strings. Children with a naming speed deficit reported fewer letters in the illegal letter string condition than children without a naming speed deficit, but these groups did not differ from each other in reporting letters from words and pseudowords. These results indicated that children with a naming speed deficit were using the orthographic redundancy in words and pseudowords to aid in letter processing. Bowers (2001) describes similar sensitivity to orthographic structure in a number of tasks for slow RAN children. These results are inconsistent with the idea that naming speed on the RAN task is related to reading through its effect on the growth of orthographic knowledge.

To date, the relationship between RAN performance and orthographic processing is poorly understood. More evidence is needed to establish how letter patterns are processed by children with and without a naming speed deficit. The main aim of the present study was to explore the relationship between RAN performance, letter processing, and the formation of memory representations of letter strings. To do this, a probe task was used in which children were briefly presented with a letter string for which they had to establish a memory representation. Following this letter string, a probe occurred. Children indicated whether or not the probe had been present in the preceding letter string. If children were able to establish a good quality representation of the letter string, accuracy for the probe would be high; if the representation was insufficient, accuracy would be low.

Three factors were manipulated to explore letter processing and the subsequent formation of memory representations for three groups of readers: average readers and poor readers with (slow RAN children) and without (fast RAN children) a naming speed deficit. The three factors manipulated were the amount of time available to study the initial letter string, the presence or absence of orthographic structure in the initial letter string, and the size of the probe. Because of their slower processing of individual letters in a string, it was expected that the slow RAN children would benefit the most from the longer study times, compared with the fast RAN children and average readers. Providing a longer study time to enable complete encoding of the initial letter string may compensate for slow letter processing and enable these children to form a better memory representation of the letter string with which to compare the probe. In addition, if slow RAN children do have a deficit in orthographic skill, these children would benefit the least from the presence of orthographic structure in the letter string. Their lower levels of orthographic skill would result in their reduced ability to use the orthographic structure found in a word compared with an orthographically illegal nonword when setting up memory representations. Thus, performance for words and nonwords should not differ greatly for the slow RAN children. However, fast RAN children, and average readers, should benefit from the orthographic structure found in words compared with nonwords as they have acquired more orthographic knowledge and can use this information to help set up the memory representations for words over nonwords.

Lastly, the size of the probe was manipulated. As the size of the probe increases, there are more letters to process, which may make the task more difficult for the slow RAN children if they are processing each letter individually, whereas the fast RAN group and the average readers may processes the larger multi-letter probes as a single unit. We examine this issue using single letter, two-letter cluster, or whole word/nonword probes.

To further explore the relation between naming speed and the probe task, a series of regression analyses were conducted to determine whether RAN performance contributed to accuracy on the probe task independently of other reading related skills such as phonological knowledge and memory span.

A related aim of the study was to directly examine, using an orthographic choice task, whether or not children with a naming speed deficit also have a deficit in orthographic knowledge as suggested by the theory of Bowers and Wolf (1993; Wolf & Bowers, 1999). Such a finding would be consistent with results reported by Bowers et al. (1999) and Manis et al. (1999).

Method

Participants

Seventy-two children in Grade 2 participated in this study. To select these 72 children, 494 children were screened in 31 schools. Two selection measures were administered for each child, and on the basis of these results, selected children were divided into three groups. First, each child was administered the word identification subtest of the Wide Range Achievement Test—Third Edition (WRAT-3). Children scoring below a standard score of 90 on the WRAT-3 were identified as poor readers. Next, each student in the sample was administered a Rapid Automatized Naming (RAN) task, adapted from Bowers and Swanson (1991). Consistent with previous research (e.g., Bowers & Swanson, 1991; Levy, Bourassa, & Horn, 1999) digits, as opposed to letters, were used to illustrate that it is not the letter knowledge *per se* that is thought to mediate the relation between RAN performance and reading; rather it is the underlying process of connecting a visual symbol with a verbal label that is critical on the RAN task. This test consisted of two matrices of digits. Each matrix contained eight rows of six digits. For each matrix the digits 1–9 occurred randomly with no immediate repetitions. The digits were presented in white on a black computer screen. The time to name all digits in the matrix was recorded via the computer. Timing began with the presentation of the matrix. When the last digit was read, the experimenter pushed a key to erase the display from the computer screen and to stop the clock. The dependent measure was the time required to read all 48 digits. The students' RAN score was the mean naming time in seconds for the two RAN trials.

On the basis of these two selection tests, participants were assigned to one of three groups. Students identified as poor readers on the WRAT-3 were divided into a fast RAN group and a slow RAN group on the basis of the criteria used in Levy et al. (1999). Levy and colleagues administered the RAN-digits task to 128 poor readers in Grade 2 and found the median RAN score on the test used here to be 41.5 s. Therefore, in the present study, 24 poor readers with a RAN score slower than 41.5 s were assigned to the slow RAN group. Twenty-four poor readers with a RAN score faster than 41.5 s were assigned to the fast RAN group. Twenty-four children with a WRAT-3 score of 90 and above, and with a RAN score faster than 41.5 s made up the average reader groups.

Measures

Orthographic knowledge

A two-alternative forced choice task was designed using a subset of items presented in Olson, Forsberg, Wise, and Rack (1994). This test included 15 pairs of words. Each pair consisted of the correct spelling of a target word, and a homophonic nonword spelling (e.g., rain–rane). Because the pairs are phonologically similar, but orthographically dissimilar, children must use word-specific knowledge of spelling, and could not rely on phonological information to complete this task. Children indicated which of the two alternatives was the correct spelling for a target word used in a sentence. The dependent measure was percent correct.

Probe tasks

Two probe tasks were used which differed only in the type of stimuli presented, one with real words and one with orthographically illegal nonwords. The two probe tasks were modifications of one used by Berninger (1987). The basic design of each probe task was the same: an initial word/nonword was presented followed by a probe. Three different probe sizes were used: a single letter, a 2-letter cluster, and a whole word/nonword. In addition, the initial word/nonword was presented for four different durations: 1, 1.5, 2, and 2.5 s. In each case, the probe followed the initial word/nonword after a 1 s interval and remained on the computer screen until a response was made. Thus, there were 12 conditions (4 study times $\times$ 3 probe types) for each probe task. Each condition was tested 16 times per participant for each probe task; for half of these trials the probe was present in the word/nonword, and for the other half the probe was not present in the word/nonword. The location of the probe letter or letter cluster varied such that on half the trials the probe was from the middle of the word/nonword, and on the other half of the trials the probe come from the beginning or end of the preceding word/nonword. For the whole word/nonword probe, half the trials had the probe word/nonword the same as the preceding word/nonword, and on half the trials the probe word/nonword changed by one letter. On the trials where the probe word/nonword changed by one letter, the position of this letter also varied from the middle, the beginning and the end position. The changing location of the probe was to ensure that participants would process the entire word/nonword rather than focus on one particular location within the word/nonword. Each participant completed 192 trials (12 conditions, 16 times each) for each probe task. In order to accommodate this large number of trials, each probe task was divided into two sessions of 96 trials each, for a total of 4 testing sessions.

Stimuli were presented on a computer screen as white words on a black background. Responses were made by pressing a key on the computer keyboard, one key used for "yes" responses and one key used for "no" responses. Trials in which the probe had and had not been present in the preceding word/nonword were randomly arranged with no more than three trials of one type occurring in a row. The dependent measures for this task were the proportion correct in each condition, as coded by the experimenter, and response time to make a decision. Response time was defined as the interval between the presentation of the probe and the key press to indicate a yes/no response and was recorded by the computer.

Stimuli used for the real word task consisted of 96 words, all four letters long and at the Grade 2 level (Educator's Word Frequency Guide, 1996). These 96 words were divided into 12 lists of eight words each. Each participant saw a different list of eight words in each of the 12 conditions. These 12 lists of words were counterbalanced across participants so that each list occurred an equal number of times in each of the three probe conditions (letter, letter cluster, and whole word) at each of the four study times. Order of presentation was counterbalanced across subjects. All study times and probe types were randomly presented. Table 1 presents an example of the stimuli used in one condition.

Ninety-six 4-letter nonwords were constructed for the nonword task. Each nonword was checked with bigram frequency norms to ensure that these combinations of letters did not occur together in any words in the English language (Mayzner & Tresselt, 1965), thus, each nonword was an orthographically illegal letter string. Counterbalancing of nonwords was the same as for words. Examples are provided in Table 1.

Memory span (DS)

The digit span subtest of the Wechsler Intelligence Scale for Children-Revised (WISC-R) was administered to ensure that any differences found between groups on the probe task were not the result of differences in memory abilities between the groups. This test provides a standard score with a mean of 10 and a standard deviation of 3.

Phonological awareness (TAAS)

The Test of Auditory Analysis Skills (Rosner, 1979) was also administered to examine the role of phonological information in performing the probe task. This test is a sound deletion task, in which children are to repeat a word spoken by the experimenter after deleting an indicated sound (e.g., say "game" without the /g/). The measure used was percent correct.

Table 1. Examples of stimuli used in probe task: words and nonwords.

Real words			Nonwords		
Letter string	"Yes" probe	"No" probe	Letter string	"Yes" probe	"No" probe
Letter probe					
feel	l	t	lndc	n	m
sent	t	d	bkrh	r	m
hill	h	k	ptrh	p	g
shop	s	c	mlcr	r	w
race	a	i	ltsr	s	m
done	o	i	ncwr	n	m
room	o	a	mtsl	t	h
slap	a	i	ftrw	w	v
Cluster probe					
wood	od	ol	gdln	gd	pd
card	rd	rt	kmrs	mr	wr
ball	ba	ha	dnhs	nh	mh
late	la	fa	bwcr	wc	mc
both	ot	at	rpdw	rp	mp
chip	hi	li	ctml	ml	mh
five	iv	in	fnwr	nw	mw
know	no	ne	bmrv	rv	rw
Whole probe					
beat	even	beak	ncdk	ncdk	ncdh
even	beat	ever	dlhw	dlhw	dltw
tall	tall	fall	lswm	lswm	tswm
cane	cane	sane	tnwr	tnwr	tnvr
made	made	make	lkmr	lkmr	lknr
love	love	live	tclv	tclv	tclw
till	till	tell	vklh	vklh	rklh
snap	snap	snip	nwtl	nwtl	nwhl

Note. Table illustrates stimuli for one study duration within a single condition. Stimuli would differ for other study durations within a condition.

Procedure

Children were individually administered the selection measures (WRAT-3 and RAN) in one 15-min session. The TAAS, DS, and orthographic choice task were administered on a different day, prior to the beginning of the experimental sessions. The Real Word probe task and the Nonword probe task were conducted concurrently. Because each probe task was divided into two parts, testing extended over a period of 4 days. The order of probe tasks was counterbalanced across participants such that half of the participants started with real words, and the other half started with nonwords. Children were all tested during the second half of the school year.

Results

Group comparisons

Analyses on the selection and pre-test measures, presented in Table 2, were conducted to verify the reliability of the groupings.

RAN scores, WRAT-3 scores, digit span scores and scores on the TAAS were each subjected to an analysis of variance with reading group as the independent factor. Analyses indicated that there were reliable effects of reading group for the WRAT-3 scores, $F = (2,69) = 120.30$, $MSe = 27.90$, $P < .001$, RAN scores, $F(2,69) = 59.96$, $MSe = 54.69$, $P < .001$, digit span scores, $F(2,69) = 5.46$, $MSe = 5.57$, $P < .01$, and the TAAS scores, $F(2,69) = 13.94$, $MSe = .05$, $P \leq .001$. *Post-hoc* analysis revealed that the slow RAN group and the fast RAN group were matched on WRAT-3 scores, TAAS scores, and digit span. Both poor reading groups had scores lower than the average reader group on these measures. RAN scores were slower for the slow RAN group than the fast

Table 2. Means (*M*) and standard deviations (SD) for selection and description measures.

Group	WRAT-3	RAN	TAAS	Digit span
Slow RAN ($n = 24$)				
M	83.21	54.25	.53	10.0
SD	6.35	11.16	.22	2.9
Fast RAN ($n = 24$)				
M	83.67	34.50	.49	8.8
SD	3.85	3.56	.28	1.7
Average ($n = 24$)				
M	103.92	33.53	.80	11.0
SD	5.35	5.19	.15	2.3

Note. WRAT-3 scores are standard scores ($M = 100$, SD $= 15$), RAN scores are seconds, TAAS is proportion correct, and digit span is standard scores ($M = 10$, SD $= 3$).

RAN group, who had RAN scores equal to the average reading group. Thus, the only measure on which the slow RAN group and the fast RAN group differed was RAN performance. These results indicate that group selection was reliable. Although these groups are similar to the categories outlined by the double-deficit hypothesis (Wolf & Bowers, 1999), in that the slow RAN group is most similar to a double-deficit group, the fast RAN group is most similar to a single phonological deficit group, and the average readers would be considered a no deficit group, we acknowledge that we have used a more lenient criteria for defining these groups than is dictated by the double-deficit hypothesis. Children in the midrange on the RAN task may be misclassified, and this must be considered when interpreting the results.

Orthographic knowledge

The results of the orthographic choice task are consistent with previous research that has found a relationship between RAN performance and orthographic knowledge. Analysis indicated a reliable main effect of reading group, $F(2,69) = 21.25$, $MSe = .01$, $P < .001$. *Post-hoc* analysis revealed that the slow RAN group (70% correct) was less accurate than the fast RAN group (79% correct), which was less accurate than the average group (92% correct). These results are suggestive of a deficit in orthographic knowledge in children with a naming speed deficit.

Probe tasks

For the probe task, latencies to respond were measured, however, no differences between groups or between probe types were found. Thus, only proportion correct is reported. The proportion correct for each reading group is presented in Table 3 (words) and Table 4 (nonwords) for letters, letter clusters and words/nonwords as a function of study time. Several observations can be made from the data. First, the slow RAN group appears to be less accurate overall than the fast RAN group and the average group. Second, all readers appear to be more accurate with words than with nonwords. How probe size and study duration interact with reader skill is less clear. An analysis of variance with reading group as the between subject factor, and probe type, stimulus type, and study duration as within subject factors was conducted to clarify these observations. There were main effects of reading group, $F(2,69) = 35.40$, $MSe = .15$, $P < .001$, stimulus type, $F(1,69) = 150.47$, $MSe = .031$,

Table 3. Proportion correct (standard deviation) for probes by group and study time: real words.

Study time	Slow RAN	Fast RAN	Average
1 s			
Letter	.68 (.14)	.83 (.11)	.92 (.08)
Cluster	.63 (.11)	.71 (.13)	.84 (.10)
Word	.71 (.15)	.82 (.14)	.90 (.12)
1.5 s			
Letter	.67 (.14)	.85 (.12)	.90 (.06)
Cluster	.65 (.13)	.78 (.14)	.86 (.11)
Word	.73 (.14)	.84 (.12)	.89 (.12)
2 s			
Letter	.68 (.13)	.84 (.14)	.89 (.12)
Cluster	.64 (.15)	.79 (.13)	.84 (.13)
Word	.76 (.16)	.86 (.11)	.90 (.11)
2.5 s			
Letter	.70 (.17)	.85 (.13)	.93 (.06)
Cluster	.67 (.13)	.81 (.15)	.87 (.09)
Word	.76 (.19)	.87 (.11)	.90 (.10)

$P < .001$, probe type, $F(2,138) = 38.95$, $MSe = .02$, $P < .001$, and study duration, $F(3,207) = 13.07$, $MSe = .009$, $P < .001$. However, these main effects were qualified by two significant interactions; an interaction between reading group and probe type, $F(4,138) = 3.66$, $MSe = .02$, $P < .05$, and a 3-way interaction between reading group, stimulus type, and study duration, $F(6,207) = 2.94$, $MSe = .009$, $P < .01$. No other interactions were significant. As reader group was implicated in all significant interactions, separate 2 (words/nonwords) $\times$ 3 (probe type) $\times$ 4 (study duration) ANOVAs were conducted for each reader group to answer the following specific questions.

What are the effects of longer study durations?

There was no main effect of study duration, and no significant interactions involving study duration for the slow RAN group, P's > .05, indicating that longer study durations did not improve performance for the slow RAN group with either words or nonwords, or for any of the different probes. However, a longer study duration did improve performance for the fast RAN group, $F(3,69) = 6.43$, $MSe = .009$, $P = .001$, across both words and nonwords. For the average readers, study duration interacted with stimulus type, $F(3,69) = 6.57$, $MSe = .006$, $P = .001$,

Table 4. Proportion correct (standard deviations) for probes by group and study time: nonwords.

Study time	Slow RAN	Fast RAN	Average
1 s			
Letter	.56 (.10)	.75 (.10)	.77 (.13)
Cluster	.56 (.14)	.67 (.09)	.64 (.14)
Nonword	.61 (.11)	.73 (.11)	.74 (.11)
Word	.68 (.14)	.88 (.12)	.92 (.12)
1.5 s			
Letter	.56 (.12)	.75 (.11)	.80 (.11)
Cluster	.57 (.15)	.65 (.13)	.75 (.12)
Nonword	.63 (.13)	.74 (.12)	.77 (.15)
Word	.74 (.19)	.88 (.13)	.92 (.11)
2 s			
Letter	.61 (.15)	.76 (.10)	.81 (.11)
Cluster	.59 (.12)	.70 (.10)	.73 (.17)
Nonword	.65 (.12)	.78 (.13)	.79 (.13)
Word	.74 (.14)	.88 (.10)	.93 (.13)
2.5 s			
Letter	.59 (.13)	.76 (.13)	.79 (.13)
Cluster	.56 (.16)	.68 (.12)	.75 (.14)
Nonword	.62 (.74)	.80 (.12)	.83 (.13)
Word	.74 (.16)	.88 (.13)	.92 (.10)

reflecting the fact that longer study durations did improve performance for nonwords, but not for real words. Thus, while longer study durations benefited both the fast RAN group and the average reader group, the slow RAN group did not benefit from longer times to study the initial letter string. Increased processing time did not lead to improved representation of the letter string for the slow RAN children.

What are the effects of different sized probes?

Contrary to expectations, the slow RAN group did not have greater difficulties with the larger sized probes; in fact, the data indicate that the slow RAN group was at their peak performance with the whole word/nonword probe, much like the fast RAN group and the average reader group. Analyses indicated a significant effect of probe type for all three reader groups: slow RAN group, $F(2,46) = 15.10$, $MSe = .018$, $P < .001$; fast RAN group, $F(2,46) = 23.10$, $MSe = .017$, $P < .001$; average reader group, $F(2,46) = 10.46$, $MSe = .025$, $P < .001$. Stimulus type did not interact with probe size for any of the reader groups, indicating that each group showed the same pattern of results whether with words or nonwords. However, *post-hoc* analysis revealed a different pattern of results for the slow RAN group compared with the fast RAN group and the average reader group. The slow RAN group was more accurate with whole word/nonword probes than with letter or letter cluster probes. There was no difference in accuracy between letter and letter cluster probes. For both the fast RAN group and the average reader group, accuracy for whole word/nonword probes was equal to accuracy for letter probes, which was greater than for cluster probes. Generally, cluster probes proved to be most difficult for all readers.

What are the effects of orthographic structure?
Examination of the results suggests that all three reader groups perform better with words than with nonwords. Three separate analyses of variance confirmed this observation, each revealing a main effect of stimulus type: slow RAN group, $F(1,23) = 31.47$, $MSe = .04$, $P < .001$; fast RAN group, $F(1,23) = 72.06$, $MSe = .016$, $P < .001$; average reader group, $F(1,23) = 66.34$, $MSe = .032$, $P < .001$. However, stimulus type interacted with study duration for the average readers, $F(3,69) = 6.57$, $MSe = .006$, $P = .001$. As noted earlier, this finding is a reflection of the average readers' improvement with longer study durations for nonwords, but not for words. What is important is that, as earlier analysis of variance indicated, there was no interaction between reader group and stimulus type; all three groups benefited equally from the presence of orthographic structure found in real words compared with nonwords.

Relation between RAN and probe task

As accuracy for each probe type across study durations was correlated, composite variables for letter probes, letter cluster probes, and word/nonword probes for both words and nonwords were created. These six composite variables were created by taking the mean *z*-scores for each respective probe type across the different study durations. Correlations based on the entire sample for these composite variables and RAN, TAAS, and DS are presented in Table 5.

RAN performance was significantly correlated with all probe variables, with correlations ranging from −.49 to −.62. Phonological awareness was less well correlated with all probe variables (range = .24–.44), although all correlations were significant. Digit span was not significantly

Table 5. Correlations among RAN, phonological awareness, digit span and probe task variables.

Measures	1	2	3	4	5	6	7	8	9
(1) Digit span		.29	−.13	.11	.16	−.04	.09	.07	−.01
(2) Phonological awareness			−.15	.44	.44	.36	.40	.36	.24
(3) RAN				−.62	−.57	−.58	−.62	−.49	−.61
(4) Letter probe (real words)					.82	.74	.78	.65	.67
(5) Cluster probe (real words)						.68	.73	.63	.64
(6) Word probe (real words)							.62	.53	.77
(7) Letter probe (nonwords)								.78	.75
(8) Cluster probe (nonwords)									.70
(9) Nonword probe (nonwords)									

Note. All correlations at or above .29 are significant at the .05 level (two-tailed). All correlations at or above .35 are significant at the .001 level (two-tailed).

correlated with any of the probe variables. It is also interesting to note that RAN performance was not significantly correlated with phonological awareness, as measured here.

A series of six hierarchical regression analyses were conducted on the full sample to examine whether RAN performance accounted for unique variance in the six probe variables. In these analyses, presented in Table 6, RAN scores were entered into the regression after first controlling for the effects of digit span and phonological awareness in the first two steps. Digit span accounted for no significant variance for any of the six probe variables. Given the unexpected nature of this finding, the regression analyses were conducted again, separating forward digit span from backward digit span. Using raw scores from these measures, entered first into the regression, neither forward digit span nor backward digit span accounted for any significant variance in any of the six probe variables. As the regressions were conducted on the whole sample, which consisted of a large sample of poor readers, it seems likely that the restricted range of scores on this measure contributed to this nonsignificant finding.

Phonological awareness, however, accounted for significant amounts of variance with values ranging from 7% for the nonword probe to 18% for the letter probe in words. The unique contribution of RAN performance was significant for every variable, with amounts of variance accounted for ranging from 19 to 34%, with similar results found for both words and nonwords. This pattern of results suggests that naming speed makes a unique contribution to performance on the probe task.

Table 6. Hierarchical regression analyses predicting probe task performance.

Dependent variable	Predictors	Beta	R^2	R^2 change
Words				
Letter probe	Step 1: DS	−.07	.01	.01
	Step 2: PA	.37	.19	.18***
	Step 3: RAN	−.58	.51	.32***
Cluster probe	Step 1: DS	−.01	.03	.03
	Step 2: PA	.37	.20	.17***
	Step 3: RAN	−.51	.45	.25***
Word probe	Step 1: DS	−.22	.00	.00
	Step 2: PA	.34	.15	.15**
	Step 3: RAN	−.56	.45	.30***
Nonwords				
Letter probe	Step 1: DS	−.09	.01	.01
	Step 2: PA	.34	.16	.15**
	Step 3: RAN	−.58	.49	.33***
Cluster probe	Step 1: DS	−.08	.00	.00
	Step 2: PA	.32	.13	.13**
	Step 3: RAN	−.45	.32	.19***
Nonword probe	Step 1: DS	−.14	.00	.00
	Step 2: PA	.19	.07	.07*
	Step 3: RAN	−.60	.41	.34***

**P* .05; ***P* .01; ****P* .001.
Note. DS, Digit span; PA, phonological awareness; RAN, rapid automatized naming.

Discussion

The goal of the present study was to explore letter processing and the formation of memorial representation of letter strings for children with and without a naming speed deficit. Two factors were of specific interest: the amount of time available to encode a letter string and the role of orthographic information in establishing these memorial representations. One of several hypotheses outlined by Wolf and Bowers (1999) in their conceptualization of RAN performance was that performance on the RAN task was indicative of the ease of setting up representations in memory of common orthographic patterns, and that performance on the RAN task influenced reading ability through its effects on orthographic knowledge. This hypothesis received mixed support in the present study.

In support of this hypothesis, the slow RAN children were less accurate than the fast RAN children on the orthographic choice task.

While both poor reader groups had a deficit in orthographic knowledge compared with the average reader group, this discrepancy between poor and average readers may be a result of differences in amount of print exposure as suggested by Cunningham and Stanovich (1993). More importantly, the even greater deficit exhibited by the slow RAN children, despite their equivalent reading ability and phonological skills to the fast RAN group, is suggestive of a deficit in orthographic skill being related to slow naming speed.

Results from the probe task provide less clear evidence regarding the role of orthographic skill in the relation between RAN performance and reading. The slow RAN children, compared with fast RAN children and average readers, performed less accurately on the probe task across all conditions. This finding suggests that slow RAN children do have problems in the formation of memory representations for letter strings. What accounts for this difficulty is less clear. This difficulty cannot be attributed to the reduced ability of the slow RAN children to phonologically recode the stimuli, as the fast RAN group had similar levels of phonological knowledge and were more accurate at this task. Further, the regression analyses indicate that naming speed is related to performance on the probe task independently from phonological skill.

Deficits in orthographic skill also do not appear to account for this difficulty setting up representations. Despite the slow RAN children's poorer overall performance on the probe task, and their reduced levels of orthographic knowledge, they still performed better with words than with nonwords. In fact, each reading group benefited similarly from the increased orthographic structure of words over nonwords. This result is consistent with results reported by Bowers et al. (1999) in which children with and without naming speed deficits benefited equally from additional increases in orthographic structure when reporting letters from briefly presented words, pseudowords and nonwords. Bowers (2001) argued on the basis of her data that children with a naming speed deficit are able to make use of the orthographic structure found in words to aid in the formation of memory representations of letter strings. Although the present results are consistent with this interpretation, alternative explanations need to be considered. For example, this finding may be an artifact of the group selection criteria, in that in the present study there exists neither a "pure" double-deficit nor single phonological deficit group. This possibility seems unlikely given that Bowers (2001) found similar results using a more stringent definition of double-deficit and single deficit readers.

However, it is possible that other sources of information, such as semantic knowledge, are contributing to the better performance with words over nonwords. Although this possibility was not examined in the present study, Bowers (2001) reports a study that did address this issue using all nonwords on the quickspell task. The nonwords varied in the amount of orthographic structure they contained. With each increase in orthographic structure in the nonwords, there was a corresponding improvement in performance, for all children, including children with a naming speed deficit. Bowers argued that as nonwords contain no meaning, children must be using the orthographic structure found in the nonwords to aid performance. Although the use of semantic information in the present probe task needs to be examined in future studies, the results are consistent with the idea that children with a naming speed deficit are able to make use of the orthographic structure found in words to aid in the formation of memory representations of letter strings as argued by Bowers (2001).

Insufficient time to encode the letter string also does not appear to explain the difficulties slow RAN children have in forming memory representations. While longer study times did provide some benefit for both the fast RAN group and the average group on the probe task, increased processing time did not lead to improved representation of the letter string for the slow RAN children. Therefore, the difficulty exhibited by slow RAN children is not simply a problem of insufficient time to process the letter string. Rather, these results suggest that the difficulties in processing letters in a string need to be interpreted within a broader framework of naming speed performance, such as that suggested by Wolf and Bowers (1999). Due to the multi-componential nature of naming speed performance, naming speed deficits can result not only from a disruption in the timing requirements within a single component, but also from a disruption in the integration or coordination of multiple subprocesses. Meyler and Breznitz (2005) report results from an ERP study suggesting that an asynchrony between phonological processes and orthographic processes can exist within readers with dyslexia and argued that a failure to form accurate and complete representations of words results from an asynchrony in the speed of processing of various component processes, which then interferes with the ability to coordinate the information that arises from these processes. An inability to amalgamate all information together would impair the ability to establish memory representations, resulting in less accurate performance on the probe task, and more generally, impaired reading. Thus, time alone will not fix the problem. Rather, increased fluency or automaticity in the various component skills related to naming speed and reading may be needed to enable the integration of various sources of information.

Finally, one last curious finding deserves some discussion. Contrary to expectations, slow RAN children did not have greater difficulties with large, compared with small sized letter probes. All children performed best with a whole word/nonword probe. The slow RAN group in fact showed a particular disadvantage with the single letter probes compared with the fast RAN group and the average readers. That the slow RAN children are better with whole words than with letter clusters or single letters appears to be inconsistent with results reported by Levy et al. (1999) in which slow RAN children had more difficulty learning new words through whole word repetition than when using smaller onset-rime units to learn new words. However, the smaller units probed in the present study did not always correspond to units children might use to decode a word as in the Levy and colleagues study, which may have made the present task more difficult. When examining the results from the real word stimuli, a number of different interpretations are possible. The use of various sources of information, such as orthographic information, or semantic information, may account for the better performance with whole word probes over cluster or letter probes. In addition, it may be that the words probed correctly were words the children were already familiar with as sight words. While these possibilities should be investigated in future studies, the fact that the same pattern of results was found when nonwords were used suggests that these factors cannot fully explain the results.

Despite the deficit in speed of letter processing that characterizes children with naming speed deficits, performance with larger units was better than performance with smaller units. This finding may suggest that children with slow naming speed are able to process the whole word/nonword probe as a single unit, much like children without a naming speed deficit. In using a similar task with beginning readers in Kindergarten and Grade 1, Berninger (1987) reported that whole word coding developed relatively earlier than letter coding, which developed relatively earlier than letter cluster coding. Interpreting the present results within this framework, the data suggest that the slow RAN children are at an earlier level of representational development than the fast RAN children (and the average readers) despite their similar reading ability. This interpretation, however, does not provide an explanation as to the nature of the representation. This is a curious finding and deserves further investigation.

Together, the results of the present study demonstrate that children with naming speed deficits have problems forming memory representations of letter strings. This problem cannot be attributed to deficits in orthographic knowledge or to insufficient processing time. Rather, these problems in forming memory representations may be related to timing disruptions in the various component skills related to reading. In addition, the findings also suggest that these children do have deficits in orthographic knowledge. Despite this deficit, it appears that children with naming speed deficits may still be able to use the orthographic structure present in a word to aid in processing that word, as suggested by Bowers (2001). The implications of these findings for intervention programs will be briefly discussed.

Implications for intervention

A growing body of research, including the present results, supports the independent contribution of phonological skills and RAN performance to reading ability. As a result, newer forms of interventions that target the specific deficits associated with slow naming speed are required. However, developing these programs is a difficult undertaking, given our limited understanding of the multiple underlying causes of this deficit. Despite this difficulty, the present study offers a few suggestions for intervention programs that target the specific weaknesses associated with slow naming speed.

The present results suggest that although children with slow naming speed do have deficits in orthographic knowledge, they are able to use orthographic redundancy in words to aid in processing words. Thus, direct instruction in orthographic knowledge may be one route through which we can increase reading skills. Studies that have approached this problem through repeated practice reading words with shared orthographic patterns have met with some success (e.g., Levy, 2001; Thaler, Ebner, & Wimmer, 2004). Programs that increase children's knowledge of orthographic patterns, or increase their understanding that orthographic consistencies exist within words, may help to compensate for the problem children with slow naming speed have in processing letters in a string.

Alternatively, a more comprehensive approach may be required to address the multiple potential sources of disruption. If naming speed deficits, and reading difficulties, are indicative of a more general processing speed problem, such as asynchrony in the amalgamation of information from various subprocesses as suggested by Wolf and Bowers (1999), then rather than providing more time for children to set up the representations, we may need to increase the fluency of all the major component skills involved. Such an approach to remediation has been described by Wolf, Miller, and Donnelly (2000). One of the major objectives of this program is to increase automaticity in the underlying phonological, orthographic, semantic and lexical retrieval skills that are related to reading. Rather than focusing on one specific deficit, this more comprehensive approach to reading intervention is designed to address the multiple sources of reading impairment.

In conclusion, the present study contributes to our understanding of naming speed deficits in a number of ways. The present results add to a growing body of evidence suggesting the independence of phonological deficits from naming speed deficits. In addition, the present study suggests that although children with slow naming speed may have deficits in orthographic knowledge compared to other children with reading disabilities, we need to look beyond a simple explanation of orthographic skills as a mediator of the relation between naming speed performance and reading ability.

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References

Adams, M. J. (1990). *Beginning to read: Thinking and learning about print*. Cambridge, MA: The MIT Press.

Berninger, V. W. (1987). Global, component, and serial processing of printed words in beginning of reading. *Journal of Experimental Child Psychology*, *43*, 387–418.

Blachman, B. A. (1984). Relationship of rapid naming ability and language analysis skills to kindergarten and first-grade reading achievement. *Journal of Educational Psychology*, *76*, 610–622.

Bowers, P. G. (1995, April). Re-examining selected reading research from the viewpoint of the "double deficit hypothesis". Paper presented at the Annual Meeting of the Society for Research in Child Development, Indianapolis, IN.

Bowers, P. G. (2001). Exploration of the basis for rapid naming's relationship to reading. In M. Wolf (Ed.), *Dyslexia, fluency, and the brain* (pp. 41–63). Timonium, Maryland: York Press.

Bowers, P. G., & Kennedy, A. (1993). Effects of naming speed differences on fluency of reading after practice. *Annals of the New York Academy of Sciences*, *682*, 318–320.

Bowers, P. G., & Swanson, L. B. (1991). Naming speed deficits in reading disability: Multiple measures of a single process. *Journal of Experimental Psychology*, *51*, 195–219.

Bowers, P. G., & Wolf, M. (1993). Theoretical links among naming speed, precise timing mechanisms and orthographic skill in dyslexia. *Reading and Writing*, *5*, 69–85.

Bowers, P. G., Sunseth, K., & Golden, J. (1999). The route between rapid naming and reading progress. *Scientific Studies in Reading*, *3*, 31–53.

Cornwall, A. (1992). The relationship of phonological awareness, rapid naming, and verbal memory to severe reading and spelling disability. *Journal of Learning Disabilities*, *25*, 532–538.

Cunningham, A. E., & Stanovich, K. E. (1993). Children's literacy environment and early word recognition subskills. *Reading and Writing: An Interdisciplinary Journal*, *5*, 193–204.

Denckla, M. B., & Rudel, R. G. (1976). Rapid "automatized" naming (RAN): Dyslexia differentiated from other learning disabilities. *Neuropsychologica*, *14*, 471–479.

Educator's Word Frequency Guide (1996). Touchstone Applied Science Associates [Computer Software].

Ehri, L. C. (1992). Reconceptualizing the development of sight word reading and its relationship to recoding. In P. G. Gough, L. C. Ehri & R. Treiman (Eds.), *Reading acquisition* (pp. 107–143). Hillsdale, NJ: Lawrence Erlbaum Associates.

Korhonen, T. T. (1995). The persistence of rapid naming problems in children with reading disabilities: A nine-year follow-up. *Journal of Learning Disabilities*, *28*, 232–239.

Levy, B. A. (2001). Moving the bottom: Improving reading fluency. In M. Wolf (Ed.), *Dyslexia, fluency, and the brain* (pp. 357–379). Timonium, Maryland: York Press.

Levy, B. A., Bourassa, D. C., & Horn, C. (1999). Fast and slow namers: Benefits of segmentation and whole word training. *Journal of Experimental Child Psychology*, *73*, 115–138.

Lovett, M. W., Steinbach, K. A., & Frijters, J. (2000). Remediating the core deficits of developmental reading disability: A double-deficit perspective. *Journal of Learning Disabilities*, *33*, 334–358.

Manis, F. R., Doi, L. M., & Bhadha, B. (2000). Naming speed, phonological awareness, and orthographic knowledge in second graders. *Journal of Learning Disabilities*, *33*, 325–333.

Manis, F. R., Seidenberg, M. S., & Doi, L. M. (1999). See Dick RAN: Rapid naming and the longitudinal prediction of reading subskills in first and second graders. *Scientific Studies of Reading*, *3*, 129–157.

Mayzner, M., & Tresselt, M. E. (1965). Tables of single-letter and bigram frequency counts for various word-length and letter position combinations. *Psychonomic Monograph Supplements*, *1*, 13–32.

Meyer, M. S., Wood, F. B., Hart, L. A., & Felton, R. H. (1998). Selective predictive value of rapid automatized naming in poor readers. *Journal of Learning Disabilities*, *31*, 106–117.

Meyler, A., & Breznitz, Z. (2005). Impaired phonological and orthographic word representations among adult dyslexic readers: Evidence from event-related potentials. *The Journal of Genetic Psychology*, *166*, 215–238.

Olson, R., Forsberg, H., Wise, B., & Rack, J. (1994). Measurement of word recognition, orthographic, and phonological skills. In G. R. Lyons (Ed.), *Frames of reference for the assessment of learning disabilities: New views on measurement issues* (pp. 243–277). Baltimore, MD: Paul H Brookes Publishing Company.

Perfetti, C. A. (1992). The representation problem in reading acquisition. In P. B. Gough, L. C. Ehri & R. Treiman (Eds.), *Reading acquisition* (pp. 145–174). Hillsdale, NJ: Lawrence Erlbaum Associates.

Rosner, J. (1979). *Test of auditory analysis skills*. Novato, CA: Academic Therapy Publications.

Thaler, V., Ebner, E. M., & Wimmer, H. (2004). Training reading fluency in dysfluent readers with high reading accuracy: Word specific effects but low transfer to untrained words. *Annals of Dyslexia*, *54*, 89–113.

Torgesen, J. K., & Wagner, R. K. (1998). Alternative diagnostic approaches for specific developmental reading disabilities. *Learning Disabilities Research and Practice*, *13*, 220–232.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1994). Longitudinal studies of phonological processing and reading. *Journal of Learning Disabilities*, *27*, 276–286.

Torgesen, J. K., Wagner, R. K., Rashotte, C. A., Burgess, S., & Hecht, S. (1997). Contributions of phonological awareness and rapid automatic naming ability to the growth of word reading skills in second to fifth grade children. *Scientific Studies of Reading*, *1*, 161–185.

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology*, *91*, 415–438.

Wolf, M., Bally, H., & Morris, R. (1986). Automaticity, retrieval processes and reading: A longitudinal study in average and impaired readers. *Child Development*, *57*, 988–1005.

Wolf, M., Bowers, P. G., & Biddle, K. (2000). Naming-speed processes, timing, and reading: A conceptual review. *Journal of Learning Disabilities*, *33*, 387–407.

Wolf, M., Miller, L., & Donnelly, K. (2000). Retrieval, automaticity, vocabulary elaboration orthography (RAVE-O): A comprehensive, fluency-based reading intervention program. *Journal of Learning Disabilities*, *33*, 375–386.

Wolf, M., O'Rourke, A. G., Gidney, C., Lovett, M., Cirino, P., & Morris, R. (2002). The second deficit: An investigation of the independence of phonological and naming-speed deficits in developmental dyslexia. *Reading and Writing: An Interdisciplinary Journal*, *15*, 43–72.

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