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Orthographic processing efficiency in developmental dyslexia: an investigation of age and treatment factors at the sublexical level

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Abstract

Reading fluency beyond decoding is a limitation to many children with developmental reading disorders. In the interest of remediating dysfluency, contributing factors need to be explored and understood in a developmental framework. The focus of this study is orthographic processing in developmental dyslexia, and how it may contribute to reading fluency. We investigated orthographic processing speed and accuracy by children identified with dyslexia that were enrolled in an intensive, fluency-based intervention using a timed visual search task as a tool to measure orthographic recognition. Results indicate both age and treatment effects, and delineate a link between rapid letter naming and efficient orthographic recognition. Orthographic efficiency was related to reading speed for passages, but not spelling performance. The role of orthographic learning in reading fluency and remediation is discussed.

Keywords

Developmental dyslexia; Fluency; Intervention; Orthographic processing

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There is a clear contrast between dysfluent beginning reading—wherein words are sounded out slowly and deliberately, with frequent errors and corrections—and fluent oral reading—which is smooth and expressive, with pauses coordinated to sentence and phrase junctions and stress patterns cued to important details, and with animation similar to conversation or story-telling. While the developmental transition to fluent reading may be easy to

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observe, it has proven more difficult to explain in cognitive terms, with regard to what mental processes mediate the shift, or what factors are involved in the persistent dysfluency of children with developmental reading disorders. Fluent reading is regarded to involve automatic or effortless processing at multiple levels of text, word, and subword units (LaBerge & Samuels, 1974). Automatic word recognition is widely held to be a primary contributor to fluent reading (Barker, Torgesen & Wagner, 1992; Levy, Abello & Lysynchuk, 1997; Rayner, Foorman, Perfetti, Pesetsky & Seidenberg, 2001; Jenkins, Fuchs, van den Broek, Espin & Deno, 2003; Mathes, Denton, Fletcher, Anthony, Francis & Schatschneider, 2005), and many models of word recognition incorporate multiple components dedicated to processing the print, sound and meaning conveyed by words on the page (e.g., Perfetti, 1992; Berninger & Abbott, 1994; Seidenberg & McClelland, 1989; Plaut, 1997). Of these multiple orthographic, phonological, and semantic components (respectively), phonological processing has been the most studied and well-established factor in reading development and disorders. The impact of the other processes on typical and atypical reading development is less clear. The focus of the present study is on the component of orthographic processing by children with developmental dyslexia and the effects of treatment at the sublexical level.

Orthographic structure of a written language includes the probability of where certain letters appear within words (spatial redundancy), which letter sequences are permissible (sequential redundancy), and information about the pronounceability of words (phonemic-graphemic constraints) (Corcos & Willows, 1993). Coding of orthographic information is defined as the "ability to represent the unique array of letters that defines a printed word, as well as general attributes of the writing system such as sequential dependencies, structural redundancies, letter position frequencies, and so forth" (Vellutino, Scanlon & Tanzman, 1994, p. 314). The development of orthographic coding thus is based on the formation of visual long-term memory representations of letters, letter patterns, and sequences of letters that serve to map spatially the temporal sequence of phonemes within words (Ehri, 1992; 2005). We would expand this view to suggest that fluency depends on the evolving connections in the child among orthographic, phonological, morpho-syntactic, and semantic processes. Within this view a child learns to recognize words like "bat", "batter", and "batting" both in terms of their orthographically represented forms (bat, er, ing) as well as their connections to morphological, grammatic, and semantic knowledge. Thus, orthographic knowledge is intimately connected to the other critical components necessary for fluent word recognition and comprehension. It is postulated that fast letter recognition and attention to letter sequences allows for the buildup of orthographic patterns that are then associated with sound (Adams, 1981; Wolf, Bowers & Biddle, 2000). Thus, readers depend on orthography for phonology as well as phonology for recognizing orthographic clusters (Breznitz, 2006, p. 43). Presently, learning to process orthographic information is held to play a critical role in the development of automatic word recognition that supports fluency by setting up and cueing the other systems of phonology, morphology, syntax, and semantics.

In recent years, reading instruction and research has targeted the teaching of fluency as a means to improve comprehension. Good evidence suggests that fluent reading aids comprehension (Kuhn & Stahl, 2003; Therrien, 2004), so the enterprise of training children to become fluent readers is a worthwhile one. To be sure, the variety of decoding training methods exceeds the extent of fluency training methods available. Namely, the prevalent fluency training method is repeated reading, whereby students reread passages of text to increase reading speed and prosody. The relative paucity of available methods reflects in part the limited extent of theoretical models of fluency development.

A developmental conceptualization reframes reading fluency from an educational outcome to a set of integrated subskills to be targeted through instruction. Within this view, explicit training of accuracy precedes the training of speed for each component process to achieve the ultimate goal of fluent reading (see for example, Wolf, Miller & Donnelly, 2000). As argued by Wolf and Katzir-Cohen (2001) and Kame'enui, Simmons, Good and Harn (2001), the definition of fluency requires a conceptual expansion: from the more conventional emphases on fast and effortless, prosodic reading of text (Meyer & Felton, 1999), to a set of developmental processes that change across time. From this perspective, reading fluency is conceptualized as a developmental progression from the word and subword levels to passage level, with multiple component skills contributing to each level, including phonological, orthographic, semantic, morphological, and syntactic processes that must become integrated in proficient reading.

How does orthographic knowledge develop?

Orthographic development is largely attributed to reading experience in which repeated exposures to print provide the foundation for this process (Stanovich & West, 1989; Rayner et al., 2001). The process itself, though, is not clearly understood. Repeated exposure to print may invoke implicit learning of statistically based patterns (from spatial and sequential redundancy of letters processed contiguously in time), more general spelling rules (legal versus illegal forms), and/or patterns unitized to phonemes (based on phoneme-grapheme associations). However, not all readers benefit from such implicit learning with practice: many studies report that poor readers require more exposures to learn novel words than skilled readers. Given the same number of exposures to novel words with simplified spellings, younger novice and older disabled readers showed less sensitivity to altered spellings of the words, when asked to read them 3 days later (Ehri & Saltmarsh, 1995). On average, poor readers needed to be shown a novel word 9.2 times to recognize it, versus the 6.8 exposures that good readers needed. Years earlier, Reitsma (1983) showed that poor readers needed more practice with words in order to increase their speed of processing specific letter strings within the words. Further, readers who are slow on rapid automatized naming (RAN) tests, a reliable predictor of later reading fluency problems, needed more repetitions to reliably read letter patterns than poor readers who are fast on RAN tasks (Levy, Bourassa & Horn, 1999). Also, Share (2004) found that while a single exposure to a novel pseudoword was sufficient for third-grade children to recall its spelling, this was not the case with novice readers. For first-grade children reading Hebrew (a relatively transparent language) four exposures were not sufficient to learn the orthographies of pseudowords.

Cumulative research in this area indicates that mere exposure to words affords different experiences for different levels of readers. For example, preliterate children first learn to differentiate letter strings from alphanumeric strings, then consonant strings from consonants plus vowels, then letter strings containing legal versus illegal consonant clusters

(Leslie & Shannon, 1981). This is consistent with Geva and Willows (1994) observations that children can distinguish English words from those of increasingly more similar languages as they grow. That is, at age 3 children can understand that letters are not pictures, and by first grade their discrimination ability becomes increasingly sophisticated—distinguishing words with different scripts (English vs. Japanese symbols, then English vs. Russian letters), then words with the same alphabet but different orthographic structure (English vs. Spanish words). Thus, orthographic development begins with small units, like letters and letter features, prior to larger segments of letter groupings. Orthographic development of forms stands, therefore, in contrast to the development of phonology, which proceeds from larger units, such as rimes or syllables, to smaller units of phonemes. Ziegler and Goswami (2005) present this inverse progression of orthographic and phonological development in their *psycholinguistic grain size* theory (see also Berninger, 1987). Accordingly, "a major cause of the early difficulty of reading acquisition is that phonology and orthography initially favor different grain sizes…. [due to] (a) functional pressure toward smaller units that are orthographically less complex (b) linguistic pressure toward bigger units that are phonologically more accessible, and (c) statistical pressure toward units that are more consistent than others" (Ziegler & Goswami, 2005, pp. 19–20).

Spelling and reading stage models capture the above-noted progression from small-to-large, and large-to-small unit sizes. Based on observed misspelling patterns across age, models of spelling proceed from small units at the letter-name stage (e.g., spelling bk for beak), to larger units at the phonetic (e.g., syllable juncture errors at the within-word pattern stage), and morphemic stages (e.g., failure to maintain Greco-Latin roots when adding affixes) (Henderson, 1992; Bear, Invernizzi, Templeton & Johnston, 2004). Sharp, Sinatra and Reynolds' (2008) microgenetic analysis supports this general trend of predominantly using strategies focused at smaller unit sizes early in spelling development (e.g., sounding out by matching each sound with a letter or digraph), and at larger units later in development (e.g., rule use strategies or whole-word retrieval from memory). They also found that spelling strategy use was reciprocally related to the development of orthographic knowledge. Models of reading, on the other hand, describe a large-to-small grainsize progression from whole-word processing (logographic stage) to partial grapheme cueing of words (partial-alphabetic stage) to letter-by-letter decoding (orthographic stage) (Mason, 1980; Chall, 1983; Frith, 1985).

While reading and spelling tasks are primarily linked with phonemic and orthographic processing, respectively, it is important to note their interaction throughout reading development. Reading and learning orthographic patterns may actually enhance phoneme processing (Perfetti, Beck, Bell & Hughes, 1987). That is, learning to read itself is related to children's improved metalinguistic awareness of word and subword sounds within speech (Ehri, 1979, 1992), such that "children [may] begin learning about phonemes via letters … [and] grapheme knowledge in turn promotes the development and refinement of phonemic awareness" (Ziegler & Goswami, 2005, p. 19).

Interestingly, tasks that tap the ability to recognize orthographic patterns show a different developmental progression than the *psycholinguistic grain size* theory. Berninger (1987; Berninger, Yates & Lester, 1991) and Conrad and Levy (2007), using a probe task with children between grades 1 to 3, report the pattern whereby whole words are processed early on, then single letters, and lastly letter clusters. In their tasks, strings of letters (either whole words or nonwords) are briefly presented, then the child identifies whether or not a probe matches the whole string or a single one of the letters or a letter pair that was shown within the string. Thus, letter cluster coding is achieved later than single letter coding and is found to be the more difficult part of this task. Eleanor Gibson adroitly noted long ago that reading depends on decoding not at the letter-by-letter level, nor at the whole word level, but at the level of spelling patterns (Gibson, Pick, Osser & Hammond, 1962), a finding amply supported now years later with research in cognitive neurosciences by Posner and his colleagues (Compton, Grossenbacher, Posner & Tucker, 1991; McCandliss, Posner & Givon, 1997; Posner & McCandliss, 2000) and others (Maurer et al., 2006).

Invernizzi (1992) found children's level of orthographic knowledge determined which letters became stored in memory using the same probe task described above. Assigning K-5th grade children to spelling stages based on their patterns of invented spellings, she showed that letter-name (LN) spellers did not report seeing silent e's, and LN and within-word pattern (WP) spellers did not detect the double consonants at syllable junctures that syllable juncture (SJ) spellers did. Also, WP spellers were more accurate at recognizing letter patterns within rimes than those spanning the onset-rime boundary, while LN spellers did not differ. In a similar vein, Perfetti and Hart (2002) suggest that spelling knowledge contributes differently to word reading for groups of more skilled and less-skilled college readers. They pose the *lexical quality hypothesis*, where more integrated knowledge about words, including their spellings and meanings in addition to pronunciation, supports skilled reading. For instance, they showed a difference in the factor structure for high- and low-skilled readers on both accuracy and speed of lexical processing measures, with a three-factor solution for less-skilled readers versus a two-factor solution for skilled readers. Specifically, with speed measures the skilled readers exhibited orthography as a "linking variable" that loaded on more than two factors, whereas for less-skilled readers it was semantic knowledge that served as a link between factors. Thus, for less-skilled readers "orthographic knowledge may not be integrated with other lexical knowledge as powerfully as it is for skilled readers" (Perfetti & Hart, 2002, p. 209).

How is orthographic knowledge related to reading disorders?

Orthographic knowledge contributes to both reading and spelling performance, and there are widespread reports of spelling difficulties for individuals with dyslexia, across both English and more regular languages. Children defined as reading disabled have lower spelling achievement (Ehri, 1989; Treiman, 1997), and adults with histories of dyslexia have persistent problems with spelling (Miles, 1983; Scarborough, 1984; Bruck, 1993). Spelling is generally more difficult than reading, as it involves *recalling* a word's orthographic structure, as opposed to *recognizing* that structure in reading, and it relies on less consistent phoneme-to-grapheme relations that must be resolved through a weaker linkage between semantic-graphemic information, as opposed to semantic-phonemic information for reading (Bosman & Van Orden, 1997). Depending on whether spelling is assessed with production tasks, like dictation, composition or oral spelling, or with more receptive tasks, like lexical choice, the overlap with specific reading processes will vary. On tasks requiring encoding of written letter clusters, children with developmental reading disorders are known to be less accurate and slower (Corcos & Willows, 1993). Furthermore, children who are slow on serial naming tasks (RAN) are also inaccurate and slow on orthographic encoding tasks (Manis, Doi & Badha, 2000; Sunseth & Bowers, 2002).

Several models of orthographic learning pose that a timing element in serial letter processing within words is critical. For instance, according to Adams' (1981) *orthographic redundancy hypothesis* letter pattern representations are built up via the temporal overlap of processing individual letters in serial sequential positions. Similarly, Whitney's (2001) SERIOL computational model includes serial processing of letters from left to right (for English), such that, with degrading activation over time, activation strength codes for the sequential spacing of letters in the word - a process leading to the development of bigram representations. Following these models, Bowers and Wolf (1993) and Wolf, Bowers & Biddle (2000) proposed that some forms of dyslexia involving slow letter naming lead to a lack of temporal overlap in intraword letter processing, which precludes the formation of sublexical orthographic representations. Thus, orthographic knowledge is underdeveloped for these cases with a naming-speed deficit.

In sum, orthographic knowledge is held to be a key component to fluent reading that cues other integrated components (including, phonology, morphology, etc.). The evidence noted above shows that orthographic knowledge and processing differ for individuals with reading disability. As such, from a developmental perspective on fluency, orthographic processing is a candidate subskill to target through integrated instruction. Berninger and Wolf (2009) claim "children benefit from instruction in how to coordinate units of phonology, orthography and morphology information in pronouncing written words, and thinking about their meaning" (p. 68). The question addressed here is whether integrated intervention affects orthographic processing at the sublexical level, and whether, in turn, sublexical effects are related to reading proficiency effects at the word and text levels.

In the present study, we investigated orthographic processing efficiency for children with developmental reading disorders who took part in intensive intervention aimed at improving fluency. We asked how explicit instruction directed at subword, word and text levels would impact the efficiency (i.e., accuracy and speed) of visually identifying specifically trained letter patterns. Furthermore, we explored whether changes in processing efficiency at the sublexical level related to changes at the word and text level. We specifically addressed these questions:

1. Are there training-related changes in orthographic recognition efficiency across age groups?
2. Are individual differences in sublexical treatment effects related to gains in reading fluency and spelling skills?

In order to study orthographic processing at the level of the letter cluster, we chose a visual search task that targeted bigrams within letter arrays. We focused on this level for several reasons. Firstly, coding letter clusters appears both most critical for reading fluency and challenging to children with reading disability. Secondly, in contrast to most of the tasks used to assess orthographic processing, the visual search task we employ here does not entail lexical access, but rather operates at the subword level. As Vellutino et al. (1994) argued, orthographic tasks typically evaluate word identification or spelling ability, rather than the basic cognitive ability of orthographic coding common to both. We chose a task that involved neither word identification nor word spelling. Finally, the process of searching for letter pairs across rows of printed letters is similar in form to both serial reading with lines of text, and also to serial naming tasks which are one of the best predictors of reading, particularly reading fluency.

Methods

Participants

Forty-five children from Boston area public schools participated, all of whom were enrolled in a large intervention study of reading disabilities (Morris, Lovett & Wolf, NICHD #HD30970). The children ranged in age from 6–6 to 8–6, and were in grades 1 to 3 (seven first graders, 22 second graders, and 16 third graders) (none had repeated a grade). Each child met the following criterion of reading disability—they had standardized reading achievement scores that either: (1) were below 85 (i.e., one standard deviation below average); or (2) were one standard deviation below their ability-predicted reading achievement (i.e., a significant discrepancy based on achievement predicted from the Kaufmann Brief Intelligence test full-scale IQ (Kaufman & Kaufman, 1990)). Reading achievement was determined with the Woodcock Reading Mastery Test (Woodcock, 1998) word identification, word attack and passage comprehension tests, and the Wide Range Achievement Test - reading (Jastak & Wilkinson, 1984). All participants were primary English speakers with no history of primary sensory or neurologic disorders.

Reading intervention

The reading intervention consisted of combinations of the following programs given in 1-h daily sessions (as described in Morris, Lovett, Wolf, Sevcik, Steinbach, Frijters et al., 2010). Participants received the phonological component of training (a) coupled with either WIST (b), Retrieval, Automaticity,Vocabulary, Engagement, and Orthography (RAVE-O; c), or both (b+c) components:

a. Phonological Analysis and Blending: Based in part on Reading Mastery, Fast Cycle I/II (Engelmann & Bruner, 1988; Engelmann, Johnson, Carnine, Meyer, Becher & Eisele, 1988), this is a direct instruction program with a specified sequence of oral and print-based training on letter-sound correspondences, sound segmentation and blending, word attack and identification, and practice with rhyming and word analysis.

b. Word Identification Strategy (Lovett, Lacerenza & Borden, 2000): This is a metacognitive integrated phonological decoding strategy program that trains and provides practice with the use and monitoring of specific strategies to apply what is known about key words in order to decode unknown words.

c. RAVE-O (Wolf et al., 2000): This is an integrated fluency program which systematically and explicitly addresses the quality of representation and rapid rate of retrieval in phonological, orthographic, semantic, syntactic, and morphological component processes, and their interconnections, at sublexical, lexical, and connected text levels.

Measures

Orthographic tests

Orthographic visual search test: The experimental measure was a set of 5×20 letter arrays presented on a Mac iBook where the task was to search for a target letter pair. Letters were rendered in Courier New Bold 24-point font with double spacing between letters and single spacing between rows. The search target appeared at the top of the screen and was rendered in red 36-point Lucida Handwriting italicized font (to prevent simple visual matching to targets in the array). Target letter pairs were presented 9 times in the array of 100 letters arranged in pseudorandom order (i.e., without double letters or formation of words). There were between 1 and 3 targets per line, and at least two-letter transpositions were included in each array. Each array contained five nontarget letters that were either visually confusable with one of two target letters or not confusable (based on letter confusion matrices, Geyer, 1977).

The target letter pairs were either explicitly trained in the reading intervention, were untrained, or were illegal pairs. Trained and Untrained pairs had comparable positional bigram frequency (Massaro, Taylor, Venezky, Jastrzembski, & Lucas, 1980). Further, the target letter pairs were presented within letter arrays that had either visually confusable nontarget letters (referred to as confusable arrays), or nontarget letters that were not visually confusable (referred to as nonconfusable arrays). Half of the students were tested with the first version of the orthographic visual search test (OVST), wherein trained targets (BR, SH, CK, and AD), untrained targets (GN and PR), and illegal targets (CB) were each presented within two arrays: one with visually confusable and one with nonconfusable letters. The other half of the students were tested with a second version of the OVST, which consisted of confusable letter arrays for trained targets (BR, SH, CK, and PL), untrained targets (GN, KN, WR, and RY), and illegal targets (CB, FC, RJ, and KH), and nonconfusable arrays for a trained target (SH), an untrained target (GN), and an illegal target (CB). To compare students across the same arrays, data was taken from the searches for BR, SH, CK, GN, CB, and nonconfusable arrays for SH, GN, and CB targets (see Appendix for a list of the visual search targets and nontarget letters that were used in the analyses).

Pseudohomophone choice test (Olson, Kliegl, Davidson & Foltz, 1985): Twenty-five pairs of printed stimuli are presented with one pair on each row. Each pair consists of correctly and incorrectly spelled words that sound alike when decoded. The task is to circle the correctly spelled word within each pair. Number correct is scored.

Letter string choice test (Stanovich & Siegel, 1994): Twenty pairs of printed stimuli are presented with one pair on each row. Each pair consists of two nonwords, one of which is orthographically plausible. The task is to circle the nonword that looks more like a word. Number correct is scored.

Test of silent word reading fluency (TOSWRF, Mather, Hammill, Allen & Roberts, 2004): This test consists of a page of unspaced printed words presented in rows. More frequent words appear first, and word frequency decreases over the rows. The task is to identify the words in each row by drawing lines separating the words. Practice examples are first given, then the test list is timed for 3 min. The number of correctly identified words in 3 min is scored and standard scores are calculated.

Rapid naming

Rapid automatized naming (RAN, Denckla & Rudel, 1974, 1976; Norm-referenced standard scores are available in RAN/rapid alternating stimulus (RAS), Wolf & Denckla, 2004): The letter naming RAN and RAS versions were given. Each test consists of five rows of ten letters, or alternating letters and numbers presented on a card. The task is to say the name of the letters/numbers as quickly as possible. A practice test is first given to ensure the examinee knows the identity of the all the letters on the test. Total naming time and errors are recorded from start to finish. Norm-referenced standard scores are calculated.

Processing speed

Coding and sound symbol subtests (WISC-III, Wechsler, 1991): The coding test consists of a series of geometric symbols that are matched to digits (1–9). The task is to fill in boxes beneath a random series of the digits with the corresponding symbol. The symbol-digit key is in view during the test. The number of correct responses within 2 min is scored, and a norm-referenced standard score is calculated. The symbol search subtest consists of matching a given symbol to an identical symbol within a row of similar symbols by circling it. The number of correct responses within 2 min is scored, and a norm-referenced standard score is calculated.

Reading measures

Test of word reading efficiency (TOWRE, Torgesen, Wagner & Rashotte, 1999): The sight word reading subtest was given. A list of words is presented in columns, starting from more frequent to less frequent words. The task is to correctly read aloud as many words as possible within 45 s. A practice test is first given to confirm that the examinee understands the directions. Number correct per time (45 s) is scored. Norm-referenced standard scores are calculated.

Gray oral reading test (GORT-4, Wiederholt & Bryant, 2001): Tests oral reading fluency (rate and accuracy) for graded passages of text, and comprehension from multiple choice questions read by the examiner after each passage. Standard scores are determined using basal and ceiling testing procedures.

Woodcock-Johnson-III reading fluency (WJIII; Woodcock, McGrew & Mather, 2001): Short printed sentences are read for comprehension, and true–false judgements are made after reading each one. Number answered correctly within 3 min is scored. Standard scores are calculated.

Spelling measures

Peabody individual achievement test-revised/NUSpelling (PIAT-R, Markwardt, 1998): This test consists of a multiple four-choice selection of the correctly spelled version of an auditorally presented word. Standard scores are determined using basal and ceiling testing procedures.

WJIII spelling (Woodcock et al., 2001): Words are spelled from dictation. Standard scores are determined using basal and ceiling testing procedures.

Procedure

Testing with the OVST and other measures was given individually over several sessions and at different points in time during the reading intervention program. All participants were tested on the OVST at two time points—the intial time point occurred earlier in the program (after 35 or 50 sessions)—time 1; and the second time point occurred at the end of the program (after 100 sessions)—time 2. Standard administration procedures were followed for the other orthographic, phonological, naming speed, processing speed, memory and achievement tests (reading and spelling).

For the OVST, search arrays were presented in the same random order. Prior to the test trials, several practice arrays were given, where the participant had to locate and click on an "X" or an "OX" stimulus within an array of X's and O's using a mouse controlled cursor. Feedback was given for correct responses. A response was correct if it was positioned within a designated square area between the center of the first letter of the bigram (O) to the center of the second letter of the bigram (X). The practice sessions served to increase familiarity with the task instructions and to give practice with using the mouse to select targets on the screen. For the test arrays, the child was instructed to click on as many instances of the given target as quickly as he/she could find them, then to press a "done" button when they completed the search. An auditory tone provided feedback for each correct response. Correct responses were those positioned in the designated square area as described above. Response time was recorded as the time between clicking on the target and the preceeding mouseclick. For each array, median response times were calculated. The first target within each array was considered as practice and was not included in the median time. Rest breaks were provided as needed during testing.

The pseudohomophone and letter string choice tests and the Test of Silent Word Reading Efficiency were administered in the same session as the visual search test. The other measures were given as part of a larger psychoeducational assessment battery at the same session or on a different day.

Results

Question 1. Are there training-related changes to orthographic recognition efficiency?

To address this first question, comparisons were made of performance on the Orthographic Visual Search Test (OVST) across groups of grade level (1,2,3) for search targets varying in familiarity (they were trained, untrained or illegal bigrams) and in type of search array (targets were presented within visually confusable or nonconfusable letters), over time in the program (time 1 and time 2). Separate multivariate analyses of covariance (MANCOVAs) were run on OVST speed and accuracy measures. The number of sessions between time points was different for some of the children, so number of sessions served as a covariate in the analyses. Forty-one participants had complete data on the OVST across all conditions and their data were entered into the analyses.

Latency was computed as the median time per correct response on each array, and accuracy as the number of correct responses on each array. The latency data on all participants showed moderate skewness on some of the search arrays, so latencies were transformed with a log function before being entered into the analyses.

The first MANCOVA for OVST log latency was performed with a between-group factor of grade (1, 2, and 3) and repeated measures factors of familiarity (trained, untrained and illegal targets) and confusability (bigrams presented in arrays with visually confusable or nonconfusable letters) across two time points (time 1, time 2). The number of sessions between time points was entered as a covariate. Group means by the repeated measures factors are presented in Table 1. For this latency analysis, there were significant effects of time (Wilks' Lambda p=0.05), grade (p<0.01), and time by grade (p<0.01). Subsequent Student–Newman–Keuls range tests were run comparing groups within each time point separately: first graders were significantly slower than the other grades at both time points. Although the first grade group was slowest overall, they also showed the largest improvement in search speed over time (see Fig. 1). However, simple effects comparisons with Bonferroni correction showed that each grade's performance changed over time, with faster search by time 2 (p's≤0.01). There were also significant effects of confusability: a main effect (p<0.01), and interaction effects of confusability by familiarity by grade (p=0.03), and confusability by familiarity by grade by time (p=0.01). Follow-up analyses exploring the four-way interaction revealed that it was due to a three-way effect of confusability by familiarity by grade only at time 2 (p< 0.01). At this time point, each grade level showed an interaction of confusability by familiarity, where confusable arrays yielded slower search times only for untrained and illegal targets. Searches for trained targets, on the other hand, were not affected by the confusability factor. In other words, searching for the trained targets was not affected by the context of the other letters in the array. In contrast, searching for untrained and illegal targets was more difficult when embedded within visually confusable nontarget letters (Fig. 2).

The second MANCOVA for response accuracy on the OVST was performed using the same between-group factor of grade, and repeated measures factors of familiarity (3), confusability (2), and time (2) as above. The same covariate of number of sessions between time points was also entered. The analysis revealed only an interaction of confusability with grade (Wilks' Lambda p<0.01). The third and first grade groups did not show differences across confusability conditions, according to simple effects analysis (see Fig. 3). Only the second-grade group was less accurate searching for targets within arrays of confusable letters (p<0.01). Subsequent Student–Newman–Keuls range tests were run comparing groups in each confusability condition separately. In the confusable condition, grades 1 and 2 were less accurate than grade 3, whereas for the nonconfusable arrays only grades 1 and 3 differed on search accuracy.

Performance on the OVST was fairly accurate for all groups, averaging above 75% correct, but the types of errors individuals made may provide some information about how they approached this orthographic recognition task. To gain some insight in this regard, errors were classified as (1) letter confusion errors, (2) letter reversals, (3) both confusion and reversal errors, (4) motor errors, and (5) other. Letter confusion errors included responses between letter pairs with one letter that was in the target bigram and another letter that was visually confusable with the target bigram letter (e.g., for target "ck", the string "e k" was selected). Letter reversal errors were responses to letter pairs that contained both target letters, but where the order of the target letters was switched (e.g., "h s" is selected for the target bigram "sh"). Errors to both confusion and reversals included, for instance, selecting "n p" in the array for thetarget bigram "gn". Motor errors were those responses that were madeto a letter adjacent to the beginning or end of the target bigram (e.g., in the string "e c k" the "e c" was selected). Other types of responses included those that did not fit into one of these four categories, and could include sound-alike errors (e.g., selecting "sb" for the target "cb") among other errors. (The distinction between these other types of responses was not made, and is outside the scope of the present investigation).

The proportion of these different types of errors is presented in Fig. 4a, b. Firstly, visual search within confusable letter arrays showed that the proportion of letter confusion and reversal errors decreased over time for trained targets ($\chi^2_{(4)}$ = 12:25, p=0.02), even though the total number of errors was the same. Letter confusion errors dropped from 22% to 9%, and bigram reversal errors dropped from 32% to 16% between time 1 and time 2. For the nonconfusable letter arrays, tests of independence revealed that the types of errors changed over time only for the untrained targets ($\chi^2_{(1)}$ = 7:36; p<0.01). In this case, there was an increase of reversal errors over time, in contrast to the trained targets as shown in Fig. 4b (by definition, there are no letter confusion errors in these conditions, since the array letters were chosen as letters that are not confused with those of the target).

In sum, for this sample of children with reading disorders, speed and accuracy for identifying subword patterns in general increased over time, with the biggest gains in efficiency shown by the first-grade group. For trained targets in particular, visual search by all three grades was robust to the more challenging task of searching within arrays of confusable letters. Confusability of the nontarget letters did not affect search speed for trained targets, but it did affect search speed for untrained and illegal targets. Confusability of the nontarget letters affected search accuracy only for the second-grade group, which was less accurate when searching within visually confusable arrays overall. For trained targets, there were also less letter confusion and reversal errors over time, while reversal errors increased for untrained targets.

Question 2. Are individual differences in sublexical treatment effects related to gains in reading fluency and spelling skills?

To address this second question, multiple regression analyses were run on dependent measures of reading fluency (TOWRE, WJIII, and GORT), and spelling (WJIII and PIAT) at the end of training. Predictors included pretest scores on each of the measures (i.e., autoregressors, see Wagner, Torgesen & Rashotte, 1994), and latency and accuracy scores on the OVST from time 1 and time 2. The OVST measures were taken from performance with the trained targets presented within visually confusable arrays, since changes in the recognition of these specifically trained orthographic units were an important aspect of the intervention, and were of primary interest to the present investigation. A separate regression was run for each dependent measure. The unique contribution of the OVST predictors was determined using the dropping method (Tabachnick & Fidell, 1989) to assess whether the model's explained variance (R^2) declines by a significant degree after the predictor of interest is dropped from the regression equation. This method was thus used to determine the relative importance of the OVST predictors in the model. Beta values and semi-partial correlation coefficients are reported for each predictor (see Table 2).

Reading fluency was assessed with oral reading rate measures at the word level (TOWRE sight words) and passage level (GORT-4 reading rate), and silent reading at the sentence level (WJIII reading fluency). For OVST latency, visual search performance was predictive of oral reading rate at the passage level, but was not predictive of oral word reading or silent sentence reading fluency beyond the autoregressive effects in these models. OVST latency for the trained confusable condition at time 1 contributed significant, unique variance to GORT-4 reading rate outcomes. Neither time 1 nor time 2 OVST latency contributed significant variance to the TOWRE sight word or WJIII reading fluency outcomes. For OVST accuracy, neither time 1 nor time 2 predictors contributed significant variance to the reading fluency measures.

Spelling skill was assessed with the PIAT-R and WJIII spelling subtests. Regressions on these measures indicated that OVST performance, including latency and accuracy, was not predictive of the spelling outcomes beyond the autoregressive effect of pretest spelling scores. So neither spelling recognition nor recall (encoding) was related to OVST performance, in other words.

These regression analyses indicate partial support for the contribution of sublexical orthographic recognition efficiency to reading fluency, at least at the passage level, but did not support the expected link between sublexical efficiency and the standardized spelling measures. Thus the present experimental measure of orthographic visual search efficiency may be linked more closely with symbol processing speed than with a broader index of orthographic knowledge, per se. That is, naming-speed measures have been linked previously to fluency and orthographic encoding—so were the children who were faster with naming or processing speed also more efficient with the OVST after training? On the other hand, were children with greater OVST efficiency after training better at orthographic recognition tasks that rely more heavily on sublexical processing?

To investigate these questions further, correlations were performed between OVST outcomes and pretest scores on naming and processing speed, and other orthographic measures. OVST latency and accuracy from time 2 on the trained confusable array condition were first correlated with time 1 measures of general processing speed (WISC coding and symbol search) and naming speed (RAN) to assess the link between sublexical search and symbol processing speed. Secondly, correlations were run between the same OVST outcomes and time 1 performance on measures of letter string choice, pseudohomophone choice, and word segmentation (TOSWRF). For the processing speed correlations, rapid naming was significantly correlated with the speed of searching for trained bigrams within arrays of confusable nontarget letters (see Table 3). The other measures were all related to WISC coding, while none were related to OVST accuracy. For orthographic processing, speed of searching for trained bigrams was unrelated to the orthographic measures from time 1, but OVST accuracy outcome was related to word segmentation on the TOSWRF (see Table 4).

In sum, the efficiency of searching for specifically trained sublexical patterns under visually demanding conditions (within arrays of confusable letters) was related to later reading speed for text passages, but not for words. Search efficiency was not, however, related to later accuracy for general spelling knowledge as assessed with either recognition or recall tasks. Search speed for trained sublexical patterns was related to earlier naming speed, whereas trained sublexical search accuracy was related to earlier word segmentation skill. These findings indicate, at least preliminarily, that training has effects at the sublexical level that may be related to fluency at the text level, and that sublexical training is related to naming speed and segmentation skill.

Discussion

In the present study we addressed the impact of explicit decoding and fluency instruction at the subword, word and text levels on the efficiency of visually identifying specifically trained letter patterns by children with developmental dyslexia. In addition to treatment effects on sublexical processing, we observed developmental effects in a cross-sectional design. Finally, the relation of sublexical processing efficiency to reading fluency and spelling outcomes was examined.

We found age-related effects on sublexical orthographic recognition efficiency in this group of children. Timed responses from the visual search task showed that children's orthographic recognition performance developed relatively early on, with the greatest gains in search speed shown by first graders. First graders were slower at the orthographic recognition search task compared with second and third graders, and were also less accurate than third graders in identifying all the search targets. This developmental sequence is similar to findings for typically developing children on other orthographic tasks, where, for example, letter cluster encoding develops after grade 1 (Berninger et al., 1991), and where there is a shift between grades 1 and 2 from a dual to a single latent construct of spelling using orthographic patterns (Notenboom & Reitsma, 2003).

Secondly, there was evidence of treatment effects. Search times for bigrams that were explicitly trained in the intervention were not affected by the visual confusability of nontarget letters, whereas search times for untrained and illegal bigrams were slowed under the confusability condition. The four-way interaction of grade by time by familiarity by confusability factors was largely due to the release of the confusability effect by time 2 for trained targets. That is, the difference in search speed for trained targets between confusable and nonconfusable array conditions was no longer evident at time 2. This indicates that the trained targets became more robust to interference from similar-looking letters. Thus, the intervention which provided intensive repeated work with orthographic patterns through a variety of sublexical, lexical, and text-level activities appears to have improved the ease with which the disabled readers perceived the targets that were trained in the program. In this view, the trained letter patterns become developed to the extent that they are automatically recognized, with little conscious effort, from direct input from the print. As such, the patterns become unified.

In the present study, training of bigram patterns was associated with a decreased proportion of target identification errors due to letter-order reversals during visual search. Other visual search studies using non-alphabetic targets show a relation between reading ability and coding of spatial information of stimuli. Low reading ability has been related to slow search for conjunctive-feature targets (Casco, Tressoldi & Dellantonio, 1998), with limiting factors of the number of distracters (Vidyasagar & Pammer, 1999) and the targets' differentiating features with regard to spatial relationships (Casco & Prunetti, 1996). Additionally, covert attention tasks also reveal asymmetries in attentional focus and attention shift between visual fields for individuals with dyslexia (Facoetti, Paganoni, Turatto, Marzola & Mascetti, 2000; Facoetti & Molteni, 2001; Roach & Hogben, 2004). Tasks that specifically require detection of letter position are also found to be problematic for dyslexic readers (Katz, 1977; Cornelissen & Hansen, 1998; Cornelissen, Hansen, Hutton, Evangelinou & Stein, 1998; Pammer, Lavis, Hansen & Cornelissen, 2004). Thus, difficulties with attention to letter position may work to inhibit orthographic development. The present set of results suggests that this can be overcome with intensive intervention.

Studies of spelling demonstrate the difficulty reading-disabled individuals have with learning of interletter associations. For instance, even with practiced words, second- to sixth-grade children with learning disorders were unable to organize and rapidly access previously learned information for spelling (Gerber, 1984). Kemp, Parrilla and Kirby (2008) also find that adults with dyslexia make use of phonological skills to spell familiar words, but that they have "particular difficulty with the simple orthographic words, which required memory for correct letter sequences" (p. 117). Children with binocular instability as well rely more on phonology than visual memory for spelling, indicating that these children have restricted access to orthographic images (Cornelissen, Bradley, Fowler & Stein, 1994). Cornelissen et al. (1994) explain that "intermittent visual confusion of text may be sufficient to destabilize the "visual memory map" sufficiently to make it unreliable" (p. 722), suggesting that it is a perceptual coding glitch that interferes with orthographic memory formation.

The final goal in this study was to examine whether orthographic recognition efficiency contributes to reading fluency and to spelling outcomes in this group of children with developmental dyslexia. Search for the trained letter patterns at the two test points was first regressed on efficiency for reading isolated words, since there is consensus that automatic word reading is a key factor in fluency development (Samuels, 1979; Rashotte & Torgesen, 1985; Levy et al., 1997; Rayner, et al., 2001). Reading words automatically, without conscious effort, is held to require high quality representations that consist of multiple forms of information about a word's sounds, articulation, spelling, meaning and syntactic use (Perfetti, 1985; Perfetti & Hart, 2002). Orthographic knowledge is believed critical to support this process. We therefore hypothesized that orthographic recognition efficiency would predict word reading efficiency. This was not supported. Visual search efficiency for the trained bigrams did not predict oral word reading efficiency outcome as measured with the TOWRE sight words subtest. Thus, word reading automaticity may entail processing beyond what was required for the present search task, and could involve such proposed mechanisms as fast-mapping processes for written words (e.g., Apel, 2009), and the ability to quickly identify arbitrary groupings of letter patterns (e.g., Manis, Seidenberg & Doi, 1999). Neurophysiological studies of automatic word recognition further suggest that it is a form of acquired visual expertise that develops over a prolonged period of time. EEG studies reveal a negative wave component (N170) occurring 170 ms after stimulus onset (and prior to language related functions like phonic, semantic analysis) that differentiates adult responses to words versus consonant strings (Maurer, Brandeis & McCandliss, 2005). In children, Posner and McCandliss (2000) found that the differentiated EEG pattern for words did not emerge until around age 10, even though younger children (age 7) were familiar with the word stimuli. The authors conclude that familiarization alone cannot produce the neural signal associated with automatic word reading, but that automaticity involves a further level of expertise in sight word recognition. Such a process has been likened to other forms of acquired visual expertise (McCandliss, Cohen & Dehaene, 2003), and related to functioning of the left occipitotemporal fusiform gyrus (Dehaene, Naccache, Cohen, Le Bihan, Mangin, Poline et al., 2001; Cohen, Dehaene, Naccache, Lehéricy, Dehaene-Lambertz, Hénaff et al., 2000). The children in the present study are younger than 10, so they simply may have not yet reached this point of visual expertise for word forms. On the other hand, the small number of trained bigrams that were tested with the experimental OVST measure may simply not generalize to the type of orthographic patterns in sight words presented on the TOWRE.

Visual search for the trained letter patterns at the two test points was next regressed on outcomes of efficiency for reading passages of text. Oral reading rate for connected text was predicted by sublexical search efficiency, and this was specific to the initial test point that occurred earlier in the program. Hence, the degree of the children’s sublexical efficiency that predicted the GORT-4 reading rate outcome was either established early, during the first half of the intervention, or indicated their pre-existing sublexical skills before they entered the program. The silent reading measure of fluency (WJIII) was not predicted by visual search performance to trained targets, although the correlation with time 1 search latency was close to that for oral reading rate. Based on this pattern of results, it was only the oral reading speed for words in context, but not in isolation, that was uniquely related to the visual search measure.

Finally, the regression analyses showed no relation between search for the trained letter patterns on the OVST and the spelling measure outcomes, for either recognition or recall in a dictation task. Thus, it appears that orthographic efficiency for trained targets as measured with the present search task is most closely related to reading speed, and not spelling performance. The small number of trained bigrams tested with the OVST, again, may not generalize to the breadth of orthographic knowledge required by the standardized spelling measures. Follow-up investigation for correlates of the OVST outcome for trained bigrams showed that other types of orthographic measures were also unrelated to visual search speed or accuracy. Specifically, word-likeness judgment (letter-string choice) and pseudohomophone choice performance were not related to later visual search speed or accuracy. Thus visual search may offer additional information to these types of tasks, which "do not capture the rapid and automatic aspects of processing thought to be characteristic of skilled orthographic reading and …may be open to a wide range of strategic influences" (Castles & Nation, 2008, p. 2). The only measure that was related to later search accuracy was the silent word reading fluency task that required segmentation of words (TOSWRF). Here the child has to decipher unrelated words in unspaced text. This test is similar to an isolated embedded word task previously showing differences between disabled readers and chronological and reading level controls (Hultquist, 1997). The stimuli used in that study incorporated syllable boundary cues between the word and distracter letters, and showed that reading disability involved an additional problem with automatically perceiving syllable boundaries (Hultquist, 1997). This skill of detecting syllable boundaries may be particularly relevant to the sublexical orthographic skills that were trained in the intervention here. This pattern of relations suggests that the visual search test employed presently may be tapping into a skill of segmenting familiar patterns from a cluttered field.

Thus, the visual search efficiency measure was related to oral reading rate and word segmentation. Additionally, rapid letter naming but not general processing speed was related to later visual search speed. Rapid letter naming is previously linked with reading fluency (Compton, 2000; Schatschneider, Fletcher, Francis, Carlson & Foorman, 2004), orthographic encoding (Manis et al., 2000; Sunseth & Bowers, 2002), and the number of repetitions needed for memory formation of letter patterns (Levy et al., 1999). It has been suggested that rapid naming-speed indexes the formation of sublexical orthographic representations, eminating from the temporal overlap in intraword letter processing. Therefore, we conclude that the speed of naming letters sequentially shares a specific mechanism with searching for and identifying legal letter clusters. Over a longer period of development than was investigated here, the accumulation of orthographic knowledge and rapid processing of orthographic patterns presumably becomes further incorporated with other sublexical processes, including phonological and morphological ones, and yields evolving connections among these and additional processes at larger scales of words and text. It is our belief that orthographic knowledge is intimately connected with these components in fluent reading, and is not as well-integrated with other forms of lexical and sublexical knowledge in reading disorders.

The current set of results, while suggestive, is by no means conclusive in this regard. For instance, limitations of the present study include a relatively small sample size, and cross-sectional design. Also, there was only a subset of letter-pattern stimuli that do not include the breadth of knowledge necessary for successful spelling performance or isolated word identification speed. These stimulus patterns also focus in on one grainsize (letter pairs), and therefore may not reveal changes at larger or smaller scales in this group of dyslexic readers. Thus, verification of these results with a wider set of orthographic patterns, and with a longitudinal design is needed. It should also be noted that the pattern of relations found between the present task and other orthographic measures was between the timed measures (OVST and TOSWRF), whereas the other measures were not timed, and this difference in task demands may have contributed to the observed correlations. Nonetheless, the current study emphasizes the importance of intervention for improving sublexical orthographic processing in developmental dyslexia and its role in reading fluency.

As others have found (e.g., Puolakanaho, Ahonen, Aro, Eklund, Leppänen, Poikkeus et al., 2008), factors beyond phonological skills must be taken in to account to understand variation in reading fluency and to foster its development. In the present study, we found support for early developmental changes in orthographic recognition efficiency in children with dyslexia and indications for effects of intensive fluency intervention on the robustness of trained orthographic patterns. As Castles and Nation (2008) note, it is of importance to our understanding of reading proficiency to discover the means with which children transition from alphabetic decoding to orthographic word reading.

Developing a deeper understanding of the nature and development of orthographic knowledge and processing efficiency is essential to this process. As Apel (2009) states:

> "clinicians may need to reexamine their current assessment and instruction and intervention approaches for early literacy development… [i.e., using a] traditional, stair-step fashion, beginning first with phonemic awareness instruction, followed by lessons about orthographic knowledge, and so forth…. Instead of the traditional approach, curricula likely will emphasize the repertoire of linguistic knowledge sources that children can be learning, introducing and teaching these knowledge sources simultaneously" (p. 50).

Better models of orthographic development are a key to multiple instructional issues, ranging from when and how to correct invented spellings, to how to sequence spelling lists to follow spelling principles across developmental stages (Ehri, 1992), how to employ computer assisted learning (CAL), and when to decrease it as concepts are learned (Olson & Wise, 1992; Ecalle, Magnan & Calmus, 2009). Directing attention to the right orthographic unit also will serve to bridge the disparate large-to-small and small-to-large grainsize progression for phonological and orthographic systems (Ziegler & Goswami, 2005). Understanding the interconnected nature of these systems will advance both the theoretical knowledge of reading acquisition and our efforts to remediate it in children with learning disabilities.

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Appendix

Table 5

Letter targets and nontargets for each of the OVST conditions. Trained, untrained and illegal letter bigram search targets

Array condition	Trained		Untrained		Illegal	
	Target bigrams	Nontarget letters	Target bigrams	Nontarget letters	Target bigrams	Nontarget letters
Visually confusable	sh	b k a e n	gn	o m h q a	cb	p e d h s
	ck	o h e f x				
	br	q p i n d				
Nonconfusable	sh	U m f j p	gn	t i k z y	cb	Y m z j w

Targets were presented within arrays of the nontarget letters that were either visually confusable with one of the target letters (confusable array condition), or within arrays of letters that were not visually confusable with the target letters (nonconfusable array condition)

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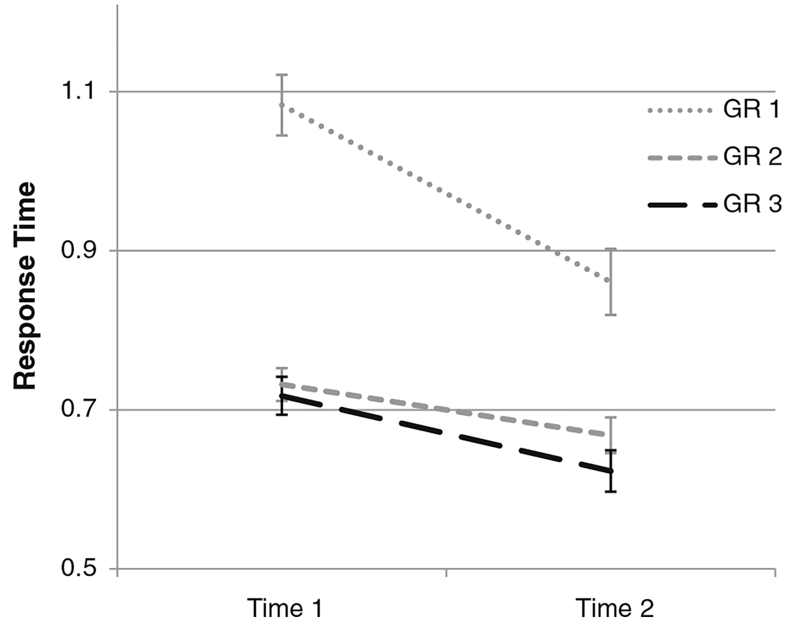

Fig. 1.
Orthographic visual search test (OVST) mean response time (per item in log s) for each grade level at time 1 and time 2 in the intervention

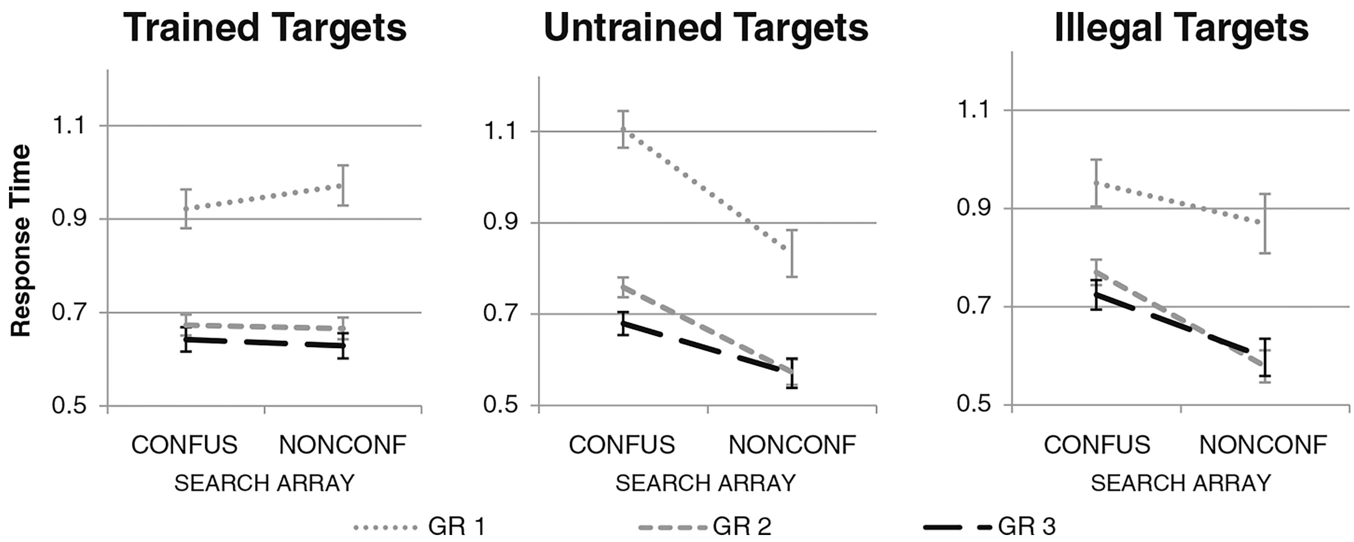

Fig. 2.

Orthographic visual search test (OVST) mean response times of control and grade groups to trained, untrained, and illegal targets presented within confusable and nonconfusable letter arrays

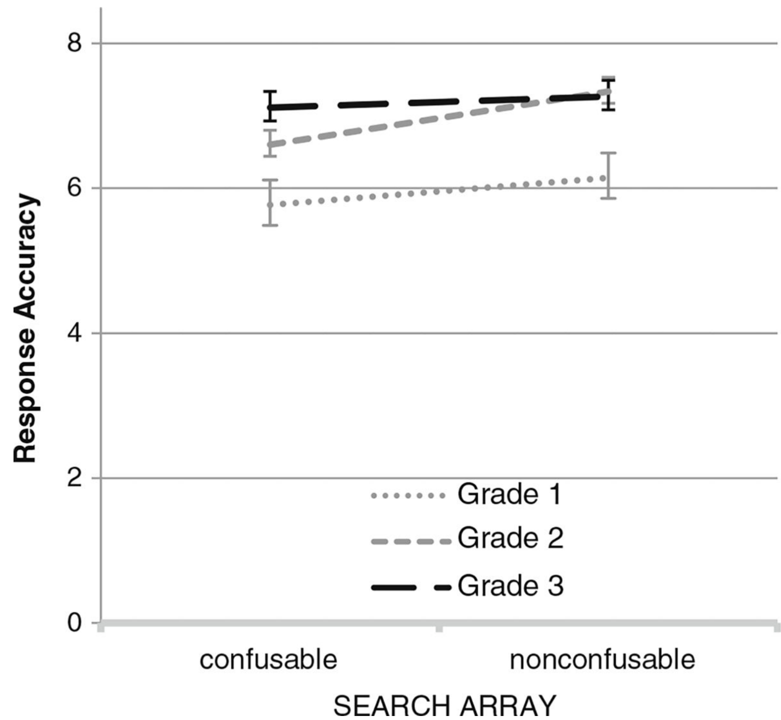

Fig. 3.

Orthographic visual search test (OVST) mean response accuracy (number correct out of eight possible) by control and grade groups for search targets presented within confusable and nonconfusable letter arrays

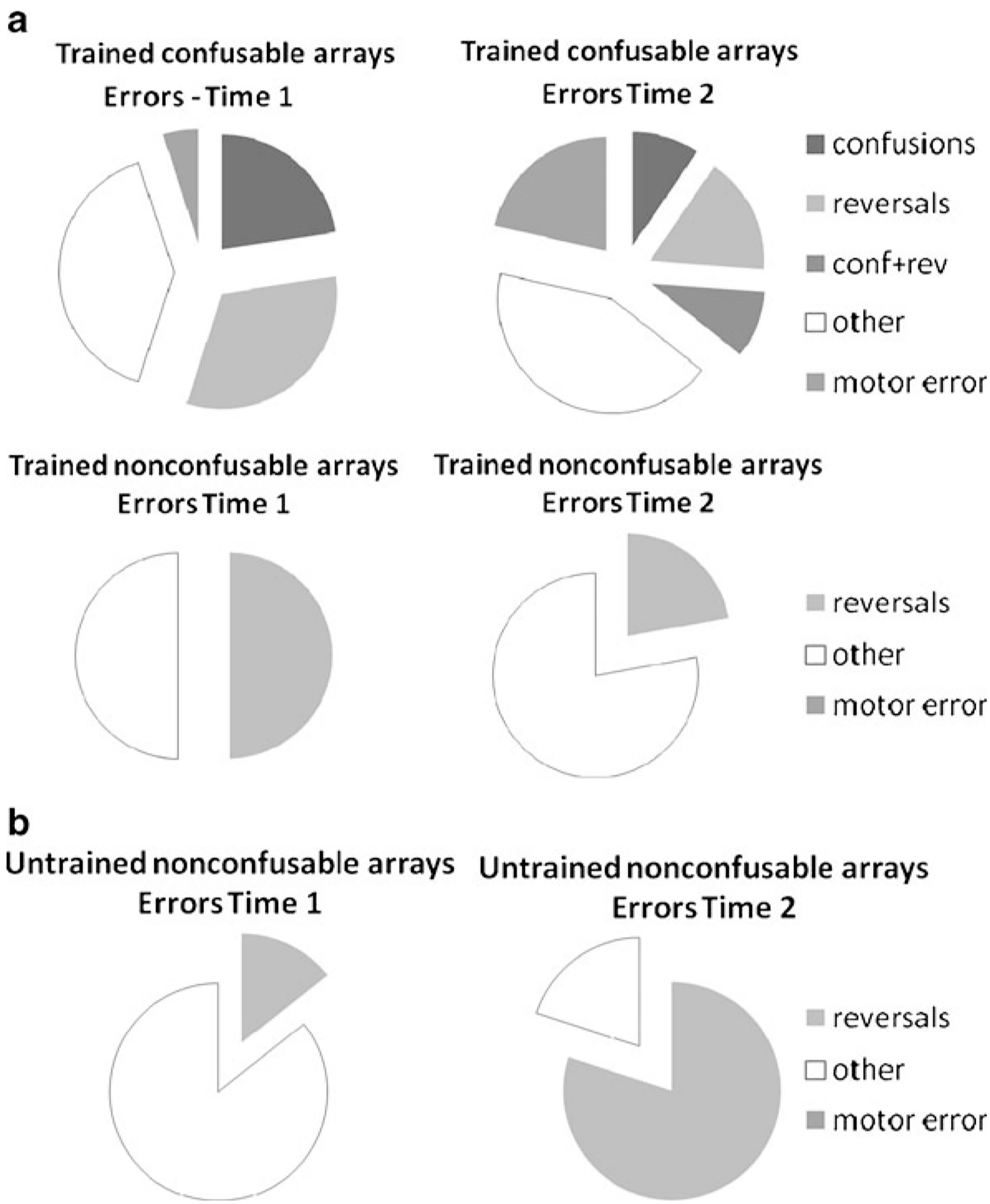

Fig. 4.

a OVST errors made when searching within confusable letter arrays for trained targets, including letter confusion, reversal, motor and other errors (time 1 presented on the *left* and time 2 on the *right side*). **b** OVST errors made when searching within nonconfusable letter arrays for trained targets (*upper panel*) and untrained targets (*lower panel*; time 1 presented on the *left* and time 2 on the *right side*)

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Table 1

Mean latencies on OVST for familiarity by confusability conditions for each grade

	Time 1						Time 2					
	Visually confusable			Nonconfusable			Visually confusable			Nonconfusable		
	Trained	Untrain	Illegal	Trained	Untrain	Illegal	Trained	Untrain	Illegal	Trained	Untrain	Illegal
Grade 1	1.022 (.045)	1.146 (.050)	1.067 (.056)	1.076 (.047)	0.993 (.064)	0.930 (.078)	0.789 (.052)	1.029 (.066)	0.801 (.058)	0.84 (.051)	0.636 (.066)	0.779 (.060)
Grade 2	0.677 (.024)	0.792 (.027)	0.787 (.030)	0.696 (.025)	0.580 (.034)	0.594 (.041)	0.636 (0.27)	0.692 (.035)	0.718 (.031)	0.608 (.027)	0.530 (.035)	0.532 (.032)
Grade 3	0.683 (.028)	0.685 (.031)	0.760 (.035)	0.662 (.029)	0.620 (.039)	0.632 (.048)	0.569 (.032)	0.641 (.041)	0.653 (.036)	0.568 (.031)	0.485 (.041)	0.532 (.037)

Mean OVST latencies (log seconds) and standard deviations for the grade level groups for each of the familiarity conditions (trained, untrained, and illegal target searches) by confusability conditions (search within arrays of visually confusable vs. nonconfusable letters) by test time

Table 2

Multiple regressions: predicting reading fluency and spelling outcomes with OVST efficiency

Reading skill		**Test point**	**OVST latency-trained confusable**		**OVST accuracy-trained confusable**	
			β	***r***	**β**	***r***
Oral fluency—words	TOWRE sight word	Time 1	−0.102	−0.085	0.113	0.113
		Time 2	−0.067	−0.056	0.091	0.089
Oral fluency—passages	GORT-4 rate	Time 1	−0.286 *	−0.235	0.132	0.131
		Time 2	0.082	0.067	0.165	0.163
Silent fluency—sentences	WJIII reading fluency	Time 1	−0.264	−0.233	0.213	0.207
		Time 2	0.006	−0.054	0.056	0.054
Spelling—recognition	PIAT-spelling	Time 1	0.053	0.041	−0.034	−0.034
		Time 2	0.067	0.052	−0.051	−0.048
Spelling—from dictation	WJIII spelling	Time 1	−0.025	−0.019	0.114	0.110
		Time 2	−0.019	−0.015	0.092	0.090

OVST latency and accuracy were entered into separate regression analyses as predictors of end of year scores on reading fluency and spelling measures. Predictors in each model included an autoregressor (i.e., pretest scores on the reading or spelling measures) and time 1 and time 2 OVST measures from searches with trained targets in visually confusable arrays. Beta values (β) and semi-partial correlation coefficients (*r*) are presented for each predictor within each model

* $p<0.05$, significant change in R^2 due to the predictor

Table 3

Correlation matrix for OVST and processing speed measures

Processing speed	OVST latency-trained confusable time 2	OVST accuracy-trained confusable time 2	WISC coding	WISC symbol search
WISC coding	−0.197	0.081		
WISC symbol search	−0.012	0.175	0.564 *	
RAN letters	−0.446 **	0.117	0.467 *	0.273

Pearson's correlation coefficients for OVST latency and accuracy outcomes (time 2) on the trained confusable search condition, with processing speed (WISC-III coding and symbol search) and RAN pretest scores

RAN rapid automatized naming

* $p<0.05$;

** $p<0.01$

Table 4

Correlation matrix for OVST and orthographic processing measures

Orthographic processing	OVST latency-trained confusable time 2	OVST accuracy-trained confusable time 2	Letter string choice	PH choice
Letter string choice	0.174	0.380		
PH choice	−0.243	0.378	0.548**	
TOSWRF	−0.238	0.507**	0.640**	0.607*

Pearson's correlation coefficients for OVST latency and accuracy outcomes (time 2) on the trained confusable search condition, with letter string choice, pseudohomophone choice (PH choice), and TOSWRF pretest scores

TOSWRF test of silent word reading fluency

* $p<0.05$

** $p<0.01$