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Executive function in the classroom: Cognitive flexibility supports reading fluency for typical readers and teacher-identified low-achieving readers



Kelly B. Cartwright^{a,*}, Timothy R. Marshall^a, Cathy M. Huemer^b, Joan B. Payne^b

^a Christopher Newport University, 1 Avenue of the Arts, Newport News, VA 23606, USA

^b Newport News Public Schools, 2465 Warwick Boulevard, Newport News, VA 23606, USA

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ABSTRACT

Background: Dominant explanations of reading fluency indicate automatic phonological decoding frees mental resources for processing meaning. However, decoding automaticity does not guarantee attention to meaning. Recent neurocognitive work suggests executive functioning (EF) may contribute to fluency beyond decoding automaticity.

Aims: Two studies examined contributions of an understudied EF, cognitive flexibility, to fluent reading and tested a teacher-administered EF intervention to improve fluency in teacher-identified low-achieving (LA) readers.

Methods and procedures: Study 1 assessed word reading fluency, automatic decoding, reading comprehension, verbal and nonverbal ability, and reading-specific and domain-general cognitive flexibility in 50 1st and 2nd grade typically-developing (TD) readers. Study 2 compared TD and LA readers' cognitive flexibility and examined effectiveness of cognitive flexibility intervention for improving fluency in 33 LA 2nd and 3rd graders.

Outcomes and results: Reading-specific flexibility contributed to fluency beyond automatic decoding and all other control variables in TD readers who had significantly higher cognitive flexibility than LA readers. Teacher-administered EF intervention improved reading fluency for LA readers.

Conclusions and implications: These findings expand understanding of the neurocognitive basis of reading fluency and add to the growing body of evidence that EF underlies learning differences and serves as a useful target of intervention for LA students.

1. What this paper adds

Dominant explanations of reading fluency suggest automaticity in decoding processes frees mental resources for attention to semantic aspects of text, thus enabling reading comprehension (LaBerge & Samuels, 1974). However, automaticity in decoding processes does not guarantee attention to meaning, suggesting additional processes may underlie fluency. This research expands understanding of the cognitive bases of reading fluency by linking fluency to a broader, more recent neurocognitive research base in executive functioning. Fluency involves coordination of semantic and phonological processes while reading (Kuhn & Stahl, 2003). We show a reading-specific executive function that involves coordinating the semantic and phonological aspects of text, *graphophonological-semantic cognitive flexibility* (GSF), contributes uniquely to word reading fluency beyond automatic decoding, verbal and

* Corresponding author.

E-mail addresses: kewright@cnu.edu (K.B. Cartwright), tmarshal@cnu.edu (T.R. Marshall), hppdirector@hiddenwood.org (C.M. Huemer).

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nonverbal ability, and domain-general cognitive flexibility, even when reading comprehension is controlled. Further, we show teacher-identified low-achieving readers demonstrate significant deficits in GSF compared to typically developing students, and teacher-administered GSF intervention improves text reading fluency and GSF in low-achieving students. These findings provide a broader explanation of the neurocognitive processes involved in fluency than has heretofore been offered, and provide a practical application of these findings for teacher-administered executive function intervention, which improves text reading fluency in low achieving readers.

2. Introduction

Since the United States [National Reading Panel \(2000\)](#) identified oral reading fluency as an important predictor of reading comprehension, fluency has received increasing attention in research and practice ([Rasinski, Blachowicz, & Lems, 2012](#)). Fluency involves accuracy, automaticity, and prosody or expressiveness in oral reading, reflecting seamless coordination of the decoding and meaning-making processes necessary for skilled reading ([Fuchs, Fuchs, Hosp, & Jenkins, 2001](#); [Kuhn & Stahl, 2003](#); [Kuhn, Schwanenflugel, & Meisinger, 2010](#)). For this reason, some have suggested fluency provides an index of reading competence ([Fuchs et al., 2001](#)). Indeed, growth in oral reading rate produces improvements in reading comprehension for elementary-aged readers ([Kim, Petscher, Schatschneider, & Foorman, 2010](#); [O'Connor, Swanson, & Geraghty, 2010](#)), and bidirectional relations have emerged between fluency and reading comprehension ([Kim, 2015](#); [Little et al., 2017](#)). Furthermore, fluency interventions that involve repeated reading of a variety of texts improve reading fluency and reading comprehension in grades K to 5 students (see [Stevens, Walker, & Vaughn, 2017](#) for a review).

The relation of reading fluency to reading comprehension changes as fluency develops: word reading fluency (i.e., context-free fluent word identification) contributes to reading comprehension of less fluent readers, whereas context-dependent text-reading fluency contributes to more fluent readers' reading comprehension, suggesting context (semantics) is more influential as reading develops ([Jenkins, Fuchs, van den Broek, Espin, & Deno, 2003](#)). These findings are consistent with work by [Bialystok and Niccols \(1989\)](#) who observed a shift in children's attention from phonological to semantic features of printed words across the elementary school years. Indeed, context-free word reading fluency is related to reading comprehension in beginning and average readers, whereas context-dependent text-reading fluency is related to reading comprehension in slightly older and more skilled readers ([Kim, Wagner, & Foster, 2011](#); [Kim, Wagner, & Lopez, 2012](#)), suggesting semantic processes increase in influence with reading skill development. For these reasons, we include an assessment of context-free word reading fluency in Study 1 with beginning readers and include a measure of text reading fluency in Study 2 with slightly older readers. It is worth noting that semantic facilitation of reading varies according to readers' skills in other ways, too. There is some evidence that dyslexic children may benefit from semantic, contextual cues more than skilled readers, as a possible compensation of their poor phonological decoding skills ([Nation & Snowling, 1998](#)).

The importance of reading fluency itself, beyond reading comprehension, should not be understated. Reading fluency predicts academic outcomes in 4th to 9th grade students in language arts, mathematics, history, geography, and science even when the effects of reading comprehension on academic performance are controlled ([Bigozzi, Tarchi, Vagnoli, Valente, & Pinto, 2017](#)). Despite these positive findings regarding fluency's relation to academic achievement, the underlying nature of reading fluency is still poorly understood. The general consensus in research and practice, which stems from seminal work ([LaBerge & Samuels, 1974](#)), is that fluency reflects the automatization of phonological decoding processes, thus freeing cognitive resources for processing meaning (see [Kuhn et al., 2010](#), for a review). Indeed, phonemic activation occurs in fluent word identification, even for skilled adult readers ([Perfetti & Bell, 1991](#)). However, phonological processes are not the only processes invoked in fluent word reading ([Kuhn et al., 2010](#)). For example, semantic processes contribute to fluent word reading beyond phonological decoding processes in elementary school children ([Eason, Sabatini, Goldberg, Bruce, & Cutting, 2013](#); [Nunes, Bryant, & Barros, 2012](#); [Vellutino, Tunmer, Jaccard, & Chen, 2007](#)), and even beginning readers show semantic activation when reading printed words ([Nation & Cocksey, 2009](#)). Thus, fluency appears to depend on both automatic phonological decoding and semantic processes, consistent with more recent views that describe fluency as involving the coordination of phonological and semantic processes during reading, ([Kuhn et al., 2010](#); [Samuels, 2006](#)).

Taken together, these findings suggest the development of skilled reading reflects an increasing ability to integrate or coordinate semantic aspects of text with automatic word decoding processes. A subgroup of students, poor comprehenders, illustrate this point. These students demonstrate fluent, automatic phonological decoding processes but are unable to shift attention to meaning while reading ([Cartwright, Bock, Coppage, Hodgkiss, & Nelson, 2017](#); [Cartwright, Coppage et al., 2017](#); [Yuill & Oakhill, 1991](#)), resulting in surprisingly poor reading comprehension in comparison to decoding skills ([Applegate, Applegate, & Modla, 2009](#); [Catts, Compton, Tomblin, & Bridges, 2012](#); [Riddle Buly & Valencia, 2002](#)). Thus, automaticity in phonological decoding processes does not necessarily enable simultaneous coordination of semantic information alongside phonological processing while reading. These results, as well as recent findings regarding impacts of semantic processes on reading fluency, indicate the cognitive mechanisms underlying reading fluency may go beyond automaticity in phonological decoding. Thus, the purpose of the studies reported here was to explore the cognitive bases of reading fluency by drawing on recent research on the roles of executive function in reading processes to better understand the potential relation between fluency and reading comprehension.

Executive functions (EFs) are top-down neurocognitive processes associated with frontal lobe function that enable the management of complex, goal-directed behavior. EFs include three core skills, working memory, inhibition, and cognitive flexibility, which underlie more complex skills such as planning and monitoring ([Diamond, 2013](#); [Friedman & Miyake, 2017](#)). Working memory involves storage and processing operations, such as holding text meaning in mind while updating that meaning during reading.

Inhibition involves the ability to suppress dominant responses or irrelevant information, such as suppressing irrelevant word meanings for polysemous words while reading. Finally, cognitive flexibility involves the ability to switch between multiple processes or aspects of a task, such as switching back and forth between graphophonological information and meaning while reading. Recently, EFs have emerged as important predictors of reading comprehension, and poor comprehenders demonstrate deficits in EFs, such as working memory (Locascio, Mahone, Eason, & Cutting, 2010), inhibition (Borella, Carretti, & Pelegrina, 2010), and cognitive flexibility (Cartwright, Coppage et al., 2017).

Given that fluent reading involves the simultaneous, fluid management of (at least) decoding and semantic processes, EFs seem likely to be involved in supporting the development of reading fluency. However, in comparison to reading comprehension, considerably less work has examined the relation of fluency to EF, and extant studies have focused primarily on working memory. For example, in a longitudinal study of children in 2nd to 6th grades, Lipka (2017) demonstrated working memory contributes to word reading fluency, though phonological decoding remained the strongest predictor of word reading fluency across grades. Furthermore, in a training study comparing multiple fluency interventions, Swanson and O'Connor (2009) found pretest working memory was a stronger predictor of posttest fluency performance, irrespective of treatment condition. Finally, Locascio et al. (2010) demonstrated working memory and inhibition contributed to deficits in fluent word reading, though these differences were mediated through phonological processing.

Because fluency requires simultaneous management of decoding and semantic processes (Rasinski et al., 2012; Samuels, 2006), one EF in particular that may be relevant for reading fluency is cognitive flexibility, or the ability to manage multiple aspects of a task simultaneously and actively switch between them while engaging in the task (Cartwright, Coppage et al., 2017; Chevalier & Blaye, 2008; Colé, Duncan, & Blaye, 2014). Cartwright (2002) adapted a cognitive flexibility task to the particular cognitive demands of reading fluency, providing an index of individuals' ability to coordinate flexibly the semantic and phonological aspects of print, called *graphophonological-semantic cognitive flexibility* (GSF). Subsequent work has shown GSF makes a unique contribution to reading comprehension beyond semantic processing, phonological processing, and general cognitive ability in elementary school students (Cartwright, Coppage et al., 2017; Cartwright, Marshall, Dandy, & Isaac, 2010; Colé et al., 2014). Furthermore, GSF mediates the contribution of reading strategy use to reading comprehension processes (Gnaedinger, Hund, & Hesson-McInnis, 2016). Additionally, GSF can be taught, which results in improved GSF and reading comprehension for second to fourth grade typically developing readers (Cartwright, 2002) and third grade poor comprehenders (Cartwright, Coppage et al., 2017).

Because fluency requires attention to both phonological and semantic aspects of words, it seems logical that GSF, an executive function that enables management of semantic and phonological properties of printed words, would contribute uniquely to reading fluency. One recent study demonstrated GSF contributes unique variance to word reading fluency beyond decoding skill and a general (non-reading) measure of cognitive flexibility in 3rd grade French-speaking students (Colé et al., 2014). The current studies were designed to further explore this relation in English-speaking samples of elementary school students. Specifically, we set out to determine whether GSF contributes uniquely to context-free word reading fluency in beginning readers beyond additional control variables and whether training in GSF would improve context-based text reading fluency in slightly older readers identified by teachers as low-achieving in reading. The following research questions guided our inquiry.

1. Does GSF contribute to context-free word reading fluency in typically developing beginning readers, after controlling for automaticity in decoding, semantic processing, domain-general executive function, and nonverbal reasoning?
2. Do typically developing readers and teacher-identified low-achieving readers differ on GSF?
3. Does a teacher-delivered GSF intervention improve context-based text reading fluency in low-achieving readers?

3. Study 1

3.1. Method

3.1.1. Participants

Fifty typically developing 1st and 2nd grade students¹ who were part of a larger project (the Family Reading Project) participated in Study 1 (25 1st graders, 25 second graders; 22 boys, 28 girls; mean age = 91.24 months, *SD* = 8.24 months). Participants were recruited from two schools in a large, urban school district via permission letters sent home with students. Parents/guardians provided informed consent for children to participate by returning signed permission forms, and all children who returned permission forms were included in the study, resulting in the sample presented here. Children provided verbal assent prior to participation. The research protocol was approved by the Institutional Review Boards of the university and the participating school district, and all participants were treated in accordance with the ethical principles of the American Psychological Association. The sample was diverse and reflected the composition of the school district from which it was drawn: 28% African American, 2% Asian American, 4% Latino/a, 2% Pacific Islander, 60% White, and 4% other/not reported.

3.1.2. Procedure

Participants were tested individually in the fall of the academic year in a quiet location in their school building (either the

¹ Thirteen of these students' data were included in a larger matched sample study, the citation and justification for which will be included after Cartwright, Coppage et al. (2017).

cafeteria, library, or at a desk in the hallway) by the principal investigator or a trained research assistant in one session. The testing session lasted approximately one hour per child, and the order of presentation of tasks was counterbalanced across participants.

3.1.2.1. Reading measures. Each child completed the Word Identification subtest of the Woodcock Reading Mastery Tests-Revised (WRMT, Woodcock, 1987) to assess fluent, context-free word identification. This measure required children to produce fluent oral readings of individual, real words within about 5 s. According to the Examiner's Manual for the WRMT, “for a response to be considered correct, the subject must produce a natural reading of the word in about five seconds” (Woodcock, 1987, p. 24). Thus, assessors mentally counted 5 s. If students did not produce fluent, accurate oral readings of individual words within the allotted time, the assessor encouraged them to “Try the next one.” Any response provided after that period was not counted as correct. The median split-half reliability coefficient for the Word Identification subtest is .97 for first graders through adults (Woodcock, 1987). Children completed the WRMT Word Attack subtest, which required them to produce correct pronunciations of nonwords within about 5 s, following the procedure described above for WRMT Word Identification, to assess automatic, accurate decoding skill and control for phonological processing. The median split-half reliability coefficient for the Word Attack subtest is .87 for first graders through adults (Woodcock, 1987). Finally, children completed the WRMT Passage Comprehension subtest, which required them to supply missing words for prose passages, to assess reading comprehension. The median split-half reliability coefficient of the Passage Comprehension subtest is .92 for first graders through adults (Woodcock, 1987).

3.1.2.2. Kaufman brief intelligence test. Children completed the Verbal Subscale of the Kaufman Brief Intelligence Test (K-BIT; Kaufman & Kaufman, 1990), which yields standardized scores of verbal ability, to control for semantic processing. Split-half reliability coefficients for the K-BIT Verbal scale range from .89 to .98 (mean = .92). Children also completed the Matrices Subscale of the K-BIT to assess nonverbal ability and control for general intellectual ability. Because matrix reasoning tasks are highly correlated with working memory tasks (Hutton & Towse, 2001; Salthouse, 1993; Salthouse & Pink, 2008), we also used the K-BIT Matrices scores to control for variance associated with working memory. Split-half reliability coefficients for the K-BIT Matrices scale range from .74 to .95 (mean = .88).

3.1.2.3. Cognitive flexibility tasks. Children completed multiple classification tasks to assess their domain general cognitive flexibility (Bigler & Liben, 1992; Bock, Gallaway, & Hund, 2015) and graphophonological-semantic cognitive flexibility (GSF; Bock et al., 2015; Cartwright, 2002). The procedures for these sorting tasks were structurally identical, and required students to sort stimuli on multiple dimensions simultaneously, indicating the ability to consider flexibly and actively switch between multiple features of stimuli. Children's sorting accuracy and speed were recorded and combined into composite scores as in prior work. The domain-general and graphophonological-semantic flexibility composite scores are highly reliable, with Cronbach's alphas of .86 and .90, respectively (Cartwright et al., 2010).

The researcher demonstrated a correct sort with one set of cards and provided a verbal description of the correct 2×2 sort. The general cognitive flexibility task required children to sort four sets of 12 picture cards by color and type of object concurrently into a 2×2 matrix, while the GSF task required them to sort four sets of 12 printed word cards by initial phoneme and word meaning simultaneously into a 2×2 matrix (see Fig. 1 for an example of a correct graphophonological-semantic sort). Prior to sorting, children were asked to sort the cards “two ways at the same time, by how the words sound and what they mean.” Additionally, to provide decoding support and reduce potential confounds of variability in word reading skill, children were told, “If you don't know a word, that's okay. I can tell you.” The assessor thus read words for students if they had decoding difficulty on the task. After sorting, children were asked to describe their correct sorts (e.g. “I put the /f/ words and the /t/ words in different piles going across, and I put the body parts and animals in different piles going up and down.”). However, if a student sorted incorrectly, the researcher corrected the sort and then requested a verbal description for the corrected sort from the student. (That is, students only provided verbal explanations for correct or researcher-corrected sorts.) The two cognitive flexibility tasks were scored as follows, following prior

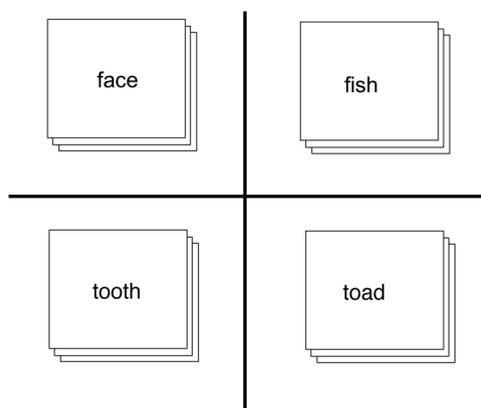


Fig. 1. A correct sort on the GSF task (i.e., by initial phoneme, /f/and/b/, and by semantic category, body parts and animals).

Table 1
Descriptive data for all variables in study 1 ($N = 50$).

Measure	Mean	Standard deviation	Minimum value	Maximum value
WRMT				
Word identification	45.66	16.43	12	77
Word attack	17.00	11.10	0	39
Passage comprehension	24.10	9.95	2	43
Cognitive flexibility				
Domain-general	16.91	10.55	0	42.11
Graphophonological-semantic	5.72	7.15	0	26.24
K-BIT verbal	101.42	14.93	71	130
K-BIT matrices	106.20	14.20	79	140

Note. K-BIT Verbal and K-BIT Matrices scores are standard scores with $M = 100$ and $SD = 15$. WRMT-R Word Identification, Word Attack, and Passage Comprehension scores could range from 0 to 106, 0 to 45 and 0 to 68 correct, respectively. Graphophonological-Semantic and Domain-General Flexibility scores are the respective sorting accuracy and speed composites. There is no explicit range for these scores because there was no ceiling on participants' sorting speeds (they were allowed as much time as necessary to complete each sort).

work.

Children's sorting accuracy, explanation accuracy, and sorting speed (in seconds) were recorded for each sort. For each set of 12 cards, children received 1 point for a correct sort and two points for a correct verbal explanation, yielding 3 possible points per card set. Thus, children could earn up to 12 points across the 4 card sets for each cognitive flexibility assessment task, domain-general and GSF. Because children are usually able to perform tasks correctly before they are able to articulate verbally the reasons for their correct performance, this scoring scheme reflects the usual course of cognitive development (Flavell, Miller, & Miller, 2002; Karmiloff-Smith, 1993). Lower (faster) sorting speeds indicated greater cognitive flexibility, while higher accuracy scores indicated greater cognitive flexibility. Thus, as in prior work, for each cognitive flexibility task, students' accuracy and speed were combined into composite scores by dividing total accuracy (i.e., number of points earned out of 12 possible points) by mean sorting speed (across the four card sets) and multiplying these ratios by 100 to facilitate interpretation. Children with the greatest degree of cognitive flexibility achieved the highest accuracy and the lowest (fastest) speed scores, resulting in the highest composite ratio scores (i.e., high accuracy/low speed). However, children who were low in cognitive flexibility achieved the lowest accuracy and the highest (slowest) speeds, yielding the lowest composite ratio scores (i.e., low accuracy/high speed).

3.2. Results and discussion

Significant positive correlations emerged between GSF scores and fluent word identification ($r = .63$, $p < .001$), automatic decoding ($r = .49$, $p < .001$), reading comprehension ($r = .62$, $p < .001$), verbal ability ($r = .36$, $p < .001$), nonverbal ability ($r = .58$, $p < .001$), and domain-general, color-shape cognitive flexibility (DGF) scores ($r = .51$, $p < .001$). No scores were significantly related to children's age (in months), thus age was excluded from further analyses. See Table 1 for descriptive data on all variables in Study 1.

3.2.1. Test of research question 1

For all regression analyses reported below, Cook's and Mahalanobis distances indicated no outliers. To test whether GSF contributes to context-free word reading fluency in typically developing beginning readers, after controlling for automatic phonological decoding skill and semantic processing, we conducted a hierarchical linear regression analysis. For this analysis, all standardized residuals were within the -3.0 to 3.0 range, with no evidence of autocorrelation (Durbin-Watson = 1.857). Additionally, no evidence of multicollinearity emerged. All predictor intercorrelations were less than $.7$, and all predictors were significantly correlated with the criterion at levels above $.3$. All VIFs were below 1.2 , indicating no issues with multicollinearity (Myers, 1990 and Stevens, 2002 indicate VIF values above 10 indicate multicollinearity). Fluent word identification scores were the dependent measure. On the first step of the analysis, children's automatic phonological decoding (WRMT Word Attack) and semantic processing (K-BIT Verbal Ability) scores were entered as predictors. GSF composite scores were entered on Step 2 and contributed significant, unique variance to fluent word identification beyond phonological and semantic processing, $R^2 = .776$ (adjusted $R^2 = .767$), $\Delta R^2 = .04$, $ps < .001$. See Table 2. Additionally, to corroborate findings in prior work with GSF, we ran a parallel regression analysis predicting reading comprehension and replicated prior work (Cartwright et al., 2010; Colé et al., 2014). For this analysis, all standardized residuals were within the -3.0 to 3.0 range, with no evidence of autocorrelation (Durbin-Watson = 1.791). Additionally, no evidence of multicollinearity emerged. All predictor intercorrelations were less than $.7$, and all predictors were significantly correlated with the criterion at levels above $.3$. All VIFs were below 1.4 . GSF predicted reading comprehension beyond automatic phonological decoding and verbal ability, $R^2 = .674$ (adjusted $R^2 = .660$), $\Delta R^2 = .05$, $\beta = .025$, $p = .010$.

To provide a stronger test of research question 1, we conducted a second hierarchical regression analysis, controlling for automatic phonological decoding (WRMT Word Attack), semantic processing (K-BIT Verbal Ability), nonverbal reasoning (K-BIT Matrices scores), and domain general cognitive flexibility on Step 1. Additionally, because reading comprehension has a bidirectional relation with reading fluency, reading comprehension scores were controlled on Step 1; GSF scores were entered on Step 2 and contributed

Table 2Summary of hierarchical regression analysis predicting fluent word identification ($N = 50$).

Variable	<i>B</i>	SE <i>B</i>	β
Step 1			
Word attack scores	1.24	0.11	.82**
K-BIT verbal scores	0.12	0.08	.11
Step 2			
GSF Scores	0.57	0.17	.24**

Note. $R^2 = .77$ for Step 1; $\Delta R^2 = .04$ for Step 2 ($ps < .001$).

* $p < .05$.

** $p < .01$.

significant, unique variance to fluent word identification beyond control variables, $R^2 = .905$ (adjusted $R^2 = .894$), $p < .001$, $\Delta R^2 = .01$, $p = .022$. For this analysis, all standardized residuals were within the -3.0 to 3.0 range, with no evidence of autocorrelation (Durbin–Watson = 1.983). Additionally, no evidence of multicollinearity emerged. All predictor intercorrelations were less than .7 with the exception of reading comprehension and nonword decoding, as would be expected ($r = .76$, $p < .001$), and all predictors were significantly correlated with the criterion at levels above .3, except domain-general cognitive flexibility ($r = .21$, $p = .158$). All VIFs were below 5.2. See Table 3. We acknowledge that the number of predictors in this analysis (6) is not ideal, given the small size of our sample. Thus, we also report the adjusted R^2 .

Finally, because the contribution of GSF to word reading fluency may be mediated by the speeded components of the tasks, we ran these regression analyses with GSF Accuracy scores, which indicate students' ability to actively switch between the phonological and semantic aspects of printed words without the timed components of the task. Contributions of GSF to reading fluency remained significant in both regressions, as did contributions of GSF to reading comprehension in the parallel analysis that assessed replication of prior work.

3.2.2. Discussion

These results indicate GSF, a reading-specific assessment of EF, makes an independent contribution to fluent word identification in typically developing beginning readers even when other indicators of EF were controlled (domain-general cognitive flexibility and matrix reasoning, which shares significant variance with working memory), beyond significant contributions of automatic decoding, and beyond the significant contribution of reading comprehension. Furthermore, the relation between GSF and word reading fluency does not depend on the speeded nature of the tasks, because GSF's relation to fluency remained significant, even when the speeded portion of the GSF task was not included in analyses. Additionally, we replicated prior work that showed GSF contributes to reading comprehension beyond automatic decoding and verbal ability (Cartwright, 2002; Cartwright et al., 2010; Colé et al., 2014). As predicted, the ability to switch actively between the phonological and semantic aspects of printed words appears to contribute to fluent word reading in typically developing beginning readers. Thus, we conducted Study 2 to compare typically developing students to students identified by teachers as having low achievement in reading and to assess the impact of GSF training on fluency for low-achieving students.

4. Study 2

4.1. Method

4.1.1. Participants

Forty-seven 2nd and 3rd grade students (mean age = 96.74 months, $SD = 7.01$ months) participated in Study 2. The sample was

Table 3Summary of hierarchical regression analysis predicting fluent word identification ($N = 50$).

Variable	<i>B</i>	SE <i>B</i>	β
Step 1			
Word Attack Scores	0.59	0.12	.40**
K-BIT Verbal Scores	-0.08	0.06	-.08
K-BIT Matrices Scores	0.08	0.08	.07
DGF Scores	-0.12	0.10	-.07
Reading Comprehension	1.03	0.18	.62*
Step 2			
GSF Scores	0.35	0.15	.15*

Note. $R^2 = .91$ for Step 1, $p < .001$; $\Delta R^2 = .01$ for Step 2, $p = .022$.

* $p < .05$.

** $p < .01$.

diverse and included 68.1% African American students, 4.3% Latino/a students, 23.4% White students, and 4.3% who identified as “other” race or ethnicity. Participants were recruited from a large, urban school district via permission letters sent home with students. Parents/guardians provided informed consent for children to participate by returning signed permission forms, and children provided verbal assent prior to participation. All pupils who returned permission forms were included in the study. The research protocol was approved by the Institutional Review Boards of the university and the participating school district, and all participants were treated in accordance with the ethical principles of the American Psychological Association.

Thirty-three of the students participated in the GSF training study (19 second graders, 14 third graders; 11 boys, 22 girls; mean age = 96.68 months, $SD = 7.38$ months). These students were identified by teachers as low-achieving readers (LA) because they did not meet the school district's benchmarks for grade-level reading performance, based on school assessment data. Fourteen of the students (6 second graders, 8 3rd graders; 7 boys, 7 girls; mean age = 96.89 months, $SD = 6.31$ months) were identified by teachers as typically developing (TD) because they met school district grade-level reading benchmarks; and, these 14 students provided a comparison group for assessing differences in GSF scores between LA and TD students (research question 2). The school district permitted no other research assessments for the project, due to a heavy school assessment schedule for the students; thus, we could not validate the teachers' classification of students into TD and LD groups with additional researcher-delivered measures. However, we were able to assess differences between the groups on the school district's reading measures to corroborate the groupings, which we report below. TD and LD students did not differ on race, age, grade level, or sex. The pretest GSF scores for these students were part of a larger project investigating the development of GSF via a cross-sectional comparison of 2nd to 5th grade elementary school students (The DEFT Readers Project). We note that only 47 of these students are included in the current study, because they are the only students for whom we have Phonological Awareness Literacy Screening (PALS; [Invernizzi, Juel, Swank, & Meier, 2004](#)) data, provided by the participating school.

4.1.2. Procedure

Students selected by the teachers for intervention were randomly assigned to intervention and control groups in a randomized wait list control group design. (The students who served as control students in the fall of the academic year received the intervention in the spring of the academic year to maximize project benefits for all students.) Children's fluency was assessed with the Phonological Awareness Literacy Screening (PALS; [Invernizzi et al., 2004](#)), which yielded assessments of context-based text fluency reading rate (words read correctly per minute) and expressiveness (which was rated on a 3-point Likert scale where 1 = not expressive and 3 = expressive). The PALS fluency task required students to read brief passages of approximately 200 words (2nd and 3rd grade passages ranged from 197 to 232 words; [Invernizzi, 2014](#)), while the assessor timed students' oral reading and recorded the students' oral reading errors. The number of words read correctly per minute was calculated. Additionally, students' GSF was assessed as described in Study 1, Section 3.1.2.3, and yielded GSF accuracy, speed, and composite scores. University researchers assessed GSF for all students, and classroom teachers administered the PALS assessment as part of the regular school district assessment protocol.

Children's teachers administered the GSF intervention in small group lessons, one lesson per week over a five-week period, following prior work ([Cartwright, 2002](#); [Cartwright, Coppage et al., 2017](#)), using the same five sets of twelve word cards that were used for the GSF pretest assessment described in Section 3.1.2.3. Teachers used a different set of GSF word cards for each intervention lesson and provided direct instruction and feedback. The intervention proceeded in two steps. First, students were required to sort the day's set of words into two piles along one dimension (e.g., beginning sound), and then they were required to reshuffle the cards and sort the day's set of words into two piles along the other dimension (e.g., meaning). These single sorts served to highlight the multiple sorting dimensions for the students so that they more readily attended to the phonological and semantic features of each of the words in the day's target sort. Next, teachers administered the matrix completion portion of the intervention. They collected the set of word cards from the student and placed three of those cards into the 2×2 matrix which had been used for the pretest assessment, sorted by beginning sound and meaning, leaving one open spot in the matrix. Teachers repeated this procedure, using a different subset of three

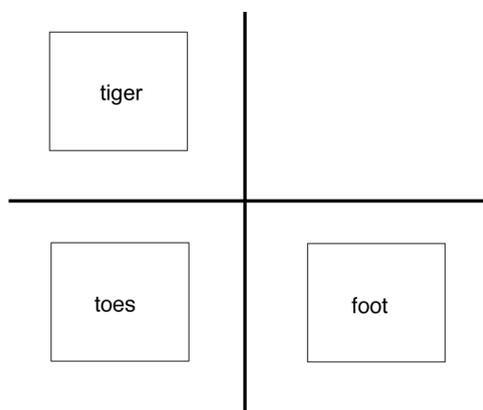


Fig. 2. A sample matrix completion exercise for the GSF intervention; students had to find a card to complete the sound-meaning sort (frog, fish, or fox would complete the sort correctly).

words each time, and varying the open spot in the 2 × 2 matrix. Students were required to successfully complete four consecutive, sound-meaning sorts in each lesson and were given as much time as necessary to reach the goal. See Fig. 2 for a sample matrix completion exercise.

4.2. Results and discussion

As in Study 1, significant, positive correlations emerged between GSF scores and reading fluency. Context-based text reading fluency, assessed with words read correctly per minute, was significantly and positively correlated with GSF ($r = .32, p = .031$) as were expressiveness ratings of students’ oral reading ($r = .33, p = .023$). No significant differences were found between the intervention and control groups or between boys and girls at pretest. As would be expected, third graders ($M = 72.36, SD = 19.60$) had significantly higher reading rates at pretest than second graders ($M = 58.74, SD = 17.78$), though they were still lower than would be expected for their grade level (see Hasbrouck & Tindal, 2017). Thus, grade level was controlled in subsequent analyses. Second and third graders did not differ on expressiveness or GSF at pretest.

4.2.1. Test of research question 2

To determine whether GSF differed in typically-developing and low-achieving readers, we completed two comparisons. First, we compared the GSF scores of the 33 teacher-identified LA students selected to participate in the intervention to the non-selected TD readers ($n = 14$) in Study 2. To account for the impact of accurate word identification on GSF and control for age, we completed an Analysis of Covariance (ANCOVA), controlling for age in months and context-based text reading fluency. This analysis indicated LA students ($M = 1.76, SD = 2.96$), scored significantly lower than TD students ($M = 4.86, SD = 4.59$) on GSF sorting accuracy, $F(1, 43) = 5.32, p = .026, \eta_p^2 = 0.11$, a large effect (Cohen, 1988; Richardson, 2011). Likewise, the LA students ($M = 3.05, SD = 5.92$) scored significantly lower than the TD students on GSF composite scores ($M = 10.09, SD = 10.00$), $F(1, 43) = 6.18, p = .017, \eta_p^2 = 0.13$, a large effect (Cohen, 1988; Richardson, 2011). Furthermore, to corroborate the school’s designation of these students as LA and TD, we compared the students on context-based text reading fluency and expressiveness ratings, controlling for age. These analyses indicated LA students ($M = 64.52, SD = 19.51$) scored significantly lower than TD students on context-based text reading fluency ($M = 83.93, SD = 27.19$), $F(1, 44) = 7.85, p = .008, \eta_p^2 = 0.15$, a large effect (Cohen, 1988; Richardson, 2011); the difference in oral reading expressiveness for the two groups, albeit in the predicted direction, did not reach significance: LA students’ expressiveness ratings ($M = 2.33, SD = 0.48$) were not significantly different from TD students’ ratings ($M = 2.57, SD = 0.65$), $F(1, 44) = 1.95, p = .170, \eta_p^2 = 0.04$, a small to medium effect (Cohen, 1988; Richardson, 2011).

Additionally, as a second test of research question 2, we compared the GSF scores of the 2nd grade typically-developing students who participated in Study 1 ($n = 25$), described in Section 3.1.1, with the low-achieving 2nd grade students who participated in Study 2 ($n = 19$), described in Section 4.1.1. Means and standard deviations for all students’ GSF scores by grade level across the two studies are provided in Table 4. Typically-developing 2nd graders scored significantly higher on GSF sorting accuracy, $t(41.49) = 2.87, p = .007$, and GSF composite scores, $t(41.98) = 2.41, p = .020$, than low-achieving readers. Of note, 3rd grade low-achieving readers had lower GSF accuracy and GSF composite scores than 1st grade typically-developing students.

4.2.2. Test of research question 3

Because LA readers were significantly lower than TD readers on GSF, we conducted an experiment to test whether GSF intervention would improve LA readers’ reading fluency. Analyses of Covariance (ANCOVAs) were conducted to examine students’ posttest fluency and GSF performance while students’ pretest performance and grade level were controlled. The intervention students ($M = 80.35, SD = 19.29$) had significantly higher oral reading rates (words read correctly per minute) at posttest than the control

Table 4
GSF scores for TD students in study 1 and pretest GSF scores for LA students in study 2 by grade level.

	TD students		LA students	
	Mean	Standard deviation	Mean	Standard deviation
First grade				
GSF accuracy	2.29	3.51	–	–
GSF sorting speed (s)	76.18	45.46	–	–
GSF composite	3.81	6.17	–	–
Second grade				
GSF accuracy	4.64**	4.30	1.53**	2.89
GSF sorting speed (s)	63.38	18.46	80.10	66.20
GSF composite	7.56*	7.66	2.63*	5.92
Third grade				
GSF accuracy	–	–	2.07	3.12
GSF sorting speed (s)	–	–	61.22	33.91
GSF composite	–	–	3.62	6.11

* $p = .020$.

** $p = .007$.

Table 5

Pretest and posttest scores for text reading fluency and GSF for low-achieving (LA) students in the intervention ($n = 17$) and control ($n = 16$) groups and typically developing (TD) comparison students ($n = 14$) in study 2.

Measure	Pretest		Posttest	
	Mean	Standard deviation	Mean	Standard deviation
Text Reading fluency (WCPM)				
LA intervention group	66.76	21.02	80.35	19.29
LA control group	62.13	18.13	68.81	16.99
TD comparison	83.93	27.19	–	–
Text reading expressiveness				
LA intervention group	2.35	0.49	2.82	0.39
LA control group	2.31	0.48	2.50	0.63
TD comparison	2.57	0.65	–	–
GSF accuracy				
LA intervention group	1.65	2.62	3.72	3.44
LA control group	1.88	3.36	1.94	3.07
TD comparison	4.86	4.59	–	–
GSF composite				
LA intervention group	3.27	6.08	7.26	7.46
LA control	2.82	5.95	4.24	6.80
TD comparison	10.10	10.00	–	–

Note. Posttest scores were not available for TD comparison students.

students ($M = 68.81$, $SD = 16.99$), $F(1, 29) = 4.48$, $p = .043$, $\eta_p^2 = 0.13$, a large effect (Cohen, 1988; Richardson, 2011). Similarly, intervention students ($M = 3.71$, $SD = 3.44$) had higher GSF Accuracy scores at posttest than control students ($M = 1.94$, $SD = 3.07$), $F(1, 29) = 5.32$, $p = .028$, $\eta_p^2 = 0.16$, a large effect (Cohen, 1988; Richardson, 2011). This finding held, even when pretest reading rate was controlled. Finally, intervention students ($M = 2.82$, $SD = 0.39$) had marginally higher expressiveness scores at posttest than control students ($M = 2.50$, 0.63), $F(1, 29) = 3.15$, $p = .086$, $\eta_p^2 = 0.10$, a medium to large effect (Cohen, 1988; Richardson, 2011). Means and standard deviations for intervention, control, and TD comparison students for GSF and fluency are reported in Table 5.

4.2.3. Discussion

As expected, LA students scored significantly lower than TD students on GSF and fluency, even when age was controlled. Furthermore, differences in GSF remained significant, even when reading fluency (i.e., accurate word reading ability) was controlled, indicating the differences in GSF were not due to differences in word reading ability. Thus, LA beginning readers appear to have difficulty coordinating flexibly the graphophonological and semantic features of printed words that is independent of their accurate word reading ability. Furthermore, as expected, GSF intervention produced improvements in reading fluency for LA students, and inspection of means in Table 5 indicates intervention students' posttest fluency rates ($M = 80.35$) were comparable to TD students' pretest rates ($M = 83.93$).

5. General discussion

Neurocognitive research holds promise for expanding understanding of reading processes and reading difficulties. The current findings indicate GSF, a reading-specific executive function that involves coordinating phonological and semantic properties of printed words, contributes uniquely to reading fluency beyond automatic decoding in typically developing primary grades students, even when semantic processing, other indicators of executive function, and reading comprehension were controlled. Our findings add to the literature, providing novel insight into the neurocognitive basis of reading fluency beyond the favored explanation that fluency reflects automaticity in decoding, enabling attention to meaning (LaBerge & Samuels, 1974). Additionally, we confirmed prior work that demonstrated unique contributions of GSF to reading comprehension (Cartwright, Coppage et al., 2017; Colé et al., 2014; Søndergaard Knudsen, López, & Archibald, 2018). Taken together these findings suggest executive coordination of reading sub-processes or features of text, such as graphophonological and semantic processes, is important to the development of skilled reading and is deficient in low achieving readers. Future research should further explore the role of GSF in skilled reading processes as well as GSF's relation to various reading disabilities.

Ours is the first study to demonstrate low achieving readers are significantly lower in GSF than TD peers. Given that GSF contributes uniquely to reading fluency, this finding suggests a potential avenue for remediation of low reading achievement in classroom settings. In support of this notion, our teacher-delivered GSF intervention in a randomized controlled trial improved oral reading fluency in 1st and 2nd grade teacher-identified low-achieving readers. These findings have important implications for practitioners in the field, as GSF can be trained in as few as five lessons, resulting in improvements in students' reading-specific executive functioning and reading fluency. Furthermore, these findings confirm recent work that indicates domain-specific EF interventions are more effective for improving academic skills (Cartwright, 2002; Cartwright et al., 2010; Melby-Lervåg & Hulme,

2013) than interventions that train isolated, domain-general EFs. Future work should develop additional reading-specific assessments of EF to better articulate the specific ways EF supports skilled reading, which may lead to additional opportunities for intervention and remediation of reading difficulties.

Although our samples are small, the findings we present are robust and are consistent across studies as well as with prior work. These findings are an important first step toward a broader understanding of the neurocognitive basis of reading fluency. Automaticity in decoding does not guarantee that readers can successfully coordinate the word-level and semantic processes necessary for skilled reading. However, GSF, a reading-specific executive function, provides additional explanation for the neurocognitive basis of reading fluency, advancing our understanding of this important reading skill.

6. Conclusion

This research (1) expands our knowledge of the cognitive bases of reading fluency by linking fluency to a broader, more recent research base in cognitive neuroscience, (2) provides a broader explanation of the processes involved in fluency than has heretofore been offered, and (3) offers practical applications for executive function interventions, which can improve reading fluency in low achieving readers, that are accessible for classroom teachers.

Declaration of interests

None.

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