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Cognitive flexibility in beginning decoding and encoding

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Abstract

The development of beginning decoding and encoding skills is influenced by linguistic skills as well as executive functions (EFs). These higher-level cognitive processes include working memory, inhibition, and cognitive flexibility, and individual differences in these EFs have been shown to contribute to early academic learning. The present study extends the prior research on EFs by examining the relationship between one type of EF, cognitive flexibility, and decoding and encoding development in English-speaking kindergarteners with limited alphabet knowledge. Pooling data from two cohorts of kindergarten children who took part in a brief phonics intervention (N = 125 from 23 classrooms at one U.S. public school), we estimated the unique effect of cognitive flexibility on decoding and spelling gains, controlling for potential confounds. Results showed that initial cognitive flexibility significantly positively predicted word-level decoding and spelling gains (uniquely explaining an average of approximately 5% of the variance in gains for these measures), but the effect on decoding gains was stronger for children with lower incoming alphabet skills (5-7 letters or fewer). These findings are consistent with the earlier research on EFs and reading acquisition with older children, and also indicate that greater alphabetic skills may compensate for lower initial EF in decoding development for children learning alphabetic languages.

Cognitive Flexibility in Beginning Decoding

Decoding—the process of translating print to speech—is a pivotal skill that typically emerges during the period when children's fluid abilities (i.e., flexible cognitive resources) for learning skills are still developing (see Duncan, 2013). The influence of linguistic skills, including phonological awareness, on reading development is well established (e.g., Hogan et al., 2005). Ample evidence also confirms that general cognitive processes like executive functions (EFs) are involved in early reading acquisition (Cartwright et al., 2010; Blair & Razza, 2007; Engel et al., 2011; Morgan et al., 2018; van de Sande et al., 2017, 2018; van der Sluis et al., 2007EFs are a suite of domain-general cognitive processes involved in goal-directed behavior that include three constructs: working memory, inhibitory control, and shifting or "cognitive flexibility" (Cartwright, 2012; Diamond, 2013; Monette et al., 2015). These EFs are thought to facilitate fluid decoding (Cartwright et al., 2020a; Georgio et al., 2008, 2018), oral reading fluency (Cartwright et al., 2019; Cirino et al., 2019; Nguyen et al., 2020), and reading comprehension (Cartwright, 2012; Cartwright et al., 2017; Cole et al., 2014). Individual differences in learning and remembering information, and the developmental timetable for EFs contribute to individual differences in learning to read. The present study extends the prior research in this area by examining the extent to which one EF process, cognitive flexibility, predicts decoding and encoding skill acquisition for English-speaking kindergarteners with limited alphabet knowledge, and whether alphabet knowledge (albeit limited) may compensate for lower cognitive flexibility.

Inside Decoding

During kindergarten in the U.S., most children are first introduced to the two key prerequisites for decoding development: alphabet knowledge and phonemic awareness. Letter name and sound knowledge are well-established, reliable predictors of learning to read (Adams, 1990; Bond & Dykstra, 1967; Catts et al., 2001; de Jong & van der Leij, 1999; Muter et al., 1997; Tunmer et al., 1988), as is phonemic awareness, particularly during early elementary grades (Wagner et al., 1997). Both letter sound knowledge and phonemic awareness are necessary for children to establish the alphabetic principle (Byrne & Fielding Barnsley, 1989; 1990), and early growth in in these two skills have been shown to be intertwined (Lerner & Lonigan, 2015). Understanding the alphabetic principle—how printed letters in words map onto the sounds in spoken words—is required for children from alphabetic languages such as English to read and to spell words (Perfetti & Bolger, 2004).

Systematic instruction in the alphabet affords children insight into phonemes (de Graaff et al., 2009), and pre-kindergarten encounters with printed words help many children learn that this sound-symbol relationship is systematic. Children's early oral language experiences and vocabulary knowledge also sharpen their awareness of the phonemes in words by drawing upon their accumulated store of phonological representations to pronounce a word correctly (Metsala & Walley, 1998; Walley et al., 2003). The Simple View of Reading (SVR) (Gough & Tunmer, 1986) model of reading comprehension describes individual differences in decoding and language comprehension. Fine-grained phonological representations and fast retrieval from memory of stored visual representations help children develop accurate and fluent decoding (Verhoeven et al., 2016) to support comprehending text. Children's initial decoding skill is correlated with irregular word reading (Wagner & Torgesen, 1987) and predicts later variation in irregular word reading (Ricketts et al., 2007).

A suite of cognitive abilities and language skills not included in widely held theories of reading also contribute to individual differences in early reading development, in particular differences in acquiring the skills required for decoding words (Morgan et al., 2019; Peng & Kievet, 2020: Shaul & Schwartz, 2014). When children first learn to decode, they must coordinate their recent understandings of alphabet knowledge and phonemic awareness and apply these skills to blending sounds to pronounce or read a word. The child must pay attention to each letterform in a word, retrieve the sound from memory, repeat the process for each letter, remember all of the sounds, and push the sounds together. While many children discover the relationship between phonemic awareness and the alphabetic principle with classroom phonics instruction, struggling beginners may require more explicit demonstration and practice to blend letter sounds to decode words (O'Connor, 2011). These include children with limited early literacy knowledge and oral language skills, including children at risk for reading difficulties, and emergent bilingual students (EBs) (Tunmer & Chapman, 2012a). Struggling readers may arrive at kindergarten knowing few or no letter names or sounds and with limited phonological awareness. As children learn how sounds correspond to each letter in words, the quality of their phonological representations improves. By gradually developing accuracy and efficiency in their knowledge and memory for these representations, children become able to blend sounds together. This is a complex and challenging learning task for many at-risk beginning readers. These children may need more support learning to sound out words before they are able to retrieve the blended pronunciations to decode.

Previous research indicates that EFs play a role in early orthographic knowledge and initial word decoding, in particular when the decoding process is "most effortful" (Haft et al., 2019), when children are introduced to these code-oriented skills and when their EFs are not yet fully developed or structured (Davidson et al., 2006). In their study of Hebrew-speaking kindergarten children, Shaul and Schwartz (2014) found that EF (composite of inhibition and cognitive flexibility) significantly contributed to early literacy skills, with the strongest relationship found for predicting children's orthographic knowledge, "a very complex ability, which is based on a number of highly synchronized skills such as phonemic awareness, grapheme-phoneme correspondences (GPCs), visual perception, identification and discrimination, print knowledge, and word pattern recognition" (p. 764). In a more recent study of English-speaking kindergarten-age children, Haft et al. (2019) found that EFs (composite of working memory, inhibitory control, sustained attention) predicted decoding, controlling for age and oral language skills, and further, that EFs had an indirect link to reading comprehension through decoding. This EF-decoding relationship has also been reported for more transparent languages in which word reading acquisition is more rapid than in English: in their study of French-speaking second graders, Colé et al. (2014) found that one EF in particular, cognitive flexibility, predicted both word reading and comprehension.

Individual Differences in Decoding Prerequisites

As mentioned above, the path through the initial stages of word reading development is less smooth for some children who require explicit instruction and practice in key processes to support their learning. Below we review these decoding prerequisites.

The paired-associate learning task for letter names and sounds. This skill in matching letters and sounds in words is not necessarily intuitive, and learning obstacles occur outside of the primary and significant paired associate learning tasks of matching individual names and sounds to printed letters (Roberts et al., 2018, 2019; Piasta et al., 2010). Kindergarteners with limited literacy knowledge often require more time to develop phonemic awareness, and to understand what letters mean. As they begin to acquire alphabet knowledge, they may be confused that letters have two labels (i.e., the letter name and the letter sound). Learning the correct labels may be its own learning task to establish the proper correspondences in memory, and to retrieve the correct correspondence—letter names for spelling, and letter sounds for decoding. As children are learning to decode words, they typically apply their knowledge of letter sounds. Some children initially draw upon their knowledge of letter names, which at this age often bootstraps their more limited knowledge of letter sounds (Cardoso-Martins et al., 2002; Ehri, 2005; Trieman et al., 1996). Letter names often make the more abstract phonemes in words concrete and thereby increase children's phonemic sensitivity (Elkonin, 1973). Learning about graphemes and phonemes required for decoding is a process of "spiral causality" (Dehaene, 2009) that is less smooth for some students.

Once children have accurate letter sounds and letter names, they must learn to coordinate the letter labels for either spelling or blending. As they slowly learn the demands of the new decoding task, children inhibit letter name retrieval and adjust by retrieving letter sounds. For a child with beginning alphabet knowledge, decoding requires a string of mental processes: attending to a string of letters, retrieving the proper working memory representations, and coordinating information to blend the letter sounds. Many children easily gain these insights and learn to decode with explicit classroom instruction (Slocum et al., 1993). These insights are more elusive for kindergarteners with limited alphabet skills.

The co-articulation insight. The dynamic process of phoneme blending requires children to co-articulate the sounds to obtain the word-like pronunciation, and to draw upon probabilistic and semantic knowledge to recognize and pronounce the words (Harm & Seidenberg, 1999; Muter et al., 2004). To acquire decoding skill, children must discover how sounds are co-articulated when assembled, a particular challenge for children without the English vocabulary knowledge to help them recognize the blended word. Word recognition is not surprisingly the most common obstacle for beginning readers, requiring "the skill to blend letter sounds or larger chunks into words. For this skill, a higher level of abstraction is needed, because sounds cannot be merely put one after another to obtain understandable words" (de Graaff et al., 2009, p. 331). Empirical research has informed evidence-based, explicit, systematic early reading interventions that help children learn these prerequisite alphabet and phonological skills, and are effective for many children (see Brady, 2011).

Differences in response to intervention. Many children, however, fail to respond adequately to these interventions (O'Connor & Fuchs, 2013; Simmons et al., 2014; Torgesen, 2000; Vellutino et al., 2006), leading researchers to consider influences beyond alphabet knowledge and phonemic awareness on learning to decode (Colé et al., 2014; Vadasy & Sanders, 2021). These influences include cognitive abilities that mediate student response (Vellutino et al., 2007). Precursors of reading, such as lexical retrieval and verbal short-term memory, have been shown to contribute to individual differences in early reading development (Colé et al., 2014; Morgan et al., 2019; Schaars et al., 2018). Further, early decoding skills draw upon EFs that are developmentally changing during the time when decoding is typically taught (Cartwright, 2012), and individual differences in these cognitive abilities are predictive of children's academic outcomes (van de Sande et al., 2017; Yeniad et al., 2013).

Cognitive flexibility and beginning decoding. One EF component that is particularly important for beginning word reading is cognitive flexibility, a core executive function that reflects the ability to shift among multiple elements of a task (Diamond, 2013). Cognitive flexibility has been shown to contribute directly to beginning decoding (Cole et al., 2014), beyond vocabulary knowledge and letter-sound knowledge (Cartwright et al., 2019). Beginning readers must consider multiple possible pronunciations of letter strings and process different combinations of known letter-sound pairs. Thus, cognitive abilities support developing word reading by fostering a “set for variability” that enables young readers to use their developing letter-sound knowledge flexibly, in varied situations with different letter combinations (Tunmer & Chapman, 2012b). Set for variability, “the ability to determine the correct pronunciation of approximations to spoken English words” is influenced by children’s vocabulary knowledge, phonemic awareness, and syntactic awareness (Tunmer & Chapman, 2012b). This ability is more limited in children with limited print exposure, alphabet knowledge, and vocabulary. With less vocabulary breadth to draw upon in their mental lexicon, a child is less able to problem solve and apply their set for variability to arrive at a correct word pronunciation.

Children who are poor decoders lack the accumulated orthographic representations that also contribute to set for variability (Ober et al., 2020). As an example, for children who are initially learning to decode, such flexibility would be required when they can read the word *mat* but must shift their knowledge flexibly when they encounter the letters *ma-* in the new word *map*. Pronunciations vary depending on context (e.g., *wind* is pronounced differently in a sentence about a clock than in a sentence about weather conditions). Flexible set for variability predicts beginning decoding skills (Tunmer & Chapman, 2012b). Moreover, instruction that fosters a flexible set for variability in decoding is more effective for improving word reading for at-risk first graders than instruction that does not include attention to flexibility in use of letters and sounds to decode (Savage et al., 2018). These findings suggest children’s early cognitive flexibility might play a positive role in their acquisition of decoding skills. Consistent with these results, Ober et al. (2020) conducted a systematic review of research on EFs and decoding and found a significant positive association between EFs and decoding ranging from r = .28 to .34 (mean age 8.8 years), with a weakening of the association with age.

Inside Encoding

Kindergarten children in the U.S. are also formally introduced to encoding, which requires alphabet knowledge and phonemic awareness (Paige et al., 2018; Schaars et al.). To encode children must segment the sounds in a spoken word, match each sound to letter forms, retrieve the letter forms stored in memory, and confirm the word spelling. Both decoding and spelling are related to fluency with letters, and word spelling underlies both word reading and spelling (see Berninger et al., 2107). Studies describe the contributions of language and cognitive skills to spelling development. In Aram et al.'s (2014) study of preschoolers' early spelling, literacy measures (letter naming, phonemic awareness) explained greater variance in early spelling than cognitive measures (working memory, attention, inhibition control). Although measures of behavioral regulation were not correlated with children's letter naming, they were correlated with early spelling which imposes the encoding demands noted above (see also Shatil et al., 2000). Others have reported that phonological short-term memory (being able to store phonological information in memory) is associated with spelling for beginning spellers (Bradley & Bryant, 1985; Shruhan et al., 2022). Children most rely on memory when they are learning to retrieve the correct letter sequence to spell words, and before they are able to draw upon their orthographic lexicon for word spelling. In our earlier research (Vadasy et al., 2008) examining the long-term growth of reading and spelling skills in students who received supplemental phonics intervention in grade one, we found that while first-grade RAN no longer predicted growth to third grade in letter spelling, it was the only unique significant predictor of third-grade word spelling.

In studies of slightly older students, including poor readers, that examined both reading and spelling outcomes, EF skills were associated with spelling. In Rothlsberger et al.'s (2013) comparison of spelling in preschool and kindergarten children, EF was associated with variance in spelling for the younger but not the older children (after accounting for SES, nonverbal IQ, and vocabulary), suggesting that EF has a greater influence when learning to spell initially requires more effortful processing. In a study by Papadopoulos et al. (2020) of students in grade 2 learning to read in Greek, a more transparent orthography than English, the group of students who were poor readers as well as poor spellers had deficits in phonemic awareness and RAN, as well as working memory. Findings are mixed describing the contribution of EF skills to spelling for older students. In their study of students grades 4-9 with and without learning disabilities, Berninger et al. (2017) found that measures of EF (inhibition, shifting, emotional regulation, and metacognition) were related to written language learning outcomes. However, Holmes et al. (2021), in a study of students with and without ADHD, ages 8-15 years, found that after controlling for phonological processing, EF skills were not uniquely associated with spelling. In summary, there has been less attention given to the relationship between EF skills and early encoding development. The more limited research with a specific focus on the on EF components in early spelling suggests that these cognitive skills play a greater role when children, in particular struggling learners, are initially learning to coordinate the multiple processes required for spelling. The memory and shifting process demands required by both beginning spellers and decoders decrease as they rely more on their orthographic lexicon to read and spell words.

Current Study

In the present study, we examine the effect of this particular EF, cognitive flexibility, on growth in decoding (real and nonsense words) and encoding (spelling letters and words) for young children with very limited letter knowledge. Although positive linkages between EFs and early literacy have been previously established, the prior research has not focused on English-speaking kindergarteners (5- and 6-year olds) who are in the initial stage of their decoding skill development and who have limited incoming alphabetic skills. Further, no studies to our knowledge have examined the extent to which cognitive flexibility (CF, in contrast with other EF processes) explains decoding and encoding gains—or whether the effect of initial CF on skill gains might be compensated for by alphabetic skills—for this younger age group. The present study aims to bridge this gap using data from a pooled sample of two cohorts of kindergarteners with low initial alphabetic knowledge, all of whom participated in a phonics intervention (the results from which showed no significant differences between treatments on any decoding measure). Our research questions for this study are specifically as follows.

1. Does initial CF positively predict lower-skilled kindergarten children's decoding and encoding gains during a phonics intervention, controlling for time period (fall or winter), type of phonics intervention (phonics alone vs. phonics with CF practice), child age, and initial (pretest) vocabulary and alphabetic skills?
2. Is the effect of initial CF on lower-skilled kindergartners' decoding and encoding gains, if any, moderated by initial alphabetic skills, all else held constant? In other words, can higher alphabetic skills—skills that can be taught—compensate for lower initial CF ability?

Methods

Participants

The sample was drawn from extant data for two cohorts of children who took part in one is a series of experiments testing variations in components of an extensive studied evidence based phonics intervention. The pooling of the cohorts specifically allowed us to include a relatively broader range of early alphabetic skills, albeit on the lower end, and also afforded better statistical power for testing our research questions. The researchers' institutional review board (IRB) determined the research was exempt and consent documentation was not required. One cohort was from fall (Sep-Nov, n = 68; Vadasy & Sanders, 2021) and one from winter (Jan-Mar, n = 57; Vadasy & Sanders, under review), both from the same public school from the Pacific Northwest, U.S.; combined, the two cohorts included N = 125 lower-skilled children from 23 kindergarten classrooms (21 overlapping).

Recruitment and assignment. Students were those identified by the school for the study based on the school's literacy screening for alphabet knowledge, and subsequent teacher confirmation and referral. For these children, the school sent home a parent information letter in English and in the three other major languages spoken in the district (Spanish, Ukrainian, and Vietnamese). Teachers then informed us of any parents who chose to opt out. Students were considered eligible for study participation if they knew fewer than eight of the taught letter sounds at pretest, although most student knew fewer than three sounds (measure description forthcoming). For each cohort, students were randomly assigned within classrooms to one of two phonics interventions delivered individually to students over a six-week period (treatment content description forthcoming). As noted, brief experiments were planned to pilot test benefits of malleable factors (GPC size, rate of introducing GPCs, embedded CF practice) to increase responsiveness to phonics interventions. Attrition due to chronic absences or moving from the school before posttesting included five students (7% of the original sample) in the fall cohort and two (3% of the original sample) students in the winter cohort. One student in the fall cohort was missing three of the posttests due to an absence but was included in analyses. Notably, in the winter cohort, there were nine students (13% of the original sample) who missed the last week of the intervention as well as all posttesting due to the Covid-19 pandemic; these students were excluded from analyses. Further, again due to the pandemic cutting testing short and the order of the spelling measures being last in the test battery, four students were missing one of the spelling measures and two were missing both spelling measures; however these six students are included in analyses. Figure 1 illustrates study recruitment, assignment, and attrition by cohort. [Figure 1 here]

Prior study results. In two earlier studies we reported the findings separately for the fall and winter cohorts (Vadasy & Sanders, 2021, under review). While children in both treatment conditions for each cohort made significant pretest-posttest gains, the findings comparing treatments were largely null, with conditional treatment differences on encoding (spelling) skills gains in the fall cohort favoring the simpler Plain treatment (Vadasy & Sanders, 2021) and no differences between conditions on decoding or encoding (spelling) skills gains in the winter cohort (Vadasy & Sanders, under review). Nevertheless, in all analyses for the present study, we control for treatment differences statistically.

Sample characteristics. Our pretesting occurred in September for the fall cohort and December for the winter cohort. Students in the fall cohort averaged *M* = 1.43 letter names (*SD* = 1.50) and *M* = 0.34 letter sounds (*SD* = 0.66) at pretest, and those in the winter cohort averaged *M* = 9.11 letter names (*SD* = 2.85) and *M* = 2.49 letter sounds (*SD* = 2.26) at pretest. Our definition of "lower-skilled" thus aligns with Piasta et al.'s (2012) study of letter naming benchmarks which identified the benchmark of 10 or more letter names at the end of preschool (i.e., before kindergarten) to be associated with a trajectory of literacy success.

Table 1 reports sample demographic characteristics by cohort and treatment condition. Across cohorts, the sample included 49 girls (39%), 24 (19%) children of color, 38 (30%)

emergent bilingual (EB) children (i.e., whose families spoke a language other than English in the home), and nine children identified for special education services (7%). Children in the sample represented a total of 11 home languages, with the five most frequent being English (48%), Spanish (31%), Ukrainian (7%), Vietnamese (5%), and Russian (3%). Within cohorts, there were no demographic differences between treatment conditions, and the only difference between cohorts was that there were significantly more EB children in the winter cohort (46%) compared to fall (18%) (multilevel logistic model coefficient *z*-test $p < .001$). This said, we note that many public schools are not able to identify EB children as early as fall of kindergarten due to district testing procedures, and this may explain the cohort difference. In our analyses for the present study, we control for cohort differences. [Table 1 near here]

Table 2 reports sample age and test descriptive statistics by cohort and treatment condition. With respect to age and pretests, the winter cohort was older than the fall cohort and was significantly higher than the fall cohort on alphabetics and cognitive flexibility (multilevel linear model coefficient *t*-test *p*-values < .05)[1]. With respect to pretest-posttest gains, the winter cohort also had greater growth on all outcomes except letter spelling (multilevel linear model coefficient *t*-test *p*-values < .05). (Measure descriptions are forthcoming.) Again, in all analyses for the present study, we control for cohort differences statistically. [Table 2 near here]

Treatment content. As mentioned above, children in both cohorts in this sample were randomly assigned within classroom to one of two explicit, systematic phonics treatments called "Plain" and "Flex." Each treatment included ten similar brief activities often used to teach letter

[1] We also tested whether there were treatment differences or interactions with cohort on all baseline measures (including both predictor and outcome measures used in our models). Two-level results showed no significant treatment differences or interactions with cohort (*p*s > .50); however, there remained significant differences (*p*s < .05) on all but two measures (nonsense word reading and spelling), and for these latter measures, there was a trend for cohort differences (*p*s < .10); on all measures winter cohort averaged higher than fall.

sounds, phoneme segmenting, and phoneme blending (i.e., synthetic phonics) and encoding. For both, trained research assistants recruited from the community delivered scripted instruction to children individually in 20-minute sessions.

Both treatments featured a rate for introducing and teaching grapheme-phoneme correspondences (GPCs) tested in an earlier study (Vadasy & Sanders, 2020). The focus in the "Plain" treatment lessons was practice matching printed letters and sounds and application to decoding (sounding out letters and blending to form words) and encoding. The "Flex" lessons additionally included brief practice switching naming letter names or sounds, building automatic naming of mixed names and sounds, and sorting words. Flex lessons incorporated practice in flexible thinking and inhibitory control within the phonics activities. We estimate that the unique phonics activities in the Flex lessons made up on average 5 minutes of each session during which the Plain lessons offered typical phonics practice.

Instruction in both treatments was conducted in English, and treatments were comparable in time and intensity. The GPC content in both treatments included 13 correspondences (a, s, t, oo, c, m, b, i, o, ee, p, sh, d). Single- and two-letter GPCs introduced students to knowing different combinations of letters used for English decoding and spelling. GPCs were chosen based on frequency and to allow us to create a group of words for decoding and spelling practice. The rate for introducing the correspondences in each week of the intervention was: 4, 2, 2, 2, 2, 1. Children in both conditions practiced immediately applying knowledge of taught correspondences to decoding and spelling tasks. Researchers conducted formal treatment fidelity observations of each student and tutor. Greater detail on design of phonics content for the lessons, treatment implementation and fidelity can be found in Vadasy and Sanders (2021).

Measures

Students were assessed individually by trained testers who were not the RAs delivering instruction and who were unaware of treatment assignment. Testing took place in a quiet space in the school, over two sessions to minimize student fatigue. (As previously noted, one student in the fall cohort was missing some of the posttests, and a handful of students in the winter cohort were missing posttest spelling because of the onset of the Covid-19 pandemic.) Each measure is described below, along with sample-based reliability (internal consistency) estimates across cohorts (for all measures except the cognitive flexibility measure, we used KR-20, which is a special case of Cronbach's alpha for binary items; for the cognitive flexibility measure, we used Cronbach's alpha).

Predictors

Receptive vocabulary. Receptive vocabulary was measured at pretest only for the purpose of describing the sample using the *Peabody Picture Vocabulary Test* (PPVT-4) (Dunn & Dunn, 2006). Reliability reported in the test manual is .97 for 5-year-olds; our sample reliability was estimated at .98. Raw scores were used for analyses.

Alphabetics. For letter names and sounds separately, the tester presented a printed sheet of the 13 letters taught during the intervention. Letters were arrayed in four rows of three to four items per row. Students first completed two practice items with untaught letters. The tester directed the student to point and say the name (or sound) for each item, with 5 seconds allowed for each item. If the student said the sound for the name (or vice versa), the tester prompted the student, "Yes, that's the sound, what is the name." The tester recorded 1 or 0 for each response, with a maximum score of 13 per task, or 26 total. Sample reliability was .92. Percent correct out of 26 was used for analyses.

Cognitive flexibility. A multiple classification task used in previous research to assess domain-general cognitive flexibility (Cartwright, 2002) was adapted in this study for younger children with limited language skills. Specifically, the adapted task included three sets of picture cards used for one demonstration sort, and two test sorts. Materials for each sort were a set of 12 picture cards. The demonstration set included six fruits (three yellow and three red) and six flowers (three yellow and three red). The first test sort included six dogs (three gray and three brown) and six bugs (three gray and three brown). The second test sort included six shirts (three green and three orange) and six pants (three green and three orange). For the demonstration sort, the tester named each picture, had the child repeat the word, and showed the child how to make two piles of fruits and flowers. After shuffling the cards, the tester showed the child how to make two piles of yellow and red things. Then the tester showed how to sort the cards by two dimensions on the 2 X 2 matrix, explained the sort, gave the cards to the child and asked the child to try to sort on the grid. If the child was unable to sort correctly, the tester demonstrated and explained the correct sort. For the two test sorts, the tester handed the child the set of shuffled cards, and began timing when the child looked at the first card. The tester named each picture as the child moved the card, and stopped timing when the child placed the last card. The tester recorded whether the sort was correct, the type of errors, and the total sort time. If the child's sort was correct, the tester asked the child to explain the sort, and recorded if the explanation was correct, and the type of errors. If the child explained only one dimension, the tester asked "Anything else?" If the child provided a one-pile-at-a-time explanation, the tester asked, "In what two ways did you arrange them?" If the child's sort was incorrect, the tester arranged the cards correctly and asked, "Why would we put them this way." The total score was 1 point for a correct sort and 2 points for a correct explanation, for a total of 3 points possible per block. For analyses, we computed the total percent correct across the two blocks (out of 6 points).

Messer et al. (2016) found significant correlations between a very similar task (non-verbal switching) and rapid naming speed and other EFs. The Cronbach's alpha for the original task was reported previously with older children as .86 - .90 (Cartwright, 2002, Cartwright et al., 2010). In the present study, Cronbach's alpha was .72 (treating each block total score, with a maximum of 3 points each, as an item); in addition, we computed the correlation between the two blocks at .58 using Pearson's r and .47 using Kendall's tau (ps < .001).

Decoding Outcomes

Word reading. Students read 16 CVC words constructed to test student skill to apply knowledge of taught letters that appeared in initial, medial, or final word positions. The tester first administered two practice items, demonstrating pointing to the word, blending, and reading the word fast as students learned to do in the intervention. The words were presented on a sheet in two columns. The tester directed the student to point to each word and read down each column, allowing 5 seconds per word. If the student correctly said each of the sounds within 5 seconds but did not blend the sounds, the tester prompted once to "Say it fast" and allowed 5 seconds for students to read the word. The tester recorded 1 or 0 for each response, with a total score of 16. Sample reliabilities were .74 and .94 at pretest and posttest. The difference in the percent correct at pretest and posttest was used for analyses. As noted in Figure 1, one child in the fall was missing this posttest.

Nonsense word reading. Students read a list of 15 VC or CVC nonwords composed of taught letters to test student skill applying letter knowledge to decoding. The tester first administered two practice items demonstrating pointing to each letter, blending the sounds, and reading the word. The tester then directed “Point and read” and 5 seconds were allowed for each word. The tester recorded 1 or 0 for each response, with a total score of 15. Pretest and posttest sample reliabilities were .53 and .94, respectively. (As can be seen in Table 2, the task was somewhat difficult for children at pretest.) The difference in the percent correct at pretest and posttest was used for analyses.

Encoding Outcomes

Letter spelling. For each of the taught letters, the tester dictated the taught sound for the student to write. The tester reminded the student that sometimes one letter makes the sound, sometimes two letters make the sound. Two practice items with untaught letters (z and wh) were first administered. The tester dictated each sound, and repeated the sound once, allowing 5 sec for each letter. If the student wrote only one letter of a two-letter sound, the tester prompted “This is a two-letter sound, write both letters that make this sound.” If the student wrote two letters for a one- letter sound, the tester prompted “This is a one-letter sound.” The tester recorded 1 or 0 for each response, with a maximum score of 13. Sample reliabilities were estimated at .89 and .90 at pretest and posttest, respectively. The difference in the percent correct at pretest and posttest was used for analyses. As noted earlier, one child in the fall cohort and four children in the winter cohort were missing this posttest.

Word spelling. A set of 16 CVC words used to test spelling featured taught letters that appeared in initial, medial, and final word positions. The tester dictated each word, and repeated the word once upon request, allowing 5 seconds per word. The tester recorded 1 or 0 for each response, with a total score of 16. Sample reliabilities were .87 and .96 at pretest and posttest, respectively. The difference in the percent correct at pretest and posttest was used for analyses.

Similar to the letter spelling posttest, one child in the fall and six children in the winter cohort were missing this posttest.

Analysis Plan

Pretest-posttest gains as outcomes. We modeled pretest-posttest gains, rather than posttests, because we were interested in predicting growth in children's skills. The statistical concern with modeling gain scores is that they can be less reliable (i.e., have more measurement error) than posttests. However, modeling gain scores yields the same predictor effect results as modeling posttests as long as pretests are also included in the model, analogous to modeling residualized change (e.g., Petscher, & Schatschneider, 2011). In the present study, we include each measure's corresponding pretest in our models[2].

Data structure. Due to the nesting of children (level 1, $n = 125$) within classrooms (level 2, $n = 23$), and the expectation that classroom learning environment as well as non-random assignment of children to classrooms would naturally induce dependencies among children's scores within their classrooms, we modeled pretest-posttest gains using multilevel modeling. As an empirical check, intraclass correlations (ICCs) were computed using models that only included cohort (otherwise an "empty" model). The ICCs on pretests were close to zero, and the ICCs on pretest-posttest gains ranged from .03 to .07 (*Median* = .04), indicating that classroom membership explained an average of 4% of the variance in children's decoding and spelling growth. As an added check on the appropriate nesting structure for the data, we also computed

[2] As a robustness check, we also conducted 2-level models of posttest scores, controlling for pretest (i.e., in an ANCOVA-like fashion) using the same model specifications as our forthcoming pretest-posttest gain score models. The predictor effect results were identical to our forthcoming model results, except that word spelling pretest did not significantly predict word spelling posttest ($p = .187$) the way it predicted pretest-posttest gain ($p < .001$). This difference, however, does not change the substantive findings discussed in the Results section.

the ICCs using tutors instead of classrooms and found that tutors only explained an average of 1% of the variation in children's gains (and explained no variance in pretests).

Predictor selection and coding. Our research questions are focused on the unique effects of children's initial cognitive flexibility (CF) on their decoding and encoding gains, and the potential joint effect of initial CF and alphabetics, controlling for potential confounds. To that end, our control variables included cohort, treatment condition, child age, pretest receptive vocabulary, and pretest for the measure. We note that we use receptive vocabulary rather than child emergent bilingual (EB) status because EB status was uncorrelated with pretest-posttest gains with the exception of letter spelling whereas receptive vocabulary was substantially and significantly correlated with each pretest-posttest gain; further, receptive vocabulary may also serve as a proxy for EB status given their correlation ($r = -.41$, $p < .001$). For ease of results interpretation, binary predictors were effect-coded and continuous predictors were centered and standardized as *z*-scores.

Model specification. A two-level random intercept linear model was used for each outcome. Our general model was as follows.

$$\text{Pre-PostGain}_{ij} = \gamma_{00} + \gamma_{10}\text{*Cohort} + \gamma_{20}\text{*Cond} + \gamma_{30}\text{*ZAge} + \gamma_{40}\text{*ZVocab} + \gamma_{50}\text{*ZPretest} + \gamma_{60}\text{*ZAlphab} + \gamma_{70}\text{*ZCF} + \gamma_{80}\text{*ZAlphab*ZCF} + U_{0j} + r_{ij}.$$

In the model above, the pretest-posttest gain for the i^{th} student in the j^{th} classroom on a given measure was estimated as a function of the conditional grand mean gain across all students and classrooms (γ_{00}), plus the effects of cohort and treatment condition (γ_{10}-γ_{20}: difference between mean gain for children in the winter cohort and Flex treatment compared to the grand mean gain, respectively), age (γ_{30}: difference in gain between one standard deviation increase in child age and the grand mean gain), receptive vocabulary pretest and corresponding measure pretest (γ_{40}-γ_{50}: changes in gains associated with a one standard deviation increase in pretest vocabulary and in corresponding measure pretest, respectively, alphabetics and CF pretests (γ_{60}-γ_{70}: changes in gains associated with a one standard deviation increase in pretest alphabetics and in pretest CF, respectively, the joint effect of alphabetics and CF on the mean gain (γ_{80}), and finally, the classroom- and student-level residual errors (U_{0j} and r_{ij} respectively). All models were implemented using *R* lme4 (Bates et al., 2015) with full information maximum likelihood estimation (which appropriately handles missingness on the outcomes), and Satterthwaite *df* using *R* lmerTest (Kuznetsova et al., 2017).

Effect size computation. We report model total R^2 for fixed and random effects (Rights & Sterba, 2019) using r2mlm in *R* (Shaw et al., 2020), and also provide an approximate effect size (*ES*) for each predictor by translating the predictor slope coefficient *t*-test values and associated *df* into approximate squared semi-partial correlations (sr^2), computed as t^2*(1-R^2)/*df* (e.g., Cohen et al., 2003, p. 89), where R^2 is the total variance explained by both fixed and random effects. The coefficient *ES* may be interpreted as the approximate percent of variance in pretest-posttest gains uniquely explained by the predictor, holding all other effects constant.

Results

Unadjusted pooled sample descriptive statistics, intraclass correlations, and zero-order correlations among variables used in analyses are provided in Table 3. Table 4 reports model fixed effects results for each outcome; as can be readily seen, the significant intercepts indicate that children made significant growth, on average, on all measures, with the greatest growth on letter spelling (61%) and word reading (33%). [Tables 3 and 4 near here]

Control variable effects. Although cohort, age, and receptive vocabulary were directly correlated with most pretest-posttest gains (Table 3), none were uniquely predictive (Table 4). Indeed, the only control variable uniquely predictive of gains was the letter spelling pretest, which indicated that children who started out one standard deviation higher than their peers were predicted to have 18% less growth; this makes sense given that children who start out with relatively better skills have less room for growth. Despite the lack of unique relationships, the set of control measures, taken together, did account for substantial variance in gains: when we specified a 2-level model with only the control variables (cohort, treatment condition, age, receptive vocabulary, and pretest), results indicated that this set of variables together explained 32% of the variance in word reading gains, 21% of nonsense word gains, 18% of letter spelling gains, and 26% of word spelling gains.

Focal variable effects. The full model (Table 4) with control variables and focal variables (alphabetics, cognitive flexibility, and their interaction) explained 47% of the variance in word reading gains (an increase of 15%), 41% of nonsense word gains (an increase of 20%), 23% of the variance in letter spelling gains (an increase of 5%), and 45% of the variance in word spelling gains (an increase of 19%). Classroom membership (our random effect) uniquely explained 7%, 5%, 13%, and 4% of the variance in gains, respectively, for a total of 54%, 46%, 36%, and 49% explained variance in growth in each of the skills.

Recall that our research questions center on testing the effect of children's initial cognitive flexibility (CF) on decoding and spelling gains, as well as testing whether the CF-growth relationship, if any, is moderated by children's initial alphabetics skills. As shown in Table 4, alphabetics uniquely predicted each of the four skills, and moreover, CF was uniquely predictive of growth in both decoding skills, but not encoding skills. Specifically, children who were one standard deviation higher on CF compared to their peers were predicted to have 8% greater growth in word reading (explaining approximately 7% of the variance in gains) and 12% greater growth in nonsense word reading (explaining approximately 12% of the variance in gains), all else held constant.

In addition to the unique additive effect of initial CF on decoding gains, CF interacted with alphabetics on both measures; in other words, the CF-growth relationship on each of the decoding skills was moderated by children's initial alphabetics skills. We plotted the model-implied relationship between CF and decoding gains for high (+1 *SD*) and low levels (-1 *SD*) of pretest alphabetics, with 95% confidence intervals, with standard error computed from the estimated coefficient variance-covariance matrix elements (Aiken & West, 1991; Bauer & Curran, 2005). [Figure 2 near here] As can be seen in Figure 2, Panels A-B, the positive effect of cognitive flexibility on both decoding measures was greater for children with very low initial alphabetics skills (-1 *SD*, which translates to approximately zero letter names or sounds correct at pretest in our sample). Using the Johnson-Neyman approach (Aiken & West, 1991; Bauer & Curran, 2005), we probed the interactions further to determine the point in alphabetics skills for which the relationship between cognitive flexibility and decoding growth was significant. For word reading, the significant relationship existed for children with alphabetics skills at or below 0.70 *SD*s above average (this translates to 20% correct or less on the alphabetics pretest—about 5 letter names or sounds correct—which includes $n = 89$ children of the 125 in the sample). For growth on nonsense words, cognitive flexibility's effect on growth existed at or below 1.19 *SD*s above average on alphabetics, which corresponds to 25% correct on pretest alphabetics—about 7 letter names or sounds correct ($n = 104$ children in the sample). In other words, cognitive flexibility's effect on decoding growth was observed for the majority of the at-risk students in the sample, but was not significant for children who were less at risk for reading problems (i.e., more than 5-7 letters correctly identified).

Discussion

The current paper examined whether initial cognitive flexibility (CF) had a significant unique effect on at-risk beginning readers' decoding and encoding development during their kindergarten year. Learning these reciprocal skills requires children to become flexible in applying letter-sound knowledge (Tunmer & Chapman, 2012b), to synchronize skills (Saul & Schwartz, 2014), to hold sounds in memory and retrieve them for processing, and to abstract sounds for coarticulation (de Graaff et al., 2009). Children are typically learning these skills while their EF skills are still developing. As anticipated, we found that children's initial CF predicted their word reading and spelling outcomes: for every standard deviation increase in CF, there was an expected 8% gain in word reading, 12% gain in nonsense word reading, and 10% gain in spelling, all else held constant. Moreover, we observed an interaction between initial levels of CF and initial alphabetics skills on children's gains, such that CF was more predictive of gains for children with lower incoming alphabetics, which was most of the sample in this case. However, an alternative way of thinking about this is initial CF has little to no effect for children with better alphabetics – those with more than 5-7 letters identified; in other words, better alphabetics may compensate for CF effects. "Better alphabetics" in the present sample however fell short of Piasta et al.'s (2012) end-of-preschool benchmark of 10 letters that negatively predicted risk on first-grade literacy outcomes.

The results of this study indicate that initial CF may facilitate children's progress acquiring these essential early reading skills, in particular for children with limited alphabet knowledge. Letter sound knowledge is a critical skill that children must learn to coordinate flexibly for successful decoding for both words and nonwords featuring the same taught correspondences (see Compton, 2000). For initial decoders, greater alphabet knowledge increases the success of children's decoding attempts. When alphabet knowledge is limited and slowly developing, children with more developed CF may be better able to draw upon their vocabulary and phonemic skills to decode words, while they continue to acquire more complete letter-sound knowledge. Alphabet learning and decoding present impressive cognitive challenges (Roberts et al., 2018). Children learn these skills at an age when their cognitive flexibility and other executive functions are not yet fully developed (Best et al., 2011). Children without preschool or early literacy preparation enter school with more limited alphabet and vocabulary knowledge to draw upon to read unknown words.

We found that pretest CF uniquely predicted children's growth in word reading but not spelling. The experimenter spelling measure was designed to assess basic transfer of taught GPCs. In this initial stage of kindergarten encoding, alphabet knowledge was the strongest influence. As children need to spell longer and more complex words, EF skills become more important for storing and retrieving more complex GPCs. Studies of older children with poor spelling (grades 2 and 4) in more consistent and orthographically transparent languages than English (Greek and German) describe problems storing orthographic representations in long-term memory (Melhlase et al., 2018; Papadopoulos et al., 2020).

Study limitations warrant discussion. First, the data are drawn from two previous phonics treatment experiments with kindergarteners—which involved mostly null treatment findings—that were pooled as one sample to achieve better statistical power and to represent a broader range of pretest skill levels (albeit on the lower end of the distribution) for testing our research questions. Nevertheless, we controlled for potential cohort and condition differences in all models. In a similar vein, the current study also focuses on a sample of at-risk kindergarteners who (appropriately) received a phonics-based intervention—as such, it is possible that our findings may not generalize to at-risk kindergarteners who do not receive intervention. The experiments were designed to test the influence of factors that might boost responsiveness to an empirically tested explicit synthetic phonics instruction, and therefore the interventions were quite brief. Third, the outcome measures used in the present study were experimenter created to match the taught letter content in the phonics treatments, and there were floor effects on some pretest measures for the fall study in particular. Nevertheless, the sample-based reliabilities were reasonable. Like others who study EF components that are not yet fully differentiated in kindergarten children, we faced measurement challenges (see review by Roebers, 2017). Fourth, we did not include measures of related literacy skills and EF abilities (e.g., phonemic awareness, working memory, inhibition, and rapid naming speed); however, the current study's focus is on the role of CF in early decoding development rather than other theoretically related abilities. Relatedly, we adapted for younger children a previously used CF task as our measure of EF to capture the regulatory demands of orthographic knowledge and decoding. In future studies, multiple CF measures (and other EFs) may better capture the learning demands on these core abilities (Diamond, 2013).

This study concludes a sequence of brief experiments designed to examine how discrete features in supplemental synthetic phonics instruction affect student learning (Vadasy & Sanders, 2020, 2021, under review). In brief interventions in the early experiments we introduced beginning readers to the knowledge that sounds in the English language can be represented by different combinations of letters, single and two-letter GPCs (Vadasy & Sanders, 2020). Later experiments considered whether integrated cognitive flexibility practice, hypothesized to enhance learning, supported initial learning for GPCs and acquisition of decoding, compared to a standard synthetic phonics treatment (Vadasy & Sanders, 2021, under review). Findings from these later experiments indicated no differences in reading or spelling outcomes for the integrated cognitive flexibility treatment compared to the standard phonics treatment. In this study, we combined the cohorts from the later experiments to examine the moderating effects of initial cognitive flexibility and alphabet knowledge on children's decoding and encoding gains. Future research may examine the replication of findings on these instructional features in more intensive typical Tier 2 interventions. Longer interventions would continue introducing children to insights into English orthography, teaching children that some sounds can be represented by different GPCs (e.g., the long a sound in gate, weigh, say), and that some GPCs (e.g., ow) have more than one sound. Future study may also consider whether EFs have a compensatory role, as we found with alphabet knowledge and decoding in this study, in the development of reading fluency, which

Instructional Implications

With respect to early reading instruction, an overarching question is "What are the necessary skills and understandings children need to become skilled readers?" In this study we sought to understand cognitive influences and learning mechanisms that may better help children who struggle with even the most explicit phonics instruction (Seidenberg et al., 2020). Findings suggest that kindergarten children identified at risk for reading difficulties may benefit from reading interventions that account for individual differences in cognitive abilities that influence learning to decode. However, our approach to embed EF practice (as CF) in a phonics intervention did not improve reading outcomes beyond phonics instruction alone (Vadasy & Sanders, 2021; under review). Further, in the present study, we found that higher alphabetic skills buffered the CF-decoding relationship for children. As others have recommended, the benefits of early versus late acquisition of alphabet knowledge warrants developing alphabet knowledge in pre-kindergarten (Carr et al., 2020; Ritchey & Speece, 2006). The instructional press in kindergarten for children to establish emergent literacy skills, including decoding and encoding, implies that pre-kindergarten instruction should include intentional development and monitoring of children's alphabet knowledge (Carr et al., 2020). Additionally, despite our previous studies' lack of CF training effects with kindergarteners (Vadasy & Sanders, 2021; under review), pre-kindergarten could be a critical period for also fostering children's general EF abilities, using engaging games and sorting activities (Rueda et al., 2005; Shaul & Schwartz, 2014; Thorell et al., 2008). Early literacy technology such as apps may be well suited for this role.

Conclusion

Previous research has repeatedly demonstrated the benefits of explicit phonics instruction for children at risk for reading difficulties, yet many children continue to struggle learning critical foundation skills in word reading (Blachman et al., 2014; Vaughn et al., 2020). Studies on field-based early reading interventions less often take into account individual differences in executive functioning (Seidenberg et al., 2020), and others have suggested that both reading related cognitive abilities (e.g., rapid naming speed) and print knowledge (alphabet, phonemic awareness) influence successful early reading (Compton, 2000; Vellutino et al., 1996). In the present study, we found that individual differences in cognitive flexibility, one form of executive functioning, was positively associated with differences in learning to decode and spell for kindergarteners with limited alphabetic skills, all of whom had been part of a 6-week, phonics-based instructional intervention. This may signal that, for at-risk children with less fully developed cognitive flexibility, learning critical early reading skills may be more difficult, even when receiving explicit literacy instruction.

Finally, while it may not be realistic to enhance executive function abilities through targeted intervention during kindergarten, it is well within reach to help all children attain recommended alphabet benchmarks, which we found to be the stronger predictor of decoding and spelling gains in the current study.

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Table 1

Sample Demographic Characteristics by Cohort (Unadjusted for Classroom)

	Fall Cohort						Winter Cohort						Grand Total	
	Flex *n* = 33		Plain *n* = 35		Total *N* = 68		Flex *n* = 29		Plain *n* = 28		Total *N* = 57		*N* = 125	
Characteristic	*n*	*(%)*	*N*	*(%)*	*n*	*(%)*	*n*	*(%)*	*n*	*(%)*	*n*	*(%)*	*n*	*(%)*
Female	13	(39%)	19	(54%)	32	(47%)	7	(24%)	10	(36%)	17	(30%)	49	(39%)
Child of Color	3	(9%)	6	(17%)	9	(13%)	8	(28%)	7	(25%)	15	(26%)	24	(19%)
Emergent Bilingual	7	(21%)	5	(14%)	12	(18%)	12	(41%)	14	(50%)	26	(46%)	38	(30%)
Special Education	2	(6%)	1	(3%)	3	(4%)	1	(3%)	5	(18%)	6	(11%)	9	(7%)

Note. *N* = 125 children from 23 classrooms at one school. No significant differences between treatment conditions within cohorts; the only significant difference between cohorts was on percent of emergent bilingual children (Winter > Fall).

Table 2

Sample Descriptive Statistics by Cohort and Condition (Unadjusted for Classroom)

	Fall Cohort						Winter Cohort					
	Flex *n* = 33		Plain *n* = 35		Total *N* = 68		Flex *n* = 29		Plain *n* = 28		Total *N* = 57	
Variable	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*
Pretest												
Age (Years)	5.67	(0.48)	5.63	(0.49)	5.65	(0.48)	5.88	(0.38)	5.87	(0.36)	5.87	(0.37)
Recept Vocab (raw)	62.97	(26.69)	62.37	(25.96)	62.66	(26.12)	75.48	(33.31)	76.68	(22.48)	76.07	(28.26)
Alphabetics %	3%	(3%)	4%	(4%)	3%	(3%)	23%	(8%)	22%	(9%)	22%	(9%)
Cog Flex %	5%	(14%)	7%	(16%)	6%	(15%)	18%	(29%)	13%	(21%)	16%	(25%)
Word Reading %	0%	(0%)	0%	(0%)	0%	(0%)	2%	(5%)	2%	(7%)	2%	(6%)
Nonword Reading %	0%	(0%)	0%	(1%)	0%	(1%)	1%	(3%)	1%	(4%)	1%	(3%)
Letter Spelling %	1%	(4%)	2%	(6%)	2%	(5%)	34%	(27%)	29%	(25%)	32%	(26%)
Word Spelling %	0%	(0%)	0%	(0%)	0%	(0%)	3%	(10%)	1%	(5%)	2%	(8%)
Pretest-Posttest Gain												
Word Reading %	11%	(19%)	20%	(28%)	16%	(24%)	54%	(32%)	48%	(31%)	51%	(32%)
Nonword Reading %	15%	(21%)	21%	(30%)	18%	(26%)	44%	(38%)	44%	(35%)	44%	(36%)
Letter Spelling %	63%	(30%)	68%	(32%)	66%	(31%)	55%	(22%)	54%	(21%)	54%	(21%)
Word Spelling %	9%	(22%)	19%	(33%)	14%	(28%)	50%	(35%)	42%	(37%)	46%	(35%)

Note. N = 125 children from 23 classrooms at one school, with some posttest data missing for one child in the fall cohort and six children in winter cohort. Recept Vocab = Peabody Picture Vocabulary Test-4 raw score; Alphabetics = taught letter names and sounds percent correct out of 26 possible; Cog Flex = cognitive flexibility as measured by Color Card Sort percent correct out of 6 points; Word Reading = 16 words with taught letters percent correctly read; Nonword Reading = 15 nonsense words with taught letters percent correctly read; Letter Spelling = 13 taught letter sounds percent correctly spelled; Word Spelling = 16 cvc dictated words with taught letters percent correctly spelled. The only significant differences between treatments was on spelling growth for the fall cohort only (Plain > Flex). Cohorts significantly differ on nearly all measures (Winter > Fall, except letter spelling growth where Fall > Winter).

Table 3

Pooled Sample Descriptives and Zero-Order Correlations (Unadjusted for Classroom)

Variable	*N*	*ICC*	*M*	*SD*	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.
Sample																		
1. Cohort (1 = Winter)	125	--	0.46	(0.50)	--													
2. Condition (1 = Flex)	125	--	0.50	(0.50)	.02	--												
Pretest																		
3. Age (Years)	125	.00	5.75	(0.45)	**.25**	.04	--											
4. Recept Vocab (raw)	125	.00	68.78	(27.82)	**.24**	.00	-.01	--										
5. Alphabetics %	125	.00	0.12	(0.11)	**.83**	.02	**.23**	**.39**	--									
6. Cog Flexibility %	125	.00	0.10	(0.21)	**.23**	.02	.14	**.33**	**.33**	--								
7. Cog Flex X Alphab	125	--	--	--	.11	.17	.07	**.21**	**.21**	**.57**	--							
8. Word Reading %	125	.02	0.01	(0.04)	**.24**	-.03	.01	.05	**.36**	.13	**.21**	--						
9. Nonword Reading %	125	.00	0.00	(0.02)	.15	-.04	-.01	-.12	**.24**	-.02	.02	**.32**	--					
10. Letter Spelling %	125	.00	0.16	(0.23)	**.64**	.05	.14	**.34**	**.80**	**.36**	**.53**	**.39**	**.20**	--				
11. Word Spelling %	125	.00	0.01	(0.05)	.17	.08	.01	.06	**.30**	**.23**	**.37**	**.63**	**.30**	**.35**	--			
Pretest-Posttest Gain																		
12. Word Reading %	124	.04	0.32	(0.33)	**.53**	-.01	**.19**	**.26**	**.65**	**.34**	.10	.18	.19	**.62**	.16	--		
13. Nonword Reading %	125	.03	0.30	(0.34)	**.39**	-.04	**.24**	**.23**	**.55**	**.41**	.13	**.26**	.15	**.59**	**.26**	**.87**	--	
14. Letter Spelling %	120	.07	0.54	(0.21)	**-.21**	-.06	-.04	-.10	**-.22**	-.06	**-.19**	-.17	-.03	**-.40**	-.17	.08	.02	--
15. Word Spelling %	118	.03	0.28	(0.35)	**.46**	.01	**.19**	**.28**	**.61**	**.41**	**.18**	**.21**	.14	**.67**	.13	**.82**	**.79**	-.02

Note. *N* = 125 children from 23 classrooms at one school, with some posttest data missing for one child in the fall cohort and six children in winter cohort. Cohort = Cohort status (1 = Winter, 0 = Fall); Condition = Treatment condition status (1 = Flex, 0 = Plain); Age = child age at pretest (in years); Recept Vocab = pretest Peabody Picture Vocabulary Test-4 raw score; Alphabetics = pretest taught letter names and sounds percent correct out of 26 possible; Cog Flex = pretest cognitive flexibility as measured by Color Card Sort percent correct out of 6 points; Word Reading = 16 words with taught letters percent correctly read; Nonword Reading = 15 nonsense words with taught letters percent correctly read; Letter Spelling = 13 taught letter sounds percent correctly spelled; Word Spelling = 16 cvc dictated words with taught letters percent correctly spelled. ICC = intraclass correlation = percent of variance in the variable explained by classroom membership. Pearson's correlation reported with significant values (at the .05 level, 2-tailed) boldfaced.

Table 4

Multilevel Model Fixed Effects Results Predicting Pretest-Posttest Gains

	Decoding Pretest-Posttest Gain						Encoding (Spelling) Pretest-Posttest Gain					
	Word Reading			Nonword Reading			Letter Spelling			Word Spelling		
Parameter	*Coeff*	*(SE)*	*ES*	*Coeff*	*(SE)*	*ES*	*Coeff*	*(SE)*	*ES*	*Coeff*	*(SE)*	*ES*
Intercept (Mean Gain)	0.33	(0.03) ***		0.31	(0.03) ***		0.61	(0.03) ***		0.29	(0.03) ***	
Cohort (1 = Winter)	-0.02	(0.04)	.00	-0.08	(0.04)	.01	-0.04	(0.04)	.01	-0.07	(0.05)	.01
Condition (1 = Flex)	0.00	(0.02)	.00	-0.01	(0.02)	.00	-0.01	(0.02)	.00	0.00	(0.02)	.00
Age (Z)	0.02	(0.02)	.00	0.04	(0.02)	.02	0.00	(0.02)	.00	0.02	(0.02)	.00
Recept Vocab (Z)	-0.01	(0.02)	.00	-0.01	(0.03)	.00	-0.01	(0.02)	.00	-0.01	(0.03)	.00
Measure Pretest (Z)	-0.02	(0.02)	.00	0.01	(0.02)	.00	-0.18	(0.04) ***	.15	-0.04	(0.03)	.01
Alphabetics (Z)	0.22	(0.04) ***	.10	0.21	(0.05) ***	.09	0.13	(0.05) *	.04	0.26	(0.05) ***	.13
Cog Flex (Z)	0.08	(0.03) **	.03	0.12	(0.03) ***	.07	0.05	(0.03)	.02	0.10	(0.03) **	.04
Alphab*Cog Flex	-0.05	(0.02) *	.02	-0.05	(0.02) *	.02	-0.04	(0.02)	.02	-0.03	(0.03)	.00
R^2 Fixed Effects			.47			.41			.23			.45
R^2 Random Intercept			.07			.05			.13			.04
R^2 Total			.54			.46			.36			.49

Note. *N* = 125 children from 23 classrooms at one school, with some posttest data missing for one child in the fall cohort and six children in winter cohort. Cohort = Cohort status, effect coded (1 = Winter, -1 = Fall); Condition = Treatment condition status, effect coded (1 = Flex, -1 = Plain); Age = child age at pretest, in years, standardized; Recept Vocab = pretest Peabody Picture Vocabulary Test-4 raw score, standardized; Measure Pretest = pretest corresponding to measure being modeled, standardized; Alphabetics = pretest taught letter names and sounds percent correct out of 26 possible, standardized; Cog Flex = pretest cognitive flexibility as measured by Color Card Sort percent correct out of 6 points, standardized; Word Reading = 16 words with taught letters percent correctly read; Nonword Reading = 15 nonsense words with taught letters percent correctly read; Letter Spelling = 13 taught letter sounds percent correctly spelled; Word Spelling = 16 cvc dictated words with taught letters percent correctly spelled. All models were 2-level multilevel linear models with random intercepts and fixed slopes estimated using full information maximum likelihood in *R* using lme4 and lmerTest with Satterthwaite degrees of freedom. *ES* = coefficient effect size, calculated as the approximate squared semi-partial correlation = $t^2*(1-R^2)/df$, and can be interpreted as the approximate percent of variance in gains uniquely explained by the predictor. R^2 for the total variance in gains explained by the set of predictors calculated using r2mlm in *R*.
*p < .05, **p < .01, ***p < .001.

Figure 1

Study Recruitment, Assignment, and Attrition Flow Diagram by Cohort

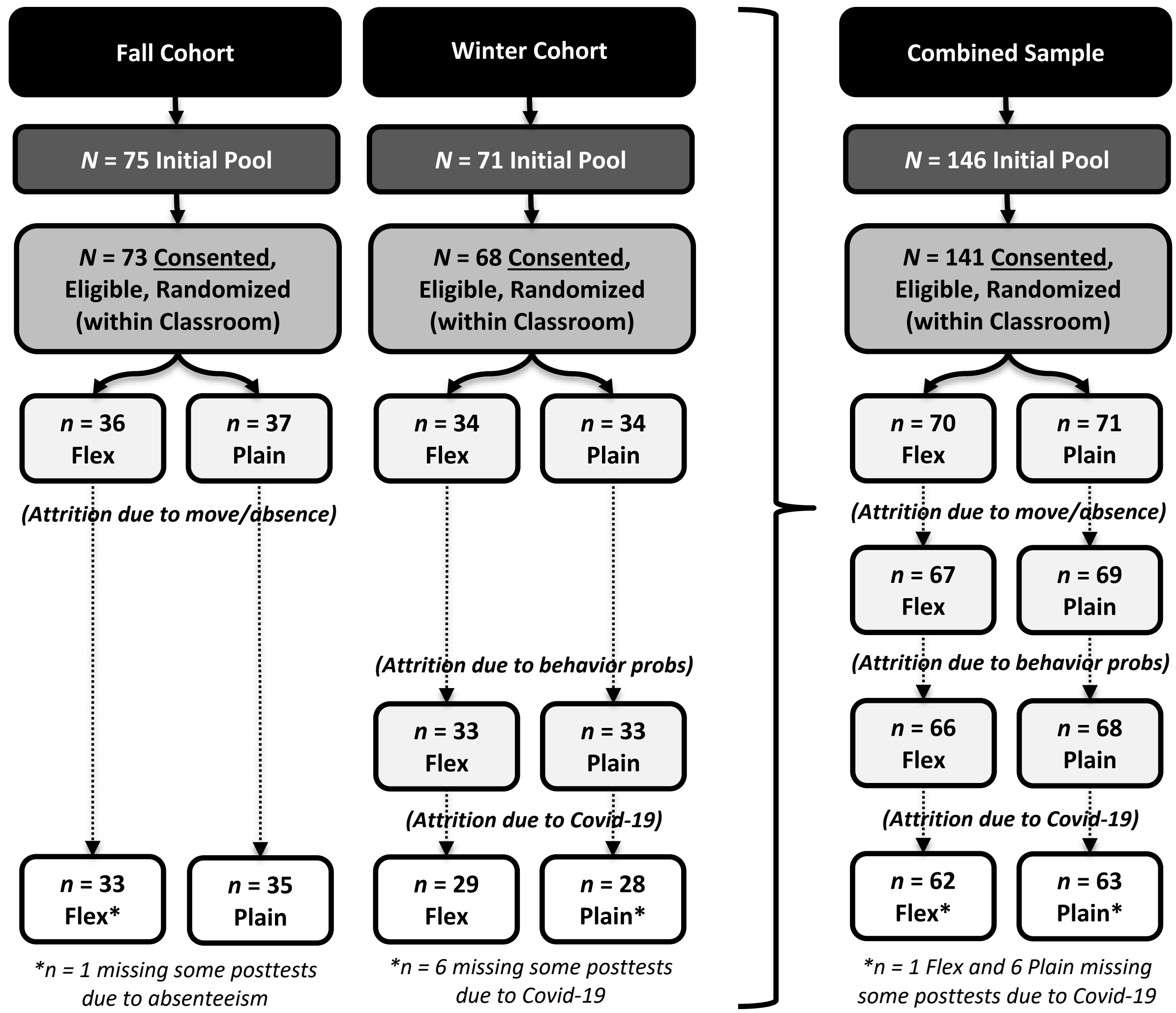
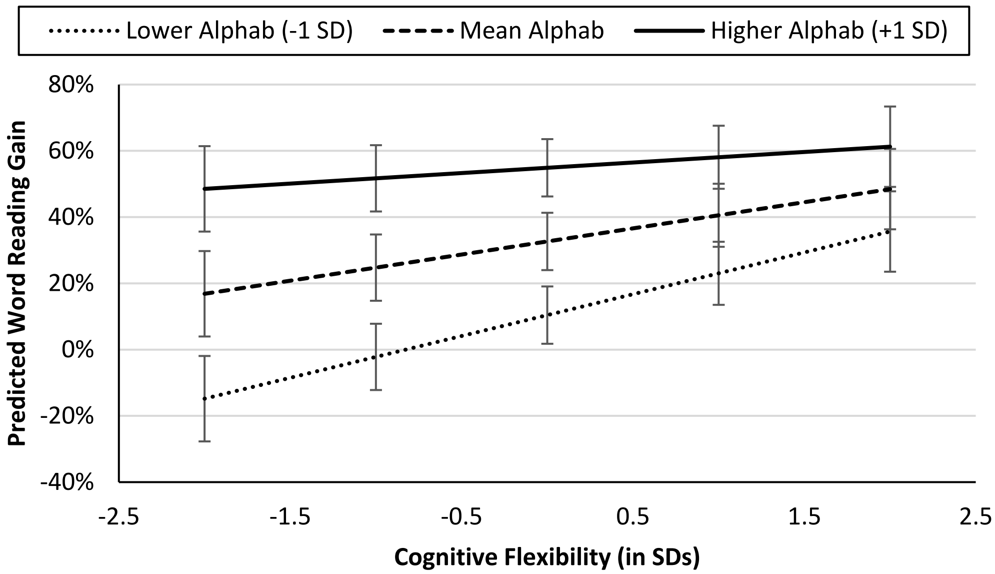


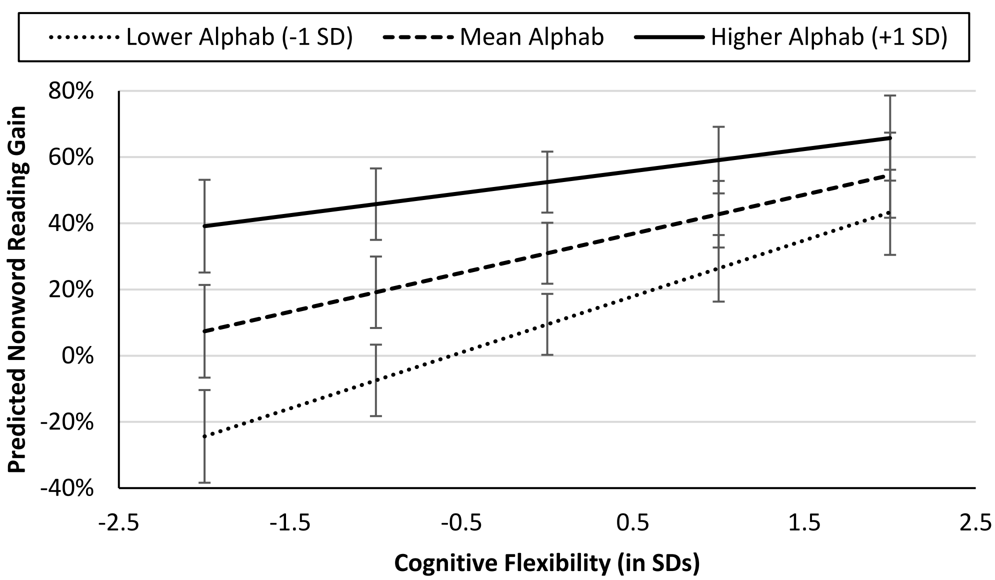
Figure 2

Model-Implied Gains for Selected Pretest Alphabetics and Cognitive Flexibility Levels

Panel A: Word Reading



Panel B: Nonsense Word Reading



Note. Model-predicted point estimates and 95% confidence intervals shown. In Panel A, cognitive flexibility's slope is significant ($\alpha = .05$, 2-tailed) for alphabetic skills at or lower than 0.70 standard deviations above average (approximately 5 letters or fewer known). In Panel B, cognitive flexibility's slope is significant for alphabetic skills at or lower than 1.19 standard deviations above average (approximately 7 letters or fewer known).