The Role of Phonological Memory and Central Executive Function in Children' s Decoding and Language Comprehension Across Grade Levels

Authors: Zhao Xin, Li Hongli, Jin Ge, Li Shifeng, Zhou Aibao, Liang Wenjia, Guo Hongxia, Cai Yaya, Jin' ge

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Abstract

A total of 256 children from grades three to six were selected to investigate the roles of phonological memory and central executive function in decoding and language comprehension across grade levels using correlation analysis and structural equation modeling. The results demonstrated that at lower grade levels, phonological memory and updating significantly predicted decoding, whereas shifting and updating significantly predicted language comprehension; at higher grade levels, only updating maintained a stable predictive effect on decoding. This suggests that phonological memory and central executive function exert differential influences on children' s decoding and language comprehension, and that these influences vary with grade level.

Full Text

The Role of Phonological Memory and Central Executive Function in Decoding and Language Comprehension Among Children of Different Grades

ZHAO Xin[1,2]; **LI Hongli**[2]; **JIN Ge**[3]; **LI Shifeng**[1,2]; **ZHOU Aibao**[1,2]; **LIANG Wenjia**[2]; **GUO Hongxia**[2]; **CAI Ya**

(1 Key Laboratory of Behavioral and Mental Health of Gansu Province, Northwest Normal University, Lanzhou 730070, China)
(2 School of Psychology, Northwest Normal University, Lanzhou 730070, China)
(3 College of Education, Lanzhou City University, Lanzhou 730070, China)

Abstract

This study examined the role of phonological memory and central executive function in decoding and language comprehension among 256 children in grades three through six, using correlation analysis and structural equation modeling. Results revealed that during the lower grade stage, phonological memory and updating significantly predicted decoding, while shifting and updating significantly predicted language comprehension. During the higher grade stage, only updating maintained a stable predictive effect on decoding. These findings indicate that phonological memory and central executive function exert differential influences on children' s decoding and language comprehension, and that these influences change with grade level.

Keywords: phonological memory; central executive function; primary school children; decoding; language comprehension

1 Introduction

Reading comprehension represents one of the most complex and important cognitive activities humans engage in (Kendeou, McMaster, & Christ, 2016). The reading comprehension process relies heavily on individual cognitive resources, with more complex reading material demanding greater cognitive capacity (Christopher et al., 2012; Perfetti & Stafura, 2014). Research has demonstrated that working memory significantly influences the development of reading ability, particularly in fully comprehending reading content (Swanson, 2000). Working memory involves the temporary storage and processing of incoming information, enabling not only short-term retention but also the retrieval of relevant information from long-term memory, which plays a crucial role in complex cognitive activities (Baddeley, 2003). Working memory is a capacity-limited system composed of three distinct subcomponents: the phonological loop, the visual-spatial sketchpad, and the central executive system (Baddeley, 1992).

Phonological memory is defined as the ability to retain phonological information and its associated sequence, representing a component of working memory that involves the phonological loop (Fortier & Simard, 2017). The phonological loop is primarily responsible for encoding, maintaining, and manipulating phonological information, preserving it in short-term phonological storage through phonological coding. It comprises two subcomponents: the phonological store and the articulatory rehearsal process. The phonological store involves the temporary retention of linguistic information (approximately 2 seconds), while the articulatory rehearsal process maintains phonological information through subvocal rehearsal to prevent decay, enabling better preservation of phonological information (Baddeley, Gathercole, & Papagno, 1998). As the core component of working memory, the central executive function primarily coordinates activities between the phonological loop and visual-spatial sketchpad, and manages resource allocation and attentional shifting (Baddeley, 2003).

Numerous studies have identified phonological memory and central executive function as two critical factors influencing reading (García-Madruga, Vila, Gómez-Veiga, Duque, & Elosúa, 2014; Ramus, Marshall, Rosen, & van der Lely, 2013; Sesma, Mahone, Levine, Eason, & Cutting, 2009). Phonological memory serves as the primary channel through which verbal information enters the reading process, participating in both oral input (directly via phonological coding) and text input (which requires conversion from orthography to phonology and semantics), making it essential for reading comprehension (Layes, Lalonde, Mecheri, & Rebaï, 2015). Layes, Lalonde, Mecheri, and Rebaï (2015) investigated the effects of phonological memory and reading-related skills on word reading and reading comprehension, finding that phonological memory predicted children' s word reading ability. Jared, Ashby, Agauas, and Levy (2016) examined the role of phonological memory in semantic activation among fifth-grade children, similarly finding that phonological memory plays an important role in early reading acquisition.

Central executive function coordinates other working memory components and governs attentional control and allocation processes during reading, which proves crucial for children' s reading comprehension (Butterfuss & Kendeou, 2018; Potocki, Sanchez, Ecalle, & Magnan, 2017). Potocki, Sanchez, Ecalle, and Magnan (2017) investigated the role of central executive function in reading comprehension among children and adolescents, revealing that central executive function significantly predicted fifth-grade children' s inferential abilities in text comprehension. Central executive function represents a complex cognitive structure comprising three independent components: inhibition, updating, and shifting (Miyake et al., 2000). Research indicates that different components of central executive function play unique roles in the reading process (Kieffer, Vukovic, & Berry, 2013).

As noted above, phonological memory and central executive function play important roles in reading comprehension. However, no research has directly examined whether these functions exert identical effects across different components of reading comprehension. Reading comprehension itself constitutes a complex process involving word decoding, language comprehension, and syntactic and grammatical analysis (Gough & Tunmer, 1986; Tunmer & Chapman, 2012). According to Gough and Tunmer' s (1986) Simple View of Reading (SVR), decoding (D) and language comprehension (C) represent two core components of reading comprehension. Decoding primarily involves the ability to recognize individual words, while language comprehension involves oral language understanding (Gough & Tunmer, 1986). Previous research on the relationship between working memory and reading comprehension has rarely distinguished between decoding and language comprehension, leaving unclear what specific roles phonological memory and central executive function play in these two components. Therefore, this study primarily examines whether phonological memory and central executive function serve different functions in decoding versus language comprehension.

Previous research has found that phonological memory significantly influences word recognition ability, particularly in semantic activation (Ramus et al., 2013). Phonological memory plays a key role in establishing connections between long-term memory and the phonological forms of word learning, being essential for constructing semantic representations of new words (Gupta & Tisdale, 2009). Studies have also demonstrated that children' s scores on phonological memory tasks better predict their performance in vocabulary knowledge acquisition (Gathercole, Tiffany, Briscoe, & Thorn, 2005). These findings provide strong support for the hypothesis that phonological memory directly influences vocabulary acquisition. Another study indicated that central executive function, as the core component of working memory, is more important for the development of reading coherence and inference (Arrington, Kulesz, Francis, Fletcher, & Barnes, 2014). Research on children with reading difficulties has also found that not all children with reading comprehension difficulties exhibit deficits in both phonological memory and central executive function (Swanson, Zheng, & Jerman, 2009). Children with specific reading difficulties (those without deficits in word recognition) do not show phonological memory deficits (Catts, Adlof, Hogan, & Weismer, 2005; Ramus et al., 2013). However, research suggests that children with specific reading difficulties are potentially limited by working memory capacity (Montgomery, Magimairaj, & Finney, 2010). Furthermore, studies have found that children who read fluently but fail to comprehend may have deficits in central executive function (Sesma, Mahone, Levine, Eason, & Cutting, 2009). Therefore, we hypothesized that phonological memory would be an important predictor of decoding, while central executive function would be an important predictor of language comprehension.

Research has found that adults' reading comprehension relies more heavily on general knowledge application, whereas working memory has a greater impact on children' s reading comprehension ability (Carretti, Cornoldi, De, & Romanò, 2005). Additionally, studies show that the relationship between reading and working memory changes with grade level, initially manifesting as working memory' s influence on reading, and gradually evolving into an interactive pattern between working memory and reading (Peng et al., 2017). Therefore, this study examines the effects of phonological memory and central executive function on children' s decoding and language comprehension, and further explores whether these influence patterns differ across grade levels. A common view of reading acquisition holds that phonological memory is critical for semantic activation in early reading development (Jared et al., 2016). As children progress through early reading instruction, word recognition gradually becomes automatic, and the role of phonological memory in reading diminishes, while working memory capacity directly influences the development of reading comprehension skills (Seigneuric & Ehrlich, 2005). As children accumulate reading experience, the primary task of reading shifts from decoding to comprehension, with background knowledge, grammar, and vocabulary accumulating in long-term memory, and working memory potentially serving to integrate linguistic and experiential knowledge to meet reading comprehension demands (Peng et al., 2017). Central executive function is closely linked to higher-level reading comprehension, including planning, organizing, and monitoring reading information (Cutting, Materek, Carolyn Cole, Levine, & Mahone, 2009). Moreover, research indicates that central executive function is a longitudinal predictor of reading achievement during primary school (Meixner, Warner, Lensing, Schiefele, & Elsner, 2018). Therefore, we hypothesized that as grade level increases, the predictive effect of phonological memory on decoding would gradually weaken, while central executive function, as the core component of working memory, would maintain a stable predictive effect on language comprehension development.

Regarding primary school reading development, researchers have proposed a "six-stage development" theory, where grades one and two represent the 启蒙 stage of reading activities, grades three and four represent the establishment stage, and grades five and six enter the application stage (Dale & Chall, 1948). After progressing through the 启蒙 stage in grades one and two, third-grade students can comprehend word meanings and master basic comprehension strategies for independent reading, making the examination of reading ability at this stage more conducive to understanding the essence of decoding and language comprehension in children' s reading. Therefore, this study investigates third- through sixth-grade children' s performance in decoding, language comprehension, phonological memory, and central executive function through a series of tasks, analyzing relationships among these tasks to test our hypotheses. Specifically, we first assessed children' s decoding ability using Chinese Character Reading, Word Reading, and Pseudo-word Reading tests, and examined their ability to comprehend input linguistic information through a Listening Comprehension test. Second, we assessed phonological memory using Digit Span and Non-word Span tasks, and evaluated subcomponents of central executive function using GO/NOGO, Stroop, Digit Shifting, and Digit Updating tasks. Finally, we tested our hypotheses through correlation analysis and structural equation modeling.

Based on Baddeley' s (1992) working memory theory, Gough and Tunmer' s (1986) Simple View of Reading, and Miyake et al.' s (2000) theory of central executive function subcomponents, combined with our research hypotheses and objectives, we sought to further investigate the role of different central executive function components in decoding and language comprehension. In this study, various task indices of central executive function reflected different cognitive abilities: the interference effect index reflected conflict inhibition ability, the NOGO accuracy index reflected response inhibition ability, and updating accuracy and shifting cost reflected updating and shifting abilities, respectively. Therefore, after controlling for age and general cognitive ability, we constructed our hypothesized theoretical model, shown in Figure 1 [Figure 1: see original paper].

Figure 1 Hypothesized theoretical model of the relationship between phonological memory, central executive function, decoding, and language comprehension. Note: Single-headed arrows indicate predictive relationships; double-headed curves indicate correlations.

2 Method

2.1 Participants

We selected 256 third- through sixth-grade students from a primary school to participate in the study. One student failed to complete all tests and was excluded from data analysis, leaving 255 valid participants (131 boys, 124 girls) aged 8.00–12.83 years (M = 10.06, SD = 1.28). Grade-level distributions are detailed in Table 1 . All participants had normal hearing and vision (or corrected vision), and parental and teacher consent was obtained for all children. Participants received compensation after completing the experiment.

Table 1 Demographic variables of participants (M±SD)

2.2 Measures

2.2.1 Decoding Tests (1) Chinese Character and Word Reading Test
The character and word reading test assesses primary school students' decoding ability (Zhang, 2017). In this study, the test comprised two independent subtests: Chinese Character Reading and Chinese Word Reading. The Character Reading test consisted of 150 Chinese characters arranged from easy to difficult. Children were required to read each character aloud sequentially from top to bottom and left to right. Each correctly pronounced character received 1 point, with the total number of correctly read characters serving as the test score (Song et al., 2015). The internal consistency reliability coefficient for this test in the current study was 0.973.

The Word Reading test was adapted from Xue et al.' s (2013) Chinese character naming test to ensure reliability and validity. Test words were selected based on standard curriculum textbooks and pilot testing, with all words appropriate for grade-level requirements. We initially selected 300 words from the Compulsory Education Chinese Language Curriculum Standard Experimental Textbook (People' s Education Press). Twelve students from each grade (two through six) named these words, and we calculated accuracy rates for each word. Selection criteria required accuracy rates between 0.10 and 0.95. These words were screened based on textbook selection and frequency data, ensuring scientific rigor and reliability. During formal testing, selected words were arranged in descending order of pilot accuracy rates and printed on A4 paper, with 30 words per sheet distributed in a 5×6 grid. Participants were required to accurately read each word without time limits, and the number of correctly read words was recorded. The Cronbach' s coefficient for this test was 0.983, indicating excellent internal consistency.

(2) Pseudo-word Reading Test
The pseudo-word reading test assesses students' mastery of orthography-phonology correspondence rules and serves as another decoding ability index

(Leong, Tse, Loh, & Hau, 2008). Unlike alphabetic languages (e.g., English) that follow a "graphophonemic consistency principle," Chinese operates on an "orthography-phonology consistency principle" (Ho & Bryant, 1997). In alphabetic systems, decoding primarily involves decomposing words into phonological segments corresponding to letters or letter sequences, with each letter having fixed pronunciation standards (e.g., "f" pronounced as /f/). In Chinese, each character represents a morpheme containing two components: one providing phonological information for morpheme pronunciation and one representing the semantic component. For example, the characters "蜂" (bee), "蝶" (butterfly), and "蚊" (mosquito) all share an insect semantic component but have completely different pronunciations. Since Chinese character pronunciation depends primarily on the component providing phonological information (the phonetic radical)—for instance, the "文" component in "蚊" indicates its phonological structure (Ho & Bryant, 1997)—we developed a pseudo-word reading test based on this orthography-phonology consistency principle to examine participants' mastery of orthography-phonology consistency when character sequences are altered.

Test development drew from non-word materials used in non-word span tasks (Wang, Chen, Ma, Sun, & Sun, 2013). Materials combined high-frequency characters from Liu et al.' s (1990) *Modern Chinese Common Word Frequency Dictionary* (e.g., "本" with a frequency of 6,516) with characters from compulsory education textbook vocabulary lists. Pseudo-word test materials were also based on pilot testing results, with all pseudo-words printed on A4 paper in a 5×9 grid. In the pseudo-word reading test, participants were required to correctly read each pseudo-word, including tone pronunciation, without time limits, and the number of correctly read pseudo-words was recorded. This individually administered test required approximately 2 minutes. The Cronbach' s coefficient was 0.926, indicating good internal consistency reliability.

2.2.2 Language Comprehension Test Language comprehension tests typically assess children' s understanding of input sentences and passages through listening comprehension tasks (Tunmer & Chapman, 2012). Our listening comprehension test materials were adapted from Song et al. (2015) and combined with test formats from the HSK (Hanyu Shuiping Kaoshi) examination developed by Hanban/Confucius Institute Headquarters. All materials were recorded in MP3 format by two graduate students majoring in broadcasting (one male, one female). The listening comprehension test comprised two main sections—dialogue comprehension and passage comprehension—to comprehensively assess language comprehension. Except for answer choices presented in text format, all content was delivered auditorily. The dialogue comprehension section included 20 items, each with four options. Participants selected the correct answer after listening to each dialogue, which was presented once. The passage comprehension section consisted of four passages (200–450 characters each), with five comprehension questions following each passage. Participants listened to each passage and then heard each question sequentially, selecting the most appropriate answer from four alternatives. One sample item was presented before the test to familiarize participants with procedures. This group-administered test required approximately 20 minutes. The internal consistency reliability coefficient was 0.777.

2.2.3 General Cognitive Ability General cognitive ability was assessed using the Chinese version of Raven' s Standard Progressive Matrices revised by Zhang and Wang (1989). This test includes 60 items, each presenting a figure with a missing piece. Children selected the option that best completed the figure from six or eight alternatives. The total number of correct responses served as the score. The internal consistency reliability coefficient was 0.862.

2.2.4 Phonological Memory Tests (1) Digit Span Task
The digit span task is a commonly used index for evaluating phonological memory ability (O' Brien, Segalowitz, Freed, & Collentine, 2007). In this task, digits 1–9 were presented auditorily in random order for 1 second each, with sequence length gradually increasing from 2 to 11 digits. Participants immediately recalled digits in order after presentation. Each length included three trials; participants advanced to the next length after two or more correct responses, otherwise testing stopped. The maximum span with three completely correct responses served as the score, with span increasing by 1/3 for one correct response at the next length. The internal consistency reliability coefficient was 0.789.

(2) Non-word Span Task
Non-word span is another task assessing phonological memory (Wang et al., 2013; O' Brien et al., 2007). Similar to the digit span task, this task used meaningless non-words as stimuli. In Chinese research, non-words consist of two characters combined to form a completely meaningless word (e.g., "句芽"). Non-word selection combined high-frequency characters from Liu et al.' s (1990) dictionary while ensuring the two-character combinations were meaningless and avoided phonological associations that might create meaning. Testing procedures and scoring were identical to the digit span task. The internal consistency reliability coefficient was 0.691.

2.2.5 Central Executive Function Tests (1) GO/NOGO Task
The GO/NOGO task assesses response inhibition ability (Zhao, Chen, & Maes, 2018). This task presents GO and NOGO stimuli, requiring participants to respond to GO stimuli and withhold responses to NOGO stimuli, with each type presented at 50% probability. The experiment included two practice blocks (10 GO and 10 NOGO trials each) and four experimental blocks (50 GO and 50 NOGO trials each), totaling 400 trials. Each block began with a 1000 ms fixation cross ("+") at screen center, followed by a 600 ms stimulus, then a blank screen before the next trial. In two experimental blocks, participants pressed "J" for letter X (GO) and withheld response for letter Y (NOGO); the remaining two blocks reversed these contingencies. Practice blocks required 85% accuracy

to advance to experimental blocks. The entire task required approximately 15 minutes.

(2) Stroop Task
The Stroop task assesses conflict inhibition ability (Zhao et al., 2018). Materials included two color words ("红" [red] and "绿" [green]) and a meaningless string ("####"). Participants responded to the ink color of presented characters by pressing "F" for red and "J" for green. The task included three conditions: congruent (red "红" or green "绿"), incongruent (red "绿" or green "红"), and neutral (red "####" or green "####"). Each block began with a 500 ms fixation cross ("+"), followed by 1000 ms blank screen, then a 1500 ms stimulus, and another blank screen before the next trial.

The practice block included 18 trials, requiring 85% accuracy to advance. The experimental phase comprised three blocks, each including 12 trials per condition (36 trials total), for 108 experimental trials total. Primary measures included mean reaction times for incongruent, congruent, and neutral conditions, and interference effects (incongruent RT minus neutral RT). The task required approximately 15 minutes, with rest periods between blocks.

(3) Digit Shifting Task
The digit shifting task assesses shifting ability (Zhao et al., 2018). Participants viewed digits 1-9 (excluding 5) in red or blue. For red digits, they judged whether the number was greater or less than 5 (Task A); for blue digits, they judged odd/even status (Task B). The task included single-task blocks (performing only Task A or B) and mixed-task blocks (performing both tasks). In Task A, red digits 1-9 (excluding 5) were presented sequentially; participants pressed "A" for numbers >5 and "L" for numbers <5. In Task B, blue digits 1-9 (excluding 5) were presented; participants pressed "A" for odd numbers and "L" for even numbers. Two single-task practice blocks familiarized participants with procedures. Participants required 75% accuracy to advance.

The experimental phase included 20 blocks (10 single-task, 10 mixed-task) presented randomly. Single-task blocks included 8 trials; mixed-task blocks included 17 trials, totaling 250 experimental trials. The task required approximately 20 minutes, with rest periods between blocks. Primary measures included mean reaction times for single, non-shift, and shift trials, plus shifting cost (shift RT minus non-shift RT) and mixing cost (mixed-task non-shift RT minus single-task RT).

(4) Digit Updating Task
The digit updating task assesses information updating ability in working memory (Zhao et al., 2018). The task included simple and difficult versions, with digit presentation times of 1750 ms and 750 ms, respectively. Participants completed the simple version first. The task presented series of digits 0–9 in lengths of 5, 7, 9, and 11 digits. Digits appeared sequentially, requiring participants to continuously rehearse presented digits while remembering the last three digits in order. For example, for the sequence 6, 8, 5, 4, 7, 2, participants would re-

hearse 6→68→685→854→547→472, then recall and input the final three digits into black boxes on screen and press spacebar to advance.

The simple version included one practice block (8 trials, two per length) and two experimental blocks (12 trials each, three per length). The difficult version included two experimental blocks (12 trials each, three per length). Mean accuracy for simple and difficult updating tasks served as the updating ability index. The entire task required approximately 20 minutes, with rest periods between blocks.

2.3 Procedure

Reading assessments were administered by class. All 256 third- through sixth-grade participants completed Chinese Character Reading, Word Reading, Pseudo-word Reading, and Language Comprehension tests. Character Reading, Word Reading, and Pseudo-word Reading were individually administered, while Language Comprehension was group-administered. General cognitive ability was assessed using Raven' s Standard Progressive Matrices. All tests were completed in quiet environments. Subsequently, participants completed all phonological memory and central executive function tasks. Digit Span and Non-word Span tasks (individual administration) assessed phonological memory, while GO/NOGO, Stroop, Digit Updating, and Digit Shifting tasks assessed response inhibition, conflict inhibition, updating, and shifting abilities, respectively. All computer-based tasks were completed in a quiet computer lab. Data collection was conducted by psychology graduate students who received professional training on test rules and procedures prior to administration.

2.4 Data Analysis

SPSS 16.0 and AMOS 17.0 were used for descriptive statistics, ANOVA, correlation analysis, and confirmatory factor analysis.

3 Results

3.1 Descriptive Statistics and Difference Tests

Table 2 presents means and standard deviations for decoding, language comprehension, phonological memory, and central executive function tasks by grade. ANOVAs revealed significant differences across grades in general cognitive ability, $F(3, 251) = 3.15$, $p = 0.03$, $^2p = 0.04$. Post-hoc comparisons showed that fifth- and sixth-grade students scored significantly higher than third- and fourth-grade students ($ps < 0.05$). Significant grade differences emerged for Character Reading, Word Reading, Pseudo-word Reading, and Listening Comprehension, with higher grades outperforming lower grades: Character Reading $F(3, 251) = 73.69$, $p < 0.001$, $^2p = 0.47$; Word Reading $F(3, 251) = 90.34$, $p < 0.001$, $^2p = 0.52$; Pseudo-word Reading $F(3, 251) = 50.39$, $p < 0.001$, $^2p = 0.38$; Listening

Comprehension $F(3, 251) = 23.34$, $p < 0.001$, $^2p = 0.22$. Detailed post-hoc results are shown in Table 2.

For phonological memory tests, significant grade differences emerged: Digit Span $F(3, 251) = 4.78$, $p = 0.003$, $^2p = 0.05$, with sixth-grade students outperforming fifth-, fourth-, and third-grade students ($ps < 0.05$); Non-word Span $F(3, 251) = 7.49$, $p < 0.001$, $^2p = 0.08$, with fifth- and sixth-grade students outperforming third- and fourth-grade students ($ps < 0.05$). For central executive function, no significant grade differences emerged for interference effects or shifting cost ($ps > 0.05$). Significant differences appeared for updating accuracy and NOGO accuracy ($Fs > 2$, $ps < 0.05$), with fifth- and sixth-grade students outperforming third- and fourth-grade students on both simple and difficult updating accuracy ($ps < 0.01$), and sixth-grade students outperforming third-grade students on NOGO accuracy ($p < 0.05$).

Table 2 Means, standard deviations, and ANOVA results for decoding, language comprehension, phonological memory, and central executive function tasks by grade

3.2 Correlation Analysis of Phonological Memory, Central Executive Function, Decoding, and Language Comprehension

Correlations among age, general cognitive ability, decoding, language comprehension, phonological memory, and central executive function tasks are presented in Table 3 . Age correlated significantly with both decoding and language comprehension [$r(255) = 0.58$, $p < 0.01$; $r(255) = 0.35$, $p < 0.01$]. General cognitive ability also correlated significantly with decoding and language comprehension [$r(255) = 0.31$, $p < 0.01$; $r(255) = 0.35$, $p < 0.01$]. Phonological memory correlated significantly with decoding [$r(255) = 0.36$, $p < 0.01$] and language comprehension [$r(255) = 0.30$, $p < 0.05$]. Regarding inhibition tests, interference effects did not correlate significantly with decoding or language comprehension [$r(255) = 0.05$, $p = 0.429$; $r(255) = 0.03$, $p = 0.590$]. NOGO accuracy correlated significantly with decoding [$r(255) = 0.15$, $p = 0.018$] and language comprehension [$r(255) = 0.20$, $p < 0.01$]. Updating accuracy correlated significantly with both decoding and language comprehension [$r(255) = 0.48$, $p < 0.01$; $r(255) = 0.47$, $p < 0.01$]. Shifting cost correlated significantly with decoding [$r(255) = 0.18$, $p < 0.01$] and language comprehension [$r(255) = 0.29$, $p < 0.01$].

Table 3 Correlation matrix among decoding, language comprehension, phonological memory, and central executive function tasks ($n = 255$)

3.3 Structural Equation Modeling of Phonological Memory, Central Executive Function, Decoding, and Language Comprehension

We tested our hypothesized model and compared it with a competing model that combined central executive function task indices into a single latent variable. All models were modified based on modification indices, with fit indices shown in

Table 4 . For grades three through six, the modified hypothesized model showed optimal fit (Figure 2 [Figure 2: see original paper]): ^{2} = 18.404, df = 24, ^{2}/df = 0.767, GFI = 0.988, CFI = 1.000, AGFI = 0.962, RMSEA = 0.000, indicating superior fit.

Table 4 Fit indices for structural equation models of phonological processing, central executive function, decoding, and language comprehension

Path analysis revealed significant path coefficients from phonological memory and updating accuracy to decoding (= 0.18, p = 0.008; = 0.25, p < 0.001), indicating that both phonological memory and updating accuracy significantly predicted decoding. Updating accuracy and shifting cost showed significant path coefficients to language comprehension (= 0.26, p < 0.001; = 0.16, p = 0.003), indicating that both significantly predicted language comprehension. Additionally, age and general cognitive ability showed significant path coefficients to both decoding and language comprehension (ps < 0.01).

Figure 2 Modified model of relationships between phonological memory, central executive function, decoding, and language comprehension for grades 3–6. Note: All path coefficients are standardized. Single-headed arrows indicate predictive relationships; double-headed curves indicate correlations. Solid lines represent significant regression paths; dashed lines represent non-significant paths. Only paths with significant correlations are shown.

3.4 Correlation Analysis by Grade Level

To further understand relationships among variables at different grade levels, we divided participants into lower grades (third and fourth) and higher grades (fifth and sixth) and conducted correlation analyses for each group. Results are presented in Tables 5 and 6 .

For grades three and four (Table 5), age did not correlate significantly with any task indices (ps > 0.05). General cognitive ability correlated significantly with decoding and language comprehension [r(158) = 0.25, p < 0.01; r(158) = 0.29, p < 0.01]. Phonological memory correlated significantly with both decoding and language comprehension [r(158) = 0.25, p < 0.01; r(158) = 0.22, p < 0.01]. For central executive function, updating accuracy correlated significantly with decoding and language comprehension [r(158) = 0.36, p < 0.01; r(158) = 0.41, p < 0.01]. Shifting cost correlated significantly only with language comprehension [r(158) = 0.27, p < 0.01]. No other indices correlated significantly with decoding or language comprehension (ps > 0.05).

For grades five and six (Table 6), age correlated significantly only with decoding [r(97) = 0.24, p = 0.020]. General cognitive ability correlated significantly with decoding and language comprehension [r(97) = 0.35, p < 0.01; r(97) = 0.39, p < 0.01]. Phonological memory correlated significantly with decoding [r(97) = 0.30, p < 0.01] but not with language comprehension [r(97) = 0.19, p = 0.069]. No central executive function indices (interference effect, NOGO accuracy) correlated significantly with decoding or language comprehension (ps > 0.05). Updating accuracy correlated significantly with both decoding and language comprehension [$r(97) = 0.41$, $p < 0.01$; $r(97) = 0.31$, $p < 0.01$]. Shifting cost correlated significantly only with language comprehension [$r(97) = 0.24$, $p = 0.020$].

3.5 Structural Equation Modeling by Grade Level

We tested our hypothesized model separately for each grade level group.

For grades three and four, the modified hypothesized model showed optimal fit (Figure 3 [Figure 3: see original paper]): ^{2} = 25.179, df = 24, ^{2}/df = 1.049, GFI = 0.974, CFI = 0.998, AGFI = 0.917, RMSEA = 0.018. Path analysis revealed significant coefficients from phonological memory and updating accuracy to decoding (= 0.19, p = 0.064; = 0.25, p = 0.004), and from updating accuracy and shifting cost to language comprehension (= 0.28, p = 0.001; = 0.16, p = 0.034). General cognitive ability showed a significant path to language comprehension (= 0.15, p = 0.047).

For grades five and six, the initial hypothesized model showed optimal fit (Figure 4 [Figure 4: see original paper]): ^{2} = 13.736, df = 25, ^{2}/df = 0.549, GFI = 0.977, CFI = 1.000, AGFI = 0.927, RMSEA = 0.000. No modification indices were generated, indicating good initial fit. Path analysis revealed non-significant paths from phonological memory to decoding and language comprehension (ps > 0.05). Among central executive function components, only updating accuracy showed a significant path to decoding (= 0.30, $p < 0.01$); all other paths were non-significant (ps > 0.05). Age showed a significant path to decoding (= 0.22, $p < 0.05$), and general cognitive ability showed significant paths to both decoding and language comprehension (= 0.26, $p < 0.01$; = 0.33, $p < 0.001$).

Figure 3 Modified model for grades 3-4. **Figure 4** Initial model for grades 5-6.

4 Discussion

4.1 Effects of Phonological Memory and Central Executive Function on Decoding and Language Comprehension

This study examined the effects of phonological memory and central executive function on children's decoding and language comprehension, and whether these effects differed across grade levels. After controlling for age and general cognitive ability, we found that phonological memory and updating accuracy predicted decoding, while updating accuracy and shifting cost predicted language comprehension.

Our findings demonstrate that phonological memory predicts children' s decoding but not language comprehension, consistent with Oakhill, Cain, and Bryant (2003), who found that phonological memory predicts word reading ability. Phonological memory plays an important role in word reading, primarily involving the construction of letter-morpheme connections (McDougall, Hulme, Ellis, & Monk, 1994). Phonological memory also involves retrieving relevant phonological information from long-term memory, including temporary storage and processing of phonological information (Gupta & Tisdale, 2009). Therefore, phonological memory may facilitate the decoding process, particularly benefiting rapid word reading in automatic contexts without contextual support. Word information is typically stored in activated networks within the verbal system, which may be more conducive to rapid word reading in decontextualized situations (Stuart, 2006).

Compared to phonological memory, central executive function plays a more important role in language comprehension. From a cognitive load perspective, language comprehension is a less controllable process than basic decoding, requiring substantial working memory resources (Peng et al., 2017). The role of phonological memory diminishes during language comprehension, while central executive function, which requires more cognitive resources, may become more important. Research has shown that working memory is more important for higher-level comprehension than for basic word recognition (Savage, Lavers, & Pillay, 2007). We also found that different components of central executive function differentially affected decoding and language comprehension, possibly because different components play unique roles in reading comprehension (Kieffer et al., 2013). This interpretation is supported by Cutting et al. (2009), who found differences among central executive function types in assessing reading comprehension. Research also confirms that not all reading comprehension tasks or questions involve central executive function (Eason, Goldberg, Young, Geist, & Cutting, 2012).

Regarding inhibition, we found that inhibitory control (both conflict and response inhibition) did not affect decoding or language comprehension. Borella, Carretti, and Pelegrina (2010) examined the role of inhibition in different aspects of reading comprehension and found that inhibiting prepotent responses could not explain individual differences in reading comprehension. Christopher et al. (2012) investigated relationships between central executive function and word reading and reading comprehension in 8- to 16-year-olds, finding that inhibition did not affect word reading or reading comprehension after controlling for naming speed and general cognitive ability. They argued that inhibition did not affect reading comprehension because general cognitive ability fully encompassed inhibition, and inhibition lacked specificity in reading comprehension. This suggests that different reading content involves different cognitive abilities, and the effect of inhibitory control on decoding and language comprehension may be influenced by other factors such as general cognitive ability and vocabulary (Christopher et al., 2012).

Updating affected both decoding and language comprehension. Serial processing of reading and text comprehension involves continuous operations and constant updating of working memory (Palladino, Cornoldi, De Beni, & Pazzaglia, 2001). Updating may still play a role in reading individual unrelated words because extensive phonological information about words stored in long-term memory requires constant updating to form effective word recognition (Palladino et al., 2001). Although decoding is the initial reading process, once readers activate word meanings through decoding, they can form linguistic understanding through grammatical structure and syntactic processing (Stuart, 2006). Decoding is the basic process that initiates reading comprehension, while language comprehension involves more cognitive resources and complex processes (Butterfuss & Kendeou, 2018). Updating ability is crucial for reading comprehension because readers must retain relevant information and exclude irrelevant information in working memory to successfully construct a coherent text representation (Butterfuss & Kendeou, 2018). Therefore, updating ability, which requires more cognitive resources, has important effects on language comprehension.

Regarding shifting, we found that shifting ability predicted language comprehension but not decoding. This may be because decoding is a basic, bottom-up process, whereas language comprehension is a higher-level process requiring coordination of bottom-up (lexical) and top-down (pragmatic) processing, which involves attentional shifting skills (Butterfuss & Kendeou, 2018). Research confirms that shifting ability affects language comprehension and the development of higher-level language comprehension skills (Kendeou et al., 2016). Studies also show that attentional shifting directly predicts reading comprehension and indirectly affects reading comprehension through language comprehension ability (Kieffer et al., 2013), indicating that language comprehension mechanisms play an important mediating role in the relationship between shifting and reading. Overall, the correlation between shifting ability and language comprehension likely stems from the need to coordinate multiple knowledge constructions during language comprehension, requiring continuous shifting of knowledge information.

4.2 Effects of Phonological Memory and Central Executive Function on Decoding and Language Comprehension Across Grade Levels

We conducted cross-sectional comparisons of phonological memory and central executive function effects on decoding and language comprehension across grade levels, finding that these effects changed with grade level. From a reading development perspective, reading progresses from decoding individual words to automatic, efficient word recognition, representing a continuous development from "learning to read" to "reading to learn" (Yovanoff, Duesbery, Alonzo, & Tindal, 2005). Seigneuric and Ehrlich (2005) longitudinally examined working memory' s role in reading comprehension, finding developmental changes in its influence across grade levels.

We found that phonological memory's predictive effect on decoding gradually disappeared with increasing grade level. Early word recognition relies more heavily on phonological memory to form orthography-phonology representations, while other reading skills may become more important with grade progression, such as orthographic rules and semantic analysis (Harm & Seidenberg, 2004). For higher-grade students, decoding skills gradually mature and reading functions change, with assessments focusing more on higher-level comprehension abilities (Kendeou et al., 2016). Research also demonstrates that as children' s reading abilities develop, word recognition becomes increasingly automatic, phonological memory's role diminishes, and working memory capacity becomes important for reading comprehension development (Seigneuric & Ehrlich, 2005).

Across grade levels, updating maintained a stable predictive effect on decoding. Updating' s effect on decoding may be achieved by regulating the underlying mechanism of information activation in working memory (Palladino et al., 2001). For lower-grade children in the decoding learning stage, constant updating of memorized information is needed to build richer mental lexicons. For higher-grade students, although decoding becomes more automatic, the broader stored information still requires updating for effective selection and maintenance. Regarding language comprehension, updating lost its predictive effect with increasing grade level. This may be because language comprehension is more complex than decoding, involving sentence processing, grammatical processing, inference, and comprehension monitoring (Sesma et al., 2009). Single updating ability may be insufficient to support all language comprehension processes; vocabulary, background knowledge, inferential ability, and working memory capacity may play more important roles (Kendeou et al., 2016). Van Dyke, Johns, and Kukona (2014) argue that the link between working memory and comprehension exists because working memory is collinear with many other reading skills, particularly intelligence. We also found that general cognitive ability maintained a stable predictive effect on language comprehension across grade levels.

Shifting ability also lost its predictive effect on language comprehension with increasing grade level. Although shifting ability affects language comprehension development, processing strategy use, and rule shifting during child development, as grade level increases and decoding and language comprehension become more mature, general knowledge application becomes more flexible. General knowledge storage and inferential ability may replace shifting ability as more important factors in comprehension. Research confirms that the relationship between working memory and reading comprehension is influenced by mastery of other reading skills, such as grammatical skills, pragmatic processing skills, and comprehension monitoring ability (Kendeou et al., 2016), suggesting that the relationship between working memory and reading undergoes a dynamic, interactive developmental pattern (Peng et al., 2017).

Our findings validate and extend previous research on working memory and reading comprehension, showing that different working memory tasks play different roles in different aspects of reading. Phonological memory is important for early decoding, while different components of central executive function differentially affect decoding and language comprehension. This suggests that children' s performance on different working memory tasks may predict only specific components of the reading process (Potocki et al., 2017). Moreover, the relationships among phonological memory, central executive function, decoding, and language comprehension differ across grade levels, indicating dynamic developmental changes in the relationship between working memory and reading comprehension (Peng et al., 2017; Seigneuric & Ehrlich, 2005). According to Gough and Tunmer' s (1986) Simple View of Reading, decoding involves individual word recognition ability, which is critical in early reading development and closely linked to phonological awareness and rapid naming ability. Language comprehension involves higher-level reading comprehension ability, which may be closely related to central executive function and general cognitive ability development (Sesma et al., 2009).

Based on our findings, early reading instruction should align with children' s cognitive developmental characteristics. First, lower-grade reading instruction should emphasize developing orthography-phonology consistency ability, promoting decoding skill and phonological awareness development through phonological memory training. Second, higher-grade reading instruction should develop more effective curricula and assessment tools based on the relationship between language comprehension and cognitive development. For example, for children with poor language comprehension, interventions combining cognitive training and language comprehension skill development may be more effective. Finally, we found that general cognitive ability maintained stable predictive effects on language comprehension across grade levels, indicating that general cognitive ability development is also important for reading development. While developing reading-related skills, we should emphasize general cognitive ability development to promote mutual supplementation and enhancement between reading ability and general cognitive ability.

4.3 Limitations and Future Directions

This study integrated previous perspectives and paradigms on working memory and reading comprehension relationships, examining relationships among phonological memory, central executive function, decoding, and language comprehension across grade levels, contributing to deeper understanding of the developmental relationship between working memory and reading components. However, several limitations remain. First, our sample included only typically developing children, lacking research on special populations (e.g., children with decoding difficulties, specific language impairment). Research indicates that different types of reading difficulty may involve different working memory component deficits (Ramus et al., 2013). Future research should examine whether deficits in different working memory subcomponents differ between children with decoding difficulties and those with specific language impairment to clarify relationships between working memory subcomponents and reading-related skills (decoding and language comprehension).

Second, this study used cross-sectional comparison rather than longitudinal tracking of developmental changes in relationships among phonological memory, central executive function, decoding, and language comprehension. Previous longitudinal research on reading comprehension, phonological memory, and working memory found that phonological memory deficits alone cannot explain long-term reading comprehension difficulties, while working memory may have sustained effects (Gathercole et al., 2005). Longitudinal methods would better illuminate dynamic developmental patterns in relationships between working memory and reading comprehension components.

Finally, whether working memory training can improve decoding and language comprehension ability represents an important future research direction. Although research shows that working memory training can improve both working memory and reading ability (Carretti et al., 2017; Loosli, Buschkuehl, Perrig, & Jaeggi, 2012), few studies have examined effects on different reading comprehension components. Future research should investigate the role of working memory training in decoding and language comprehension, including transfer and maintenance effects. This would help integrate theoretical research and practical application to further promote children' s reading and cognitive ability development.

5 Conclusion

This study examined relationships among decoding, language comprehension, phonological memory, and central executive function in third- through sixth-grade children. We found that phonological memory significantly affected decoding; updating and shifting abilities significantly affected language comprehension. However, with increasing grade level, phonological memory' s effect on decoding and shifting' s effect on language comprehension gradually weakened, while updating ability and general cognitive ability may represent more stable predictors of reading development. These findings reveal that phonological memory and central executive function have different relationships with decoding and language comprehension, and that these relationships change with grade level.

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